



November 21, 2025

California Air Resources Board
1001 I Street
Sacramento, CA 95814

Submitted via the [Workshop Comment Submittal Form](#)
and by email to cleancars@arb.ca.gov

Re: WSPA & AFPM Comments on the CARB Drive Forward Light-Duty Vehicle Program Workshop

The Western States Petroleum Association (WSPA)¹ and the American Fuels & Petrochemical Manufacturers (AFPM)² appreciate the opportunity to comment on the October 21, 2025, public workshop held by the California Air Resources Board (CARB) on the Drive Forward Light-Duty Vehicle (LDV) Program.³ WSPA and AFPM have actively participated in the development of various recent vehicle-focused programs, including Advanced Clean Cars II (ACC II), Advanced Clean Trucks (ACT), and Advanced Clean Fleets (ACF). Throughout each rulemaking process, WSPA and AFPM have consistently advocated for a cost-effective, technology-neutral, performance-based approach that preserves consumer choice and does not exacerbate existing economic burdens on the citizens of California and the United States. WSPA and AFPM offer the following comments on CARB's initial concepts for the Drive Forward LDV Program as outlined in this workshop.

WSPA and AFPM recognize the challenges California faces in meeting its air quality and greenhouse gas (GHG) emission reduction goals. While we acknowledge that addressing emissions from the transportation sector is integral to California's goals, CARB should recognize that any actions taken to further these goals, including the Drive Forward LDV Program, must strike an appropriate balance between emission reductions, affordability, and reliability. We therefore strongly urge CARB to adopt performance-based, technology-neutral standards that accurately reflect real-world conditions, are based on a complete life cycle analysis (vehicle and fuel), and account for non-exhaust emissions (NEE), while addressing energy supply and cost concerns.

As discussed in more detail below, the California Environmental Quality Act (CEQA) requires CARB to assess regulatory alternatives in accordance with Cal. Code Regs., tit. 14, § 15130. Similarly, Cal. Health & Safety Code (HSC) § 57005 requires CARB to consider any less costly but equally effective alternatives. To comply with these requirements, CARB must evaluate total life cycle GHG emissions, along with the impacts of total particulate matter (PM) emissions. In prior rulemakings, CARB failed to adequately evaluate infrastructure readiness, market demand, upstream and downstream impacts of zero-tailpipe emission vehicles (ZEVs),⁴ affordability, and alternative approaches with more diverse technology and energy mixes, which violate these statutory mandates.

We look forward to continuing to work with CARB throughout this important process. Our detailed comments are provided below:

1. CARB should adopt performance-based, technology-neutral emission reduction standards to achieve air quality and public health targets.

¹ WSPA is a non-profit trade association that represents companies that produce, refine, transport and market petroleum, petroleum products, natural gas and other energy supplies in California and four other western states, and has been an active participant in air quality planning issues for over 30 years.

² AFPM is a national trade association representing nearly 90% of U.S. refining capacity. Our members proudly produce the gasoline, diesel, jet fuel, and thousands of other products that fuel the U.S. economy and make modern life possible.

³ CARB. Public Workshop on Drive Forward Light-Duty Vehicle Program. October 21, 2025. Available at: https://ww2.arb.ca.gov/sites/default/files/2025-10/2025_10_21_Workshop_Presentation_for_ADA_V5.pdf. Accessed: October 2025.

⁴ Note that the term "zero emissions vehicle", and even near-ZEVs as used by CARB, is a misnomer. ZEVs are not actually zero-emission vehicles when accounting for the vehicle's lifecycle, including GHG and criteria pollutant emissions associated with electricity generation required for charging certain ZEVs and the production of the ZEV vehicle and battery. We recognize that CARB uses "ZEV" to refer only to those vehicles with a specific meaning under California's Drive Forward program, but for ease of review, "ZEVs" is used throughout these comments and encompasses all of the electric vehicle (EV) technologies, including plug in electric vehicles ("PEVs") such as plug-in hybrid electric vehicles ("PHEVs") and battery electric vehicles ("BEVs").

WSPA and AFPM encourage CARB to develop performance-based, technology-neutral standards that offer manufacturers and consumers the necessary flexibility to ensure timely emission reductions to meet the State's GHG emissions reduction and air quality goals in the most cost-effective manner. Under Government Code § 11346.2(b)(4)(A), CARB must consider performance standards as an alternative when it proposes a regulation that would mandate the use of specific technologies or equipment, or prescribe specific actions or procedures. A ZEV-only approach is unlawful following Congress's Resolution of Disapproval of ACC II⁵ and improperly imposes a technology standard without giving due consideration to equivalent performance standards. In evaluating requirements under the Drive Forward LDV Program, CARB must therefore evaluate performance standards that permit a diverse mix of vehicle and fuel technologies.

Similarly, CEQA requires CARB to assess "a reasonable range of alternatives to the proposed project, which could feasibly attain most of the project objectives but could avoid or substantially lessen any of the identified significant impacts." (Cal. Code Regs., tit. 17, § 60004.2). CEQA Guidelines further specify that, in developing regulatory alternatives, agencies must consider alternatives "which are capable of avoiding or substantially lessening any significant effects of the project, even if these alternatives would impede to some degree the attainment of the project objectives." Cal. Code Regs., tit. 14, § 15126.6(b). A diversified approach recognizing the value of multiple technologies and fuels would enable more rapid, reliable, and cost-effective progress toward California's GHG emissions reduction and air quality goals.

As we explained in multiple comment letters for previous rulemakings, achieving emissions reductions in the transportation sector will be most effective through a diverse mix of vehicle and fuel technologies, rather than relying solely on a ZEV pathway. Performance-based standards that leverage all available emissions reduction tools can achieve substantial emission reductions more quickly and effectively than a ZEV-only mandate. ZEV-forcing measures come with significant implementation challenges, including but not limited to insufficient charging and/or supporting electrical transmission/distribution infrastructure, constraints in electricity and hydrogen supply, uncertainty about critical mineral supplies, and ZEV unaffordability, which inhibits fleet turnover. Public discussions with original equipment manufacturers, utilities, and fleet and vehicle owners have raised concerns that deploying ZEVs at the rate necessary to achieve California emission reduction goals will be infeasible without significant infrastructure development. In contrast, a performance-based, technology-neutral framework offers the flexibility needed for sustained, sector-wide emissions reductions, allowing industry to deploy the most effective mix of technologies more quickly and enabling market and consumer choice to determine which solutions are most suitable and cost-effective.

Consistent with these rulemaking requirements, CARB should consider and evaluate multiple scenarios that use alternative liquid and gaseous fuels as pathways to meet the State's GHG emission reductions and air quality goals. Many of these alternate fuel pathways can provide immediate and scalable reductions in both GHG and criteria air pollutant emissions. Supporting these fuels will help ensure continuity of emission reduction progress, energy system resilience, and consumer affordability.

WSPA and AFPM offer the following additional recommendations for CARB's development of a performance-based standard:

- To ensure fairness, transparency, and credibility, CARB must ensure that any standards are grounded in real-world performance data that represent the full range of vehicle and fuel technology combinations, relying on reasonable, transparent implementation assumptions that reflect actual operating conditions.
- CARB should offer support for new, lower-emission internal combustion engine vehicles (ICEVs) that can help address consumer vehicle affordability while delivering near-term emission reductions. This approach would also help ensure equitable and reliable mobility options across the State, especially in regions or sectors where ZEV deployment remains challenging due to fueling infrastructure, fuel supply, vehicle availability, or cost constraints.

⁵ Congress. Public Law 119-16. Available at: <https://www.congress.gov/119/plaws/publ16/PLAW-119publ16.pdf>. Accessed: November 2025.

- CARB should offer support for efforts to expand production of hydrogen, renewable fuels, synthetic or “efuels,” and other low-NO_x, low-carbon intensity fuel options that have already demonstrated proven emission reductions.

We look forward to continuing engagement on this topic.

2. CARB must fully consider all costs associated with battery electric vehicle (BEV) fueling while evaluating their role in its rulemaking.

WSPA and AFPM urge CARB to utilize realistic electricity price projections and fully account for all ZEV charging infrastructure and electricity costs while evaluating the role of BEVs in its LDV strategy. A comprehensive cost analysis is critical for accurately assessing the affordability and equity implications of the State’s strategy to meet its GHG emissions reduction and air quality goals. CARB must clearly lay out the basis for its initial cost assumptions and consider industry and stakeholder feedback as well as current and future market trends to refine these assumptions.

First, CARB must account for rising electricity prices when evaluating the operation costs of ZEVs, as well as impacts from rising energy demands for data centers. In developing various vehicle programs, CARB assumed, without basis, that retail electricity prices would decrease over time. In reality, electricity prices in California have increased substantially and are projected to continue increasing—utilities reported significantly higher average rates over a 3-year and 10-year lookback period, with residential increases as high as 41% since January 2022, and as high as 104% since January 2015.⁶ These increases have outpaced inflation and have impacted both residential and commercial customers. Electricity costs directly affect the affordability of electric vehicles, particularly for lower- and middle-income households and in rural areas, where substantial investments in transmission and distribution are necessary.

Second, CARB must account for costs associated with ZEV charging infrastructure in evaluating the feasibility and impact of ZEV-focused requirements.

- **Installation Costs:** ZEV charging infrastructure represents a significant expenditure, with even the least expensive chargers costing several thousand dollars with equipment, electrical upgrades, and installation labor.⁷ These high costs have significantly impacted the availability of charging infrastructure, creating a major barrier to ZEV adoption.^{8,9}
- **Equitable Charging Access:** Charging equipment costs vary widely depending on charger type and installation conditions. More effective chargers typically entail substantially higher capital, operational, and demand costs—for instance, Level 1 and Level 2 chargers, which are less costly, require several hours for a full charge, while direct current fast chargers (DCFC), which can recharge vehicles in under an hour and provide a refueling experience comparable to gasoline vehicles, are significantly more expensive and reduce battery life. The costs for these more effective chargers are often prohibitive for small businesses, multi-unit housing operators, and individual consumers, resulting in inequitable access to convenient and affordable charging.
- **Public v. Private Charging Costs:** Public and workplace charging frequently incur premium commercial electricity rates, leading to per-mile fueling costs that can exceed those of conventional ICEVs.¹⁰ Previous analysis conducted by the California Energy Commission (CEC) forecasted electricity prices reaching approximately \$8-10/gallon gas equivalent for residential

⁶ PAO. Q1 2025 Electric Rates Report. May 20, 2025. Available at: <https://www.publicadvocates.cpuc.ca.gov/-/media/cal-advocates-website/files/press-room/reports-and-analyses/242005-public-advocates-office-q1-2025-rates-report.pdf>. Accessed: November 2025.

⁷ ICCT. Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas. August 2019. Available at: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf. Accessed: November 2025.

⁸ Brinkley et al., Barriers to Zero-Emission Vehicle Adoption in California: Consumer Behavior and Infrastructure Needs. Final Report. November 2024. Available at: https://ww2.arb.ca.gov/sites/default/files/2024-11/21STC021_Brinkley_Final_Report.pdf. Accessed: November 2025.

⁹ Center for Law, Energy & the Environment (CLEE), University of California, Berkeley School of Law. Financing Electric Vehicle Charging Infrastructure: Barriers and Solutions. 2024. Available at: <https://escholarship.org/uc/item/6r1147v7>. Accessed: November 2025.

¹⁰ California Public Utilities Commission (CPUC), “SB 350 — Utility Costs and Affordability of the Grid of the Future,” February 2021. Available at: <https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/public-presentation-for-cadmus-team-on-ey24-evaluation.pdf>. Accessed: November 2025.

charging in coming years.¹¹ While at-home overnight charging may be more affordable, renters and residents of multi-unit dwellings may not have the same access to home charging.

- **Housing Costs:** Limited access to home charging may result in higher housing or rental costs for units equipped with charging capability, which would present an additional barrier for renters and residents of multi-unit dwellings.

Given these realities, CARB should provide transparent and updated pricing models for EV charging that reflect real-world price variability, charging patterns, and grid demand at different times of day. Without such analysis, cost-effectiveness assessments risk underestimating the true cost burden on consumers and businesses.

Third, CARB must update its economic models to incorporate current and projected ZEV purchase costs, charging costs, and market dynamics. In ACC II and other rulemakings, CARB based its economic analyses on expectations of declining BEV costs and steady BEV market growth over time. However, recent market and federal policy developments undermine both these assumptions.

Overall, BEV total cost of ownership is increasing due to rising electricity prices and the expiration of available incentives. BEVs continue to carry a significantly higher upfront cost than ICEVs, with ZEV equivalents of the top-selling ICEV models in the U.S. priced at roughly 1.5 times more, even after accounting for available incentives.¹² Although CARB has previously stated that the higher upfront cost of BEVs can be offset over time through lower fueling costs, this assumption no longer holds in California's current energy market. In the second quarter of 2024, the cost of fueling ICEVs per 100 miles remained lower than that of comparable BEVs in the entry- and mid-priced categories, due to rising electricity prices and demand charges,¹³ which have been elaborated in the previous comment. The affordability advantage once expected from lower "fuel" costs is eroding rapidly. At the same time, the expiration of the federal \$7,500 tax credit for new BEVs and the \$4,000 credit for used BEVs has widened this affordability gap.¹⁴ These pricing impacts are further exacerbated by ongoing uncertainties in tariff policies and critical mineral supply chains, which are expected to continue driving BEV costs higher in the near term.^{15, 16, 17, 18}

Similarly, there is growing uncertainty in consumer demand for BEVs, with recent market data suggesting a slowdown in BEV adoption. Between 2024 and the first half of 2025, the BEV share of new vehicle sales in California declined from 22.0% to 19.5%, while hybrid vehicle sales increased from 14.8% to 19.2%.¹⁹ This trend suggests that many consumers are opting for hybrids as a more affordable and practical alternative amid high BEV prices and continuing infrastructure challenges, especially in rural and tribal communities, and mountainous areas.

Given these trends and updates in the BEV market, CARB must update its economic models to incorporate current and projected BEV purchase costs, charging costs, and market dynamics. The

¹¹ See CEC Transportation Energy Demand Forecast for the 2021 Integrated Energy Policy Report, dated December 2, 2021, at slide 19.

¹² ZEV Transition Council. ZEV cost: Comparison of passenger car retail prices. June 6, 2025. Available at: <https://zevtc.org/tracking-progress/zev-cost-comparison-passenger-car-retail-prices/>. Accessed: November 2025.

¹³ Anderson Economic Group. 2024 Fueling Cost Comparison: Mid-Priced ICE Cars Less Expensive to Fuel than EVs; Luxury EVs Have Cost Advantage. Available at: <https://www.andersoneconomicgroup.com/2024-fueling-cost-comparison-mid-priced-ice-cars-less-expensive-to-fuel-than-evs-luxury-evs-have-cost-advantage/>. Accessed: November 2025.

¹⁴ US DOE. Federal Tax Credits for New Plug-in Electric and Fuel Cell Electric Vehicles Acquired from January 1, 2023, through September 30, 2025. Available at: <https://www.fueleconomy.gov/feg/tax2023.shtml>. Accessed: November 2025.

¹⁵ See March 26, 2025, presidential proclamation, "Adjusting Imports of Automobiles and Automobile Parts into the United States;" available at: <https://www.whitehouse.gov/presidential-actions/2025/03/adjusting-imports-of-automobiles-and-automobile-parts-into-the-united-states/>. Accessed: November 2025.

¹⁶ See April 29, 2025, presidential proclamation, "Amendments to Adjusting Imports of Automobiles and Automobile Parts into the United States;" available at: <https://www.whitehouse.gov/presidential-actions/2025/04/amendments-to-adjusting-imports-of-automobiles-and-automobile-parts-into-the-united-states/>. Accessed: November 2025.

¹⁷ See October 17, 2025, presidential proclamation, "Adjusting Imports of Medium- and Heavy-Duty Vehicles, Medium- and Heavy-Duty Vehicles Parts, and Buses into the United States;" available at: <https://www.whitehouse.gov/presidential-actions/2025/10/adjusting-imports-of-medium-and-heavy-duty-vehicles-medium-and-heavy-duty-vehicle-parts-and-buses-into-the-united-states/>. Accessed: November 2025.

¹⁸ See April 15, 2025, executive order and fact sheet, "President Donald J. Trump Ensures National Security and Economic Resilience Through Section 232 Actions on Processed Critical Minerals and Derivative Products;" available at: <https://www.whitehouse.gov/fact-sheets/2025/04/fact-sheet-president-donald-j-trump-ensures-national-security-and-economic-resilience-through-section-232-actions-on-processed-critical-minerals-and-derivative-products/>. Accessed: November 2025.

¹⁹ New Car Dealers Association. California Auto Outlook. July 2025. Available at: <https://www.cnca.org/wp-content/uploads/Cal-Covering-2Q-25.pdf>. Accessed: November 2025.

models should transparently assess affordability across income levels and vehicle classes, including sensitivity analyses for electricity price volatility and the availability of incentives. Without such updated analysis, the program risks overestimating consumer readiness for BEV adoption and underestimating the potential for market stagnation. Ensuring accurate and realistic economic and cost modeling is essential not only for achieving California’s GHG emissions reduction and air quality goals, but also for maintaining affordability in California’s programs and preventing disproportionate impacts on lower- and middle-income households.

3. CARB’s scenario modeling should be updated to reflect real-world data on vehicle market share to project future energy demand.

CARB must account for current ICEV market shares and additional factors impacting ZEV market shares, including BEV affordability concerns and ongoing infrastructure challenges in modeling the projected vehicle fleet makeup and associated energy demand. Basing assumptions on real-world data is critical for identifying feasible emission reduction strategies and pathways that can deliver actual, measurable reductions in both GHGs and criteria pollutants. A data-driven approach will help ensure that CARB and other State agencies better anticipate transportation fuel demand and make informed decisions on other related climate policies, including the Cap-and-Invest Program and the Low Carbon Fuel Standard (LCFS) regulation.

Considering the current lag in developing charging stations and related electrification infrastructure (particularly in low-income and environmental justice communities), it is imperative that CARB take a bottom-up approach when projecting fleet makeup to ensure that the daily transportation needs of the state’s populace are met. ICEVs continue to dominate the LDV market—as workshop Slide 30 illustrates, ICEVs accounted for over 70% of vehicle sales in 2024 and will remain a significant share of the statewide fleet for the foreseeable future. CARB must account for this continued market share in evaluating anticipated demand for transportation fuels.

Similarly, CARB’s assessment of future fleet makeup must account for current obstacles to ZEV adoption. These obstacles include ZEV affordability concerns and infrastructure challenges, as outlined in Comment 2 above. In addition, CARB should evaluate potential market and policy uncertainties that may impact ZEV availability, such as federal regulations,²⁰ global EV production slowdowns,²¹ tariff increases, and limited availability of critical minerals needed for batteries.

CARB must also account for electricity supply constraints and transmission and distribution infrastructure improvements required to support increased electricity demand associated with an increasing ZEV market share. Electricity demand forecasts from CARB and the CEC show inconsistencies in projected LDV electricity use,^{22,23} highlighting a disconnect between CARB’s ZEV regulations and CEC’s electricity resource planning. These limitations must be addressed in the scenario modeling for this rulemaking. In line with these considerations, CARB’s environmental analysis must also address operational-related effects to utilities and services systems based on new demand for water, wastewater, electricity, and gas services, including new electric generating infrastructure, to meet ZEV energy demand. (Cal. Code Regs., tit. 17, § 60004.2, subd. a).

4. CARB must quantitatively assess life cycle ZEV GHG emissions, including assessments of upstream and downstream impacts, and update upstream emissions factors for ZEVs.

CARB cannot adequately evaluate the impacts of a LDV rulemaking, without conducting a full life cycle assessment (LCA) that covers upstream, operational, and downstream stages.

CEQA requires CARB to assess regulatory alternatives considering their cumulative impacts. Cal. Code Regs., tit. 14, § 15130. To comply with this requirement, CARB must conduct a life cycle

²⁰ Congress. Public Law 119-16. Available at: <https://www.congress.gov/119/plaws/publ16/PLAW-119publ16.pdf>. Accessed: November 2025.

²¹ International Energy Agency. Trends in electric car markets. 2025. Available at: <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2>. Accessed: November 2025.

²² CARB. 2022 Scoping Plan for Achieving Carbon Neutrality, December 2022. Available: <https://www2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf>. Accessed: November 2025.

²³ California Energy Commission. California Energy Demand, 2024-2040. Available at: <https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report-iepr/2024-integrated-energy-policy-report-0>. Accessed: November 2025.

emissions analysis of ZEVs to understand and evaluate significant impacts. In addition, HSC § 57005 requires CARB to consider any less costly but equally effective alternatives. Without a life cycle emissions analysis of ZEVs, CARB cannot accurately perform this analysis.

An LCA is also critical to meeting other statutory requirements. CARB has a responsibility to minimize the “leakage” potential of any regulatory activities, pursuant to HSC § 38562(b)(8). As part of this responsibility, CARB must analyze the potential for emissions reduction activities in the state to be offset by an equivalent or greater increase in GHG emissions outside the state. This analysis requires estimating the impact of emissions outside the state *from a life cycle perspective*. CARB must adequately account for upstream and downstream emissions associated with ZEVs to fulfill this statutory obligation.

CARB’s prior analysis in support of ACC II ignored important life cycle impacts, including:

- Upstream life cycle GHG emissions from out-of-state fuel production and transportation activities for California reformulated gasoline (CaRFG), electricity and hydrogen; and
- GHG emissions associated with vehicle production changes required by the proposed regulation, which may be particularly significant for minerals extraction and processing and battery production, transportation, and disposal impacts for battery electric vehicles that are not part of the baseline for ICEVs.

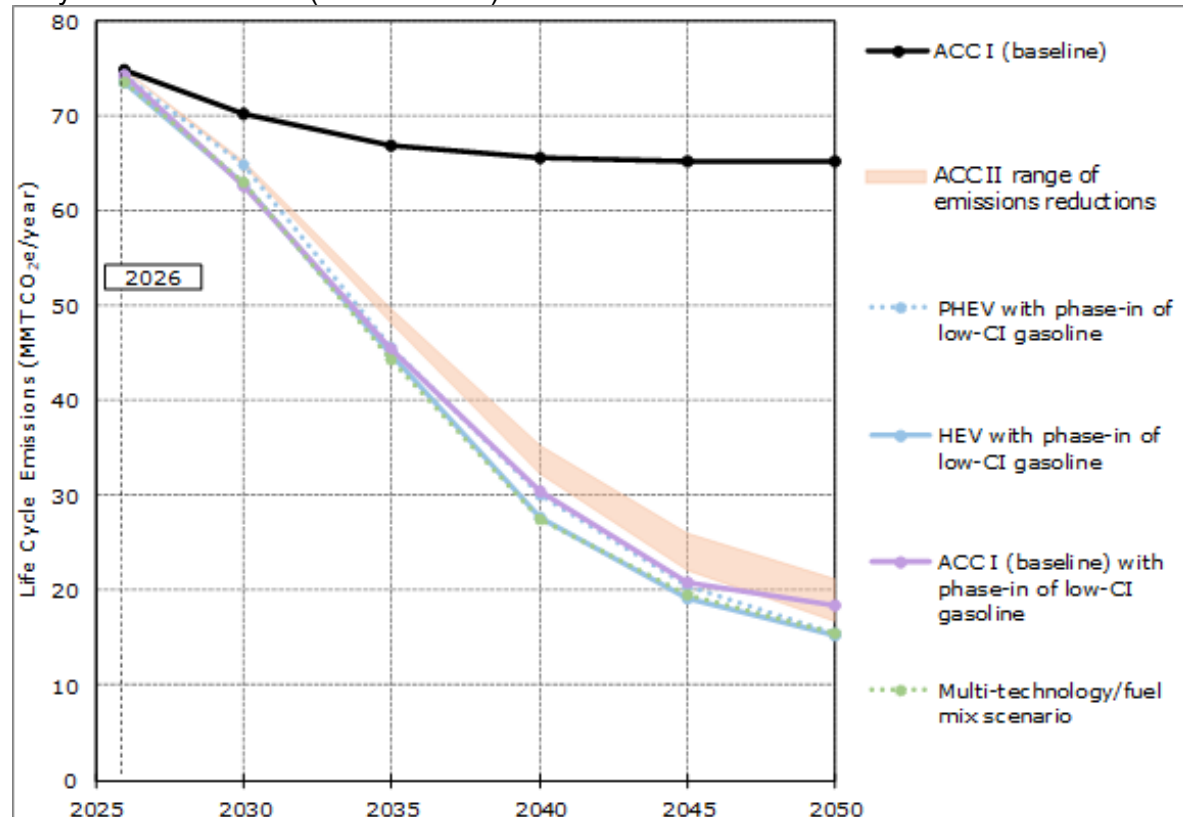
This approach skewed CARB’s analysis in favor of ZEVs, preventing the Agency from equitably considering regulatory alternatives.

Ramboll conducted a technology-neutral study of Light Duty Automobiles that analyzed and compared the full life cycle GHG emissions of a broad range of alternative technologies and fuels.²⁴ This study demonstrates that GHG emission goals can be met through many different technology mixes (Figure 1). In particular, vehicle production cycle emissions for a model year 2026 BEV (10.1 metric tons of carbon dioxide equivalent (MTCO₂e) per vehicle) were about 74% higher than those for a model year (MY) 2026 ICEV (5.8 MTCO₂e per vehicle), increasing further if the BEV undergoes a battery replacement (15.5 MTCO₂e per vehicle).²⁵

²⁴ *Id.*, Figure ES-1.

²⁵ Ramboll LCA Study, Figure 3-5. Available at: <https://www.arb.ca.gov/lists/com-attach/477-accii2022-AHcAdQBxBDZSeVc2.pdf>. Accessed: November 2025.

Figure 1: Life Cycle GHG Emissions for Key Scenarios in the Ramboll LDA Study California Light Duty Automobile Fleet (2026 to 2050)²⁶



This study illustrates the importance of evaluating ZEV impacts from a life cycle perspective.

Apart from emissions-focused impacts, CARB should also conduct a full environmental LCA to capture the broader environmental implications of battery production and deployment, including national energy security concerns (given geopolitical factors involved in manufacturing critical minerals for ZEVs) and any potential economic tariffs. This includes evaluation of the upstream environmental impacts of critical mineral mining (lithium, cobalt, nickel, etc.), which can significantly affect air and water quality, local ecosystems, and community health across the supply chain,^{27,28,29,30} as well as the downstream impacts related to battery end-of-life management.^{31,32} Current recycling capacity is limited, and available programs are only applicable to certain battery chemistries.^{33,34} Additionally, the analysis should recognize the political and economic uncertainties associated with global battery supply chains.³⁵ Variability in mineral availability, international trade restrictions, and fluctuating costs directly affect the battery manufacturing processes and, consequently, the overall environmental impacts of batteries and ZEVs. CARB cannot assess the “indirect and cumulative

²⁶ *Id.*

²⁷ See International Energy Agency (IEA). Sustainable and responsible development of minerals. Available at: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/sustainable-and-responsible-development-of-minerals>.

²⁸ Mrozik et. al. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy & Environmental Science* 14, no. 10. October 13, 2021. Available at: <https://doi.org/10.1039/D1EE00691F>. Accessed: November 2025.

²⁹ Arridsson et. al. Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery. *Int J Life Cycle Assess* 27, 1106–1118. August 11, 2022. Available at: <https://doi.org/10.1007/s11367-022-02084-3>. Accessed: November 2025.

³⁰ Brown et al. Occupational, environmental, and toxicological health risks of mining metals for lithium-ion batteries: a narrative review of the Pubmed database. *Journal of Occupational Medicine and Toxicology*. August 27, 2024. Available at: <https://doi.org/10.1186/s12995-024-00433-6>. Accessed: November 2025.

³¹ See IEA. Recycling of critical minerals, Executive Summary. Available at: <https://www.iea.org/reports/recycling-of-critical-minerals/executive-summary>.

³² Slattery et al. Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling* 174. November 2021. Available at: <https://doi.org/10.1016/j.resconrec.2021.105755>. Accessed: November 2025.

³³ See Chacana-Olivares, Jaime, et al., *Lithium-ion battery recycling: a perspective on key challenges and opportunities*, 3 npj Materials Sustainability 38 (2025). Available at: <https://www.nature.com/articles/s44296-025-00083-7>.

³⁴ Velázquez-Martínez et al. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries* 5.4. Nov. 4, 2019. Available at: <https://doi.org/10.3390/batteries5040068>. Accessed: November 2025.

³⁵ See IEA. With new export controls on critical minerals, supply concentration risks become reality. October 23, 2025. Available at: <https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality>.

impacts” of its proposal without accounting for these upstream and downstream impacts (Cal. Code Regs., tit. 14, § 15130).

An adequate assessment of ZEV emissions impacts must extend beyond tailpipe emissions to consider the full environmental footprint of ZEV technologies.

The total **upstream** impacts should therefore include, for example:

- critical mineral extraction and processing;
- battery component manufacturing;
- transportation and import of battery components; and
- electricity generation used during vehicle charging.

The total **downstream** impacts should include, for example:

- potentially eliminating emission reduction opportunities from newer, more affordable ICEVs vehicles across California’s fleet;
- battery disposal and recycling programs; and
- potential environmental contamination.

These emissions are a matter of central relevance to this rulemaking, and it would be arbitrary and capricious for CARB to continue excluding them from the environmental analysis.

5. CARB should revise its assessment of non-exhaust emissions (NEE) to account for NEE sources from tire wear and road dust resuspension.

CARB’s consideration of certain non-exhaust emissions (NEE) in this round of LDV regulatory development is a step in the right direction, as NEE from heavier vehicles may significantly contribute to vehicle PM emissions. However, CARB’s analysis is limited to NEE from brake wear, which excludes additional NEE from tire wear and road dust resuspension. We therefore urge CARB to expand its analysis beyond brake wear alone to fully account for NEE sources.

CEQA requires CARB to assess regulatory alternatives considering their indirect and cumulative impacts (Cal. Code Regs., tit. 14, § 15130). One of CEQA’s primary concerns is with “human health and safety.” See *Cal. Building Indus. Ass’n v. Bay Area Air Quality Mgmt. Dist.*, 62 Cal. 4th 369, 386 (2015); Cal. Pub. Res. Code § 21083(b)(3). Particulate matter impacts from tire wear and road dust resuspension have the potential to be greater in battery electric vehicles compared to ICEVs. There is a high correlation between these emissions and vehicle weight, and ZEVs generally weigh more on average due to the inclusion of batteries. CARB cannot meaningfully evaluate the environmental impacts of different regulatory alternatives without understanding the tradeoffs between increased vehicle weight in ZEVs, which can elevate tire wear emissions and road dust resuspension, and the reductions in brake wear achieved through regenerative braking. A California study found that brake and tire wear emissions increase with vehicle mass, although the magnitude of the increase is sensitive to vehicle deceleration.³⁶ Another study reported that battery electric vehicles may generate higher brake and tire wear emissions than conventional vehicles due to their heavier weights.³⁷ Understanding these interactions is essential to accurately assessing the net environmental impacts of BEVs and other advanced technologies.

WSPA and AFPM encourage CARB to ensure that its regulatory analysis reflects the full spectrum of NEE impacts. Doing so will support the development of more accurate, evidence-based policy decisions, better reflect real-world emissions impacts, and maintain credibility in managing the overall emissions from ZEVs and ICEVs. Without including tire wear and road dust resuspension, any comparison of NEE profiles between ZEVs and ICEVs may be misleading.

³⁶ Oroumihyeh, F., & Zhu, Y. (2021). Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity. *Atmospheric Environment X*, 12, 100121. <https://doi.org/10.1016/j.aeaoa.2021.100121> Accessed: October 2025.

³⁷ Chen et. al. Contributions of non-tailpipe emissions to near-road PM2.5 and PM10: A chemical mass balance study. October 15, 2023. Available at: <https://doi.org/10.1016/j.envpol.2023.122283>. Accessed: October 2025.

6. WSPA and AFPM support CARB's proposal to update the window sticker for ZEVs as a consumer protection measure.

WSPA and AFPM support CARB's proposal to update the ZEV window sticker as a consumer protection measure and appreciate CARB's incorporation of stakeholder feedback. Providing consumers with accurate and transparent information is essential for enabling informed vehicle purchasing decisions and to maintaining confidence in the ZEV market.

We agree that ZEV manufacturers must disclose clear information regarding vehicle range, efficiency, and performance. CARB should ensure that city and highway fuel economy and range estimates reflect real-world driving conditions. Consumers need information about expected battery performance over time, including potential degradation and its impact on vehicle range, as this information is critical for evaluating the long-term utility and value of ZEVs.

Current test-cycle are flawed because they rely on fundamentally different procedures that distort the estimated environmental benefits of ZEVs versus ICEVs. ZEV test cycles only evaluate a limited performance range compared to ICEVs, which significantly overestimates EV emissions reductions. ICEV fuel economy is estimated using the U.S. Environmental Protection Agency's (EPA's) "5-cycle method" (i.e., Federal Test Procedure-75 (FTP) at regular and cold temperatures, Highway Fuel Economy Test (HWFET), High-Speed Driving (US06), and Use of Air Conditioning (SC03)). In contrast, estimates of ZEV fuel economy evaluate a lower top speed (60 miles per hour (mph) compared to ICEVs tested at 80 mph), a lower acceleration rate (3.2 mph per second (mph/sec) compared to ICEVs tested at 8.46 mph/sec), and idealized performance temperatures (ZEVs are tested at optimal battery performance temperatures of approximately 75 °F, while ICEVs are tested at 20 °F and 95 °F).³⁸ Furthermore, ZEV testing assumes no use of air conditioning or heating.³⁹ These do not reflect real-world driving conditions and bias the comparison to favor ZEVs.

To enhance the credibility of the ZEV window sticker program, ensure consumers have a clear understanding of vehicle emissions, and support technology-neutral incentives for emission reductions across the entire vehicle market, we recommend that CARB correct its analyses and then reevaluate its claim on the draft window sticker that "Zero-emission vehicles reduce harmful emissions that cause climate change and air pollution." We recommend that CARB revise this statement in accordance with the following considerations:

- (a) **Upstream GHG emissions from battery production:** ZEVs, particularly BEVs, involve significant upstream GHG emissions associated with battery manufacturing, critical mineral extraction, and component production. These emissions should be reflected in any claim about net emissions benefits. The U.S. Department of Energy already publicly reports upstream emissions from BEVs and other vehicles as part of its official fuel economy information website at: www.fueleconomy.gov. The emissions from battery production are of direct relevance to this rulemaking and CARB's failure to account for them would be arbitrary and capricious.
- (b) **Other vehicle technologies and alternative fuels:** There are multiple pathways, including advanced lower-emission ICEV technologies, renewable fuels, and hybrid systems, that can also achieve meaningful reductions in GHGs and air pollutants. Any vehicle achieving comparable emissions reductions should be eligible for similar consumer disclosures to maintain consistency and fairness.

7. CARB's enactment of new LDV requirements is limited by state law and congressional disapproval of prior waivers.

WSPA and AFPM caution CARB against promulgating new LDV requirements that would effectively ban the sale of any vehicle category in California, such as ICEVs, by requiring accelerated deployment of electric vehicles. Executive Order N-27-25 makes clear that California seeks to maximize ZEV investments and phase out ICEVs, directing CARB to "immediately assess additional actions to advance progress on light-, medium-, and heavy-duty zero-emission vehicle adoption in

³⁸ See AFPM Comments on the Department of Energy Petroleum-Equivalent Fuel Economy Calculation and Petition for Rulemaking, 88 Fed. Reg. 21525 (April 11, 2023).

³⁹ *Id.*

California” and to incentivize vehicle manufacturers to continue following the requirements of the ACC II program, even though this program is preempted. Consistent with the Executive Order’s explicit focus on ZEVs, CARB’s LDV workshop indicates that CARB is seeking to deploy as many ZEVs as legally permissible through this rulemaking, at the expense of all other technologies.⁴⁰

The California Legislature has unequivocally denied CARB the authority to ban any vehicle category, as stipulated in HSC § 43018.5(d)(2):

The regulations adopted by the state board pursuant to subdivision (a) shall not require any of the following: . . . (2) A ban on the sale of any vehicle category in the state, specifically including, but not limited to, sport utility vehicles and light-duty trucks.

This prohibition limits CARB’s authority to promulgate “regulations that achieve the maximum feasible and cost-effective reduction of greenhouse gas emissions from motor vehicles.” HSC § 43018.5(a).

California law also prohibits the unconstitutional delegation of legislative power to unelected state agencies. See *Plastic Pipe & Fittings Assn. v. Cal. Bldg. Stds. Com.* (2004) 124 Cal.App.4th 1390, 1410. Such a delegation occurs if a statute authorizes a different administrative body to make a fundamental policy decision or fails to provide adequate direction for implementing a fundamental policy determined by the Legislature. See *id.* While the Legislature may, after declaring a policy and fixing a primary standard, confer upon administrative officers the power to “fill up the details” by prescribing administrative rules and regulations,⁴¹ any requirement that effectively bans a vehicle category would not be such a regulation that agencies may issue to “fill up the details” of legislative enactments.

WSPA and AFPM further note that such a ban would infringe upon the vested rights doctrine. The various permits obtained by oil and gas, refining, and renewable fuel companies establish a right that has been “legitimately acquired or is otherwise ‘vested.’” See *Hardesty v. Sac. Metro. Air Quality Management Dist.* (2011) 202 Cal.App.4th 404, 414. A ban on the sales of vehicle categories would infringe on the vested rights of businesses that have lawfully operated in the transportation fuel (both traditional and renewable) and petrochemical space pursuant to express permission under California law. While a ban does not expressly revoke any permits, it achieves the same objective by eliminating demand for transportation fuel products, thereby significantly reducing the value of those permits to operate in the industry.

Additionally, § 209(a) of the Clean Air Act (CAA) prohibits states from “adopt[ing] or attempt[ing] to enforce any standard relating to the control of emissions from new motor vehicles.”⁴² While California may apply for a waiver from EPA allowing it to adopt such standards under CAA § 209(b),⁴³ in the absence of such a waiver, the general prohibition applies.⁴⁴

Congress recently disapproved, pursuant to the Congressional Review Act (CRA), three federal preemption waivers previously granted to California by EPA under § 209 of the CAA.⁴⁵ These waivers purported to provide CARB with authority to enforce its ACC II, ACT, and Heavy-Duty Vehicle and Engine “Omnibus” Low NO_x (Omnibus) regulations.⁴⁶

The CRA prohibits adoption of “a new rule that is substantially the same” as a prior, disapproved rule.⁴⁷ This constrains CARB’s enactment of new LDV requirements. By disapproving EPA’s waiver for ACC II, Congress effectively prohibited California from adopting or enforcing a ZEV mandate without the appropriate EPA waiver.

⁴⁰ CARB, Drive Forward Light - Duty Vehicle Program (Oct. 21, 2025), https://www2.arb.ca.gov/sites/default/files/2025-10/2025_10_21_Workshop_Presentation_for_ADA_V5.pdf.

⁴¹ See *Kugler v. Yokum* (1968), 69 Cal.App.2d 371, 376.

⁴² 42 U.S.C. § 7543(a).

⁴³ See 42 U.S.C. § 7543(b).

⁴⁴ See *Central Valley Chrysler-Jeep v. Witherspoon*, 456 F.Supp.2d 1160, 1174 (E.D. Cal. 2006) (emphasizing that “regulations are preempted unless the EPA issues a waiver under section 209(b)”).

⁴⁵ See *id.* at 1–2. See also H.J. Res. 87; H.J. Res. 88; H.J. Res. 89; Statement by the President (June 12, 2025), <https://www.whitehouse.gov/briefings-statements/2025/06/statement-by-the-president/>.

⁴⁶ See 42 U.S.C. § 7543 (prohibiting states from “adopt[ing] or attempt[ing] to enforce vehicle emissions standards without a valid waiver).

⁴⁷ 5 U.S.C. § 801(b).

Thank you for considering our comments. We would welcome the opportunity to discuss these comments and recommendations in more detail with CARB staff.

Sincerely,

A handwritten signature in blue ink that reads "Tanya DeRivi".

Tanya DeRivi
Senior Director, California Climate and Fuels
Western States Petroleum Association

A handwritten signature in blue ink that reads "F. Turatti".

Fred Turatti
Senior Director, Fuel and Vehicle Policy
American Fuel & Petrochemical Manufacturers



ATTACHMENT A

139 STAT. 66

PUBLIC LAW 119–16—JUNE 12, 2025

Public Law 119–16
119th Congress

Joint Resolution

June 12, 2025
[H.J. Res. 88]

Providing congressional disapproval under chapter 8 of title 5, United States Code, of the rule submitted by the Environmental Protection Agency relating to “California State Motor Vehicle and Engine Pollution Control Standards; Advanced Clean Cars II; Waiver of Preemption; Notice of Decision”.

Resolved by the Senate and House of Representatives of the United States of America in Congress assembled, That Congress disapproves the rule submitted by the Environmental Protection Agency relating to “California State Motor Vehicle and Engine Pollution Control Standards; Advanced Clean Cars II; Waiver of Preemption; Notice of Decision” (90 Fed. Reg. 642 (January 6, 2025)), and such rule shall have no force or effect.

Approved June 12, 2025.

LEGISLATIVE HISTORY—H.J. Res. 88:

CONGRESSIONAL RECORD, Vol. 171 (2025):

Apr. 30, May 1, considered and passed House.

May 21, 22, considered and passed Senate.

DAILY COMPILATION OF PRESIDENTIAL DOCUMENTS (2025):

June 12, Presidential remarks and statement.





Q1 2025 Electric Rates Report

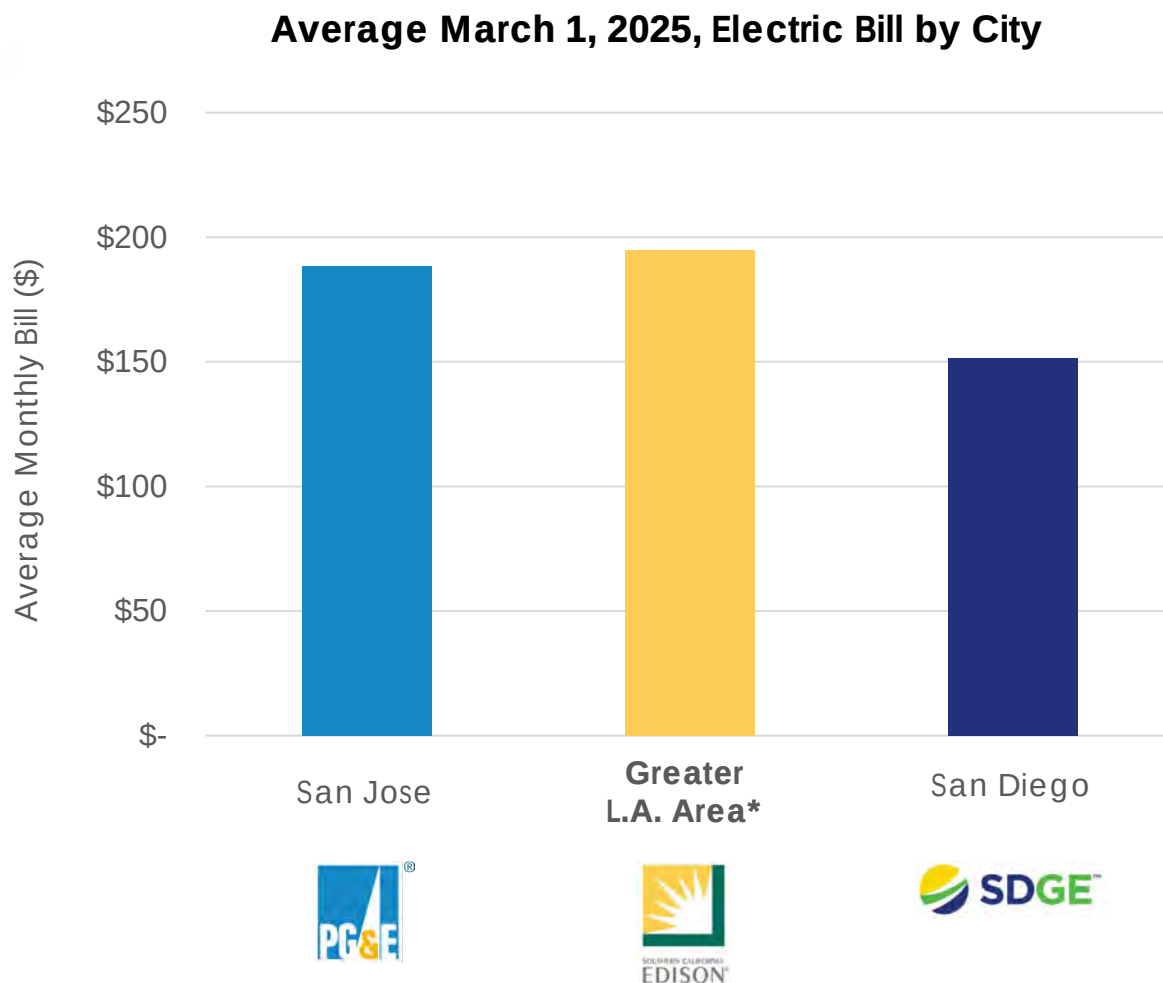
The Public Advocates Office at the California Public Utilities Commission

May 20, 2025

About

- The Public Advocates Office represents utility customers' interests primarily by participating in proceedings before the California Public Utilities Commission and engaging in other policymaking forums.
- The California electric utilities recover their operational and investment costs through the rates they charge their customers. These rates regularly change due to many factors. We track the rates and develop recommendations to minimize costs to ratepayers.
- This report summarizes residential electric rate changes across Pacific Gas and Electric (PG&E), San Diego Gas & Electric (SDG&E), and Southern California Edison (SCE) service territories through April 2025.

Bills compound affordability challenges across the state



- Over the last few years electric bills are generally rising due to **higher electricity use** (e.g., air conditioning) and **higher overall electricity prices ("rates")**.
- Low-income households are most disproportionately impacted from higher rates and bills.

Nearly 1 in 5 households are behind on their energy bills

	# of Customers in Arrears	% of Customers in Arrears	Average Amount Owed
PG&E	1,099,775	20%	\$710
SCE	863,488	19%	\$957
SDG&E	343,422	25%	\$613
Combined	2,306,685	19.8%	\$788

Residential average rates have significantly increased

	Average Rate (\$ per kWh)	3-year Change Jan 2022 to April 2025	10-year Change Jan 2015 to April 2025
PG&E	\$0.386	↑ 41%	↑ 104%
SCE	\$0.314	↑ 25%	↑ 83%
SDG&E	\$0.397	↑ 5%	↑ 71%

Main electricity rate drivers

10-Year Change

Jan 2015 to April 2025

Primary Statewide Drivers

PG&E

↑ 104%

SCE

↑ 83%

SDG&E

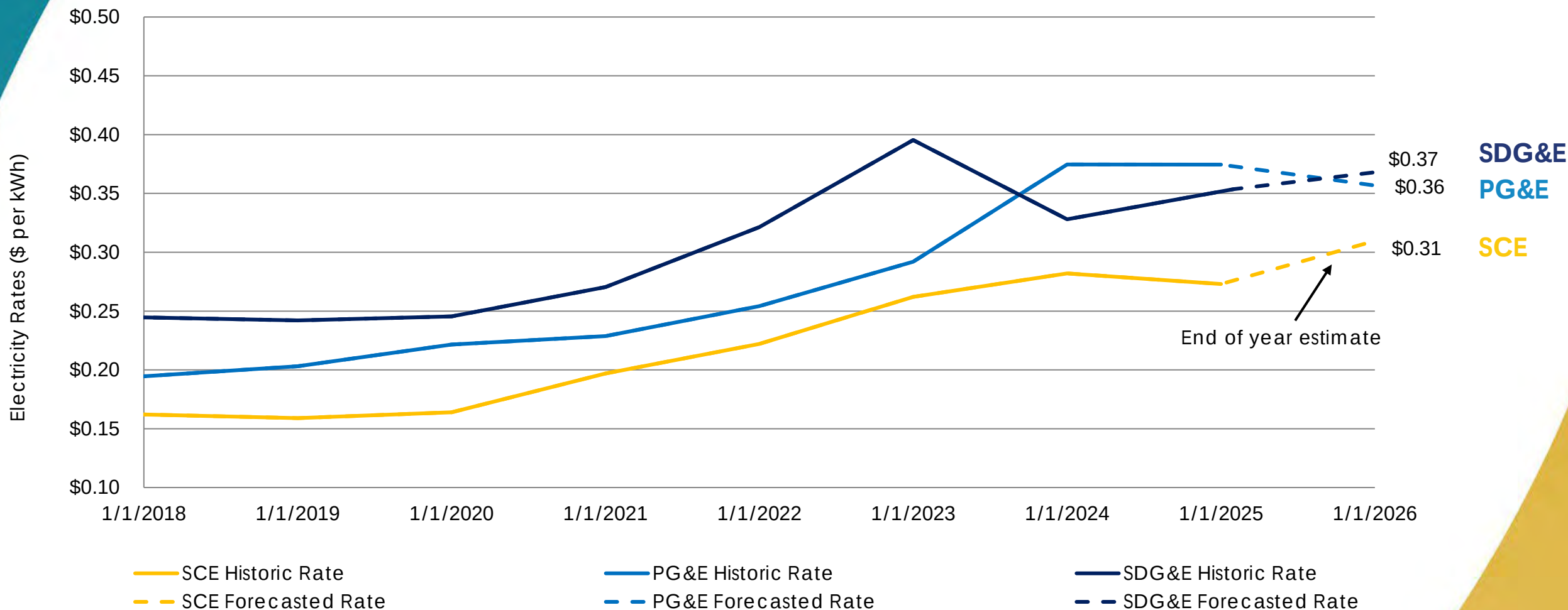
↑ 71%

1. Wildfire mitigation and insurance
2. Transmission & distribution investments
3. Rooftop solar incentives (“net energy metering”)

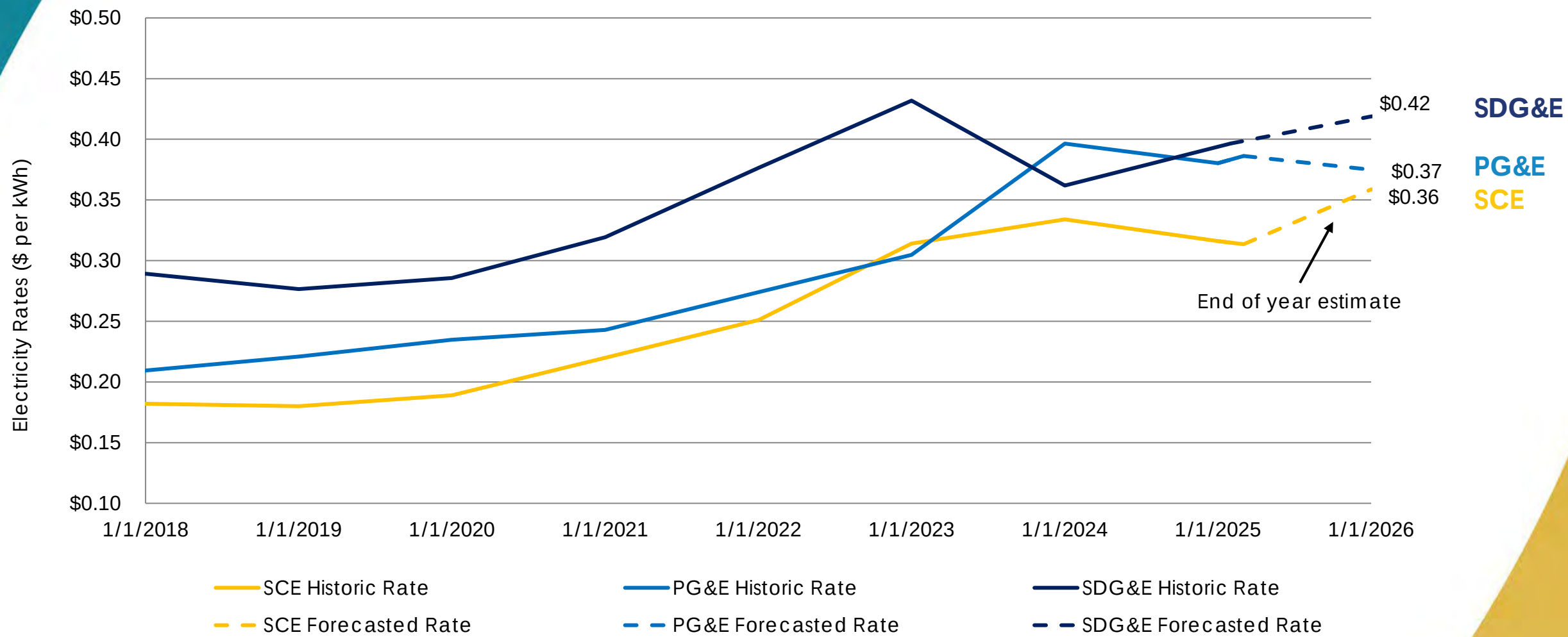
Source: California Public Utilities Commission SB 695 report: Report to the Governor and Legislature on Actions to Limit Utility Cost and Rate Increases... (2023)

Bundled System Average Rates (SAR)

System Average Rate (SAR) is the average amount paid per kilowatt-hour (\$/kWh) by customers who receive both electricity generation and delivery from their utility. It is calculated by dividing the utility's total electric revenues by the total electricity sold to bundled customers. Customer classes include residential, commercial, industrial, agricultural, street lighting, and public agencies.

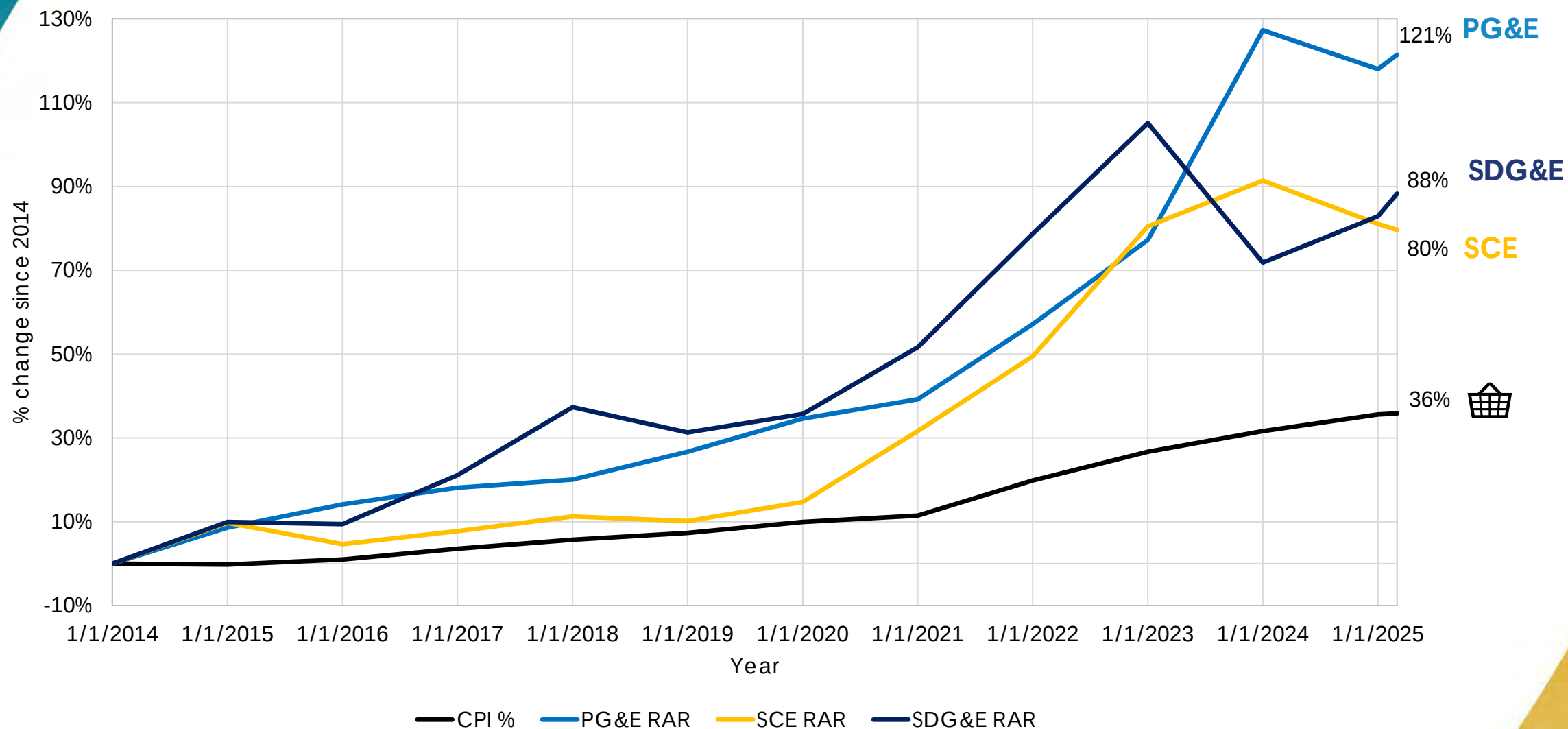


Average Residential Electricity Rates (RAR)



CA rates represent residential average rates excluding California Climate Credit. Forecasted rates only include known revenue change requests and will likely increase as future revenue change requests are filed.
Source: *Investor-Owned Utility Advice Letters (California Rates)* for historic rates and *utility submitted Cost and Rate Trackers* for forecasted rates.

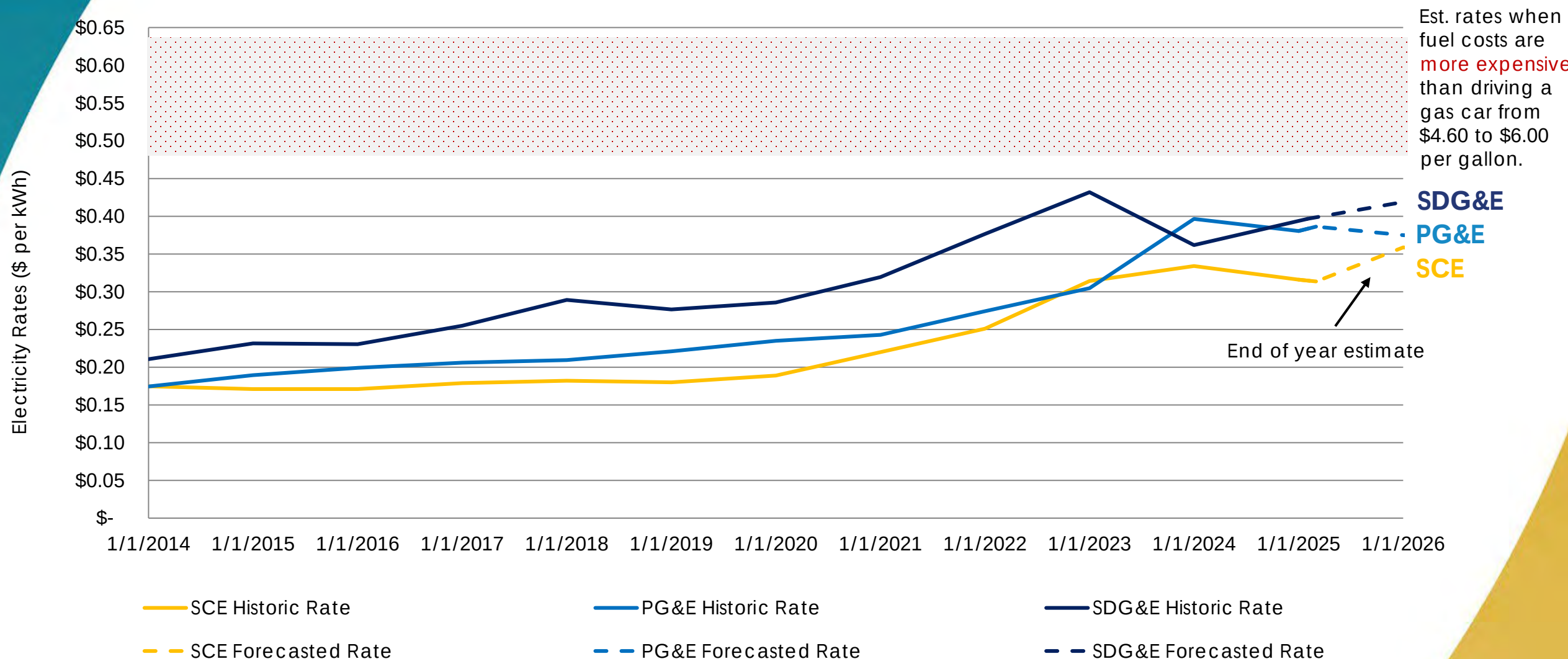
Rates have increased substantially since 2014, surpassing inflation



*Showing latest Bundled Residential Average Rates (RAR) and Consumer Price Index (CPI) for All Urban Consumers (CPI-U) found at <https://data.bls.gov/cgi-bin/dsrv?cu> as of May 15, 2025.

**For details on primary drivers of rate changes in Q1 2025, see Appendix Slides 18 through 23.

EV Fuel Price Parity w/ Bundled Residential Average Rate



Assumptions for this slide found in Appendix on Slide 18.

Avg residential rates represent average residential rate customers excluding California Climate Credit. Future estimates may be conservative as they only include pending applications.

Source: Investor-Owned Utility Advice Letters (California Residential Average Rates) for historic rates and utility submitted Cost and Rate Trackers for forecasted rates.

Wildfire-Related Revenue Requirement* (RRQ) by Utility

	Jan 2023	% of Total RRQ 2023	June 2024	% of Total RRQ 2024	Jan 2025	% of Total RRQ 2025
PG&E	\$2,398,830,000	15%	\$5,213,266,000	24%	\$4,103,465,000	21%
SCE	\$1,447,261,000	9%	\$2,026,051,000	11%	\$2,668,550,000	15%
SDG&E	\$291,158,000	7%	\$514,503,000	13%	\$585,005,000	15%

The chart above is based on latest figures as of February 2025 and includes wildfire-related insurance and the Wildfire Fund Charge. Some historical data for Jan 2023 or June 2024 may have been updated by the IOUs and reflected in any change from the figures presented in the Q3 2024 Report. For more context, please visit our website and related memo: <https://www.publicadvocates.cpuc.ca.gov/press-room/reports-and-analyses/wildfire-cost-increases-of-california-electric-ious>

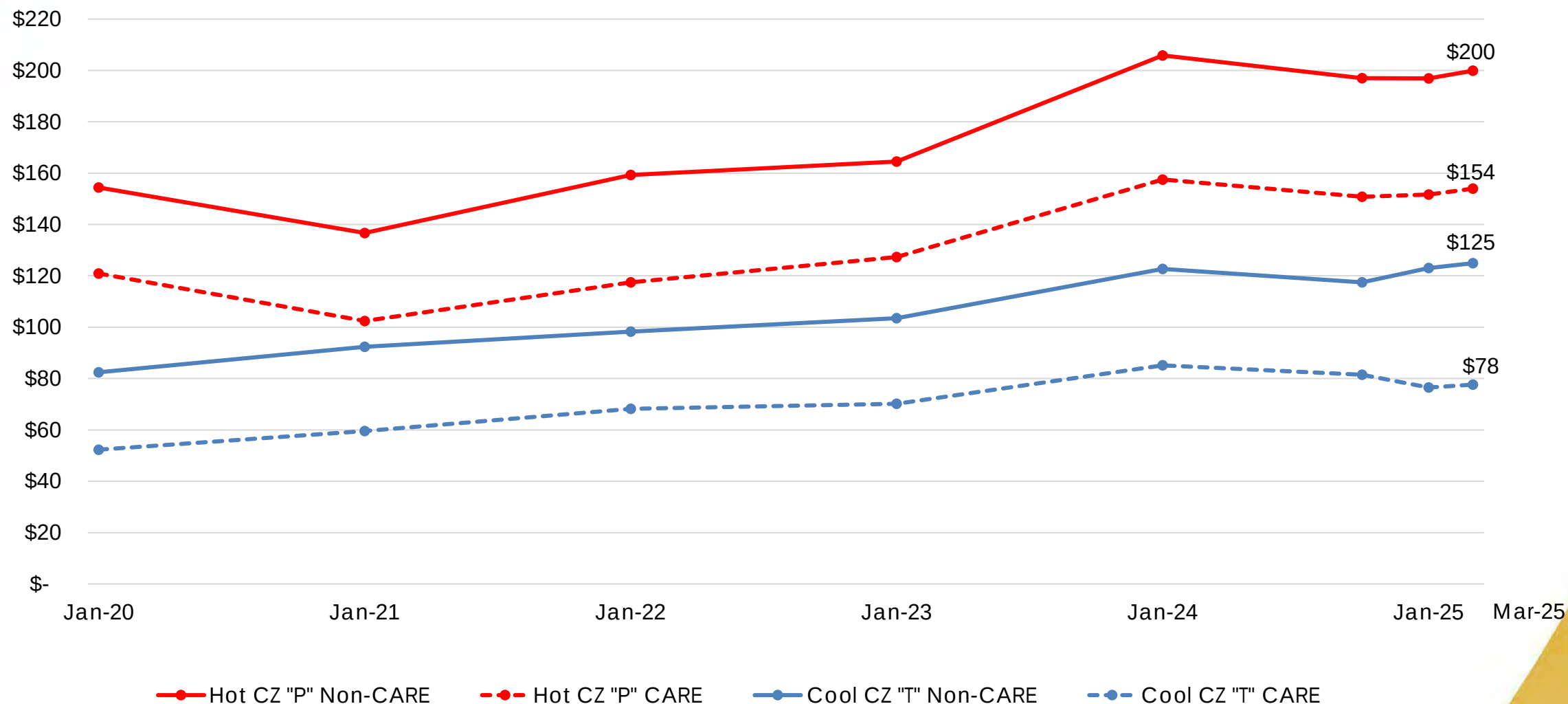
*A revenue requirement is the total amount a utility is authorized to collect from customers to cover its costs – including operations, maintenance, taxes, depreciation, and a return on investment.

Historic Trend of Average Electricity Bills for CARE* and Non-CARE Customers

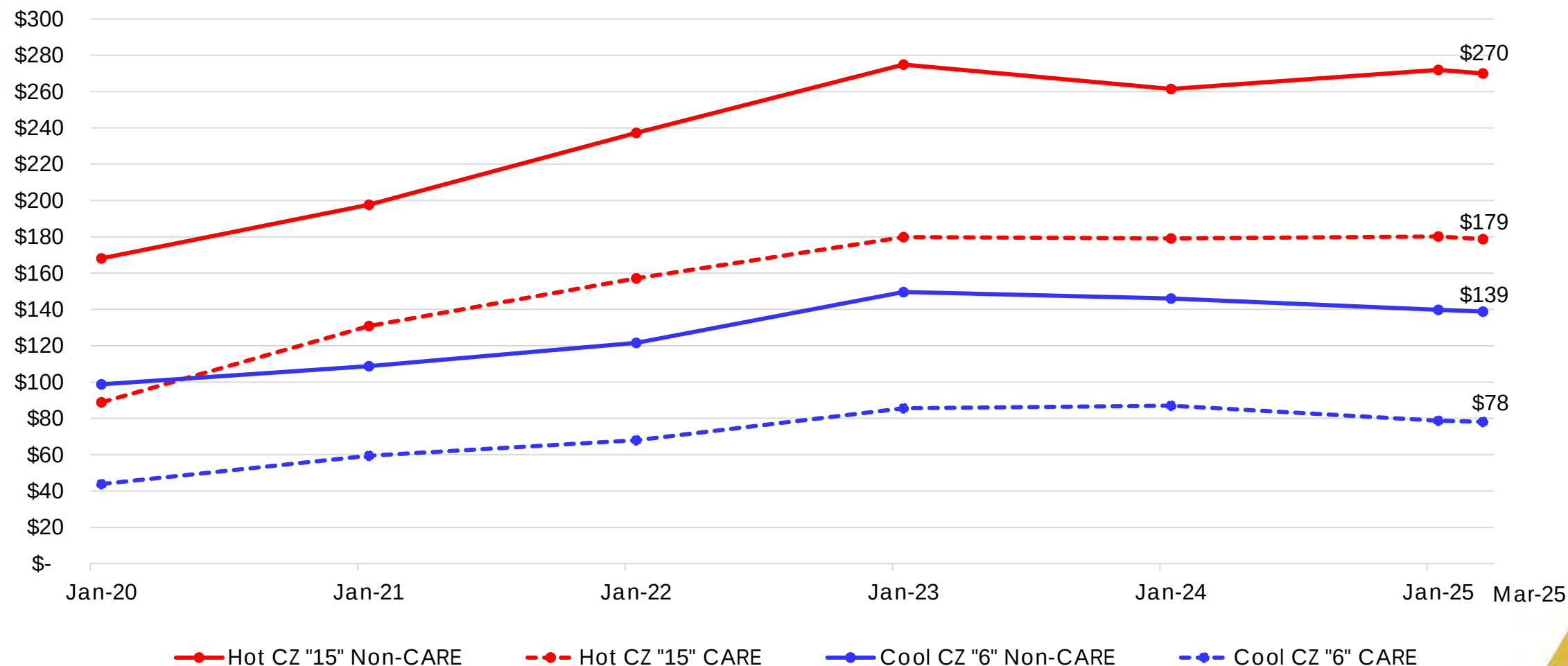
Using a Sample of Hot & Cool Climate Zones
from each IOU's Service Territory

*CARE customers are those households with incomes at or below 200% of the Federal Poverty Level and enrolled in the California Alternate Rates for Energy (CARE) program, which provides them a 20-35% discount on their energy bills.

PG&E's Average Monthly Electricity Bills for CARE & Non-CARE Customers in Hot and Cool Climate Zones

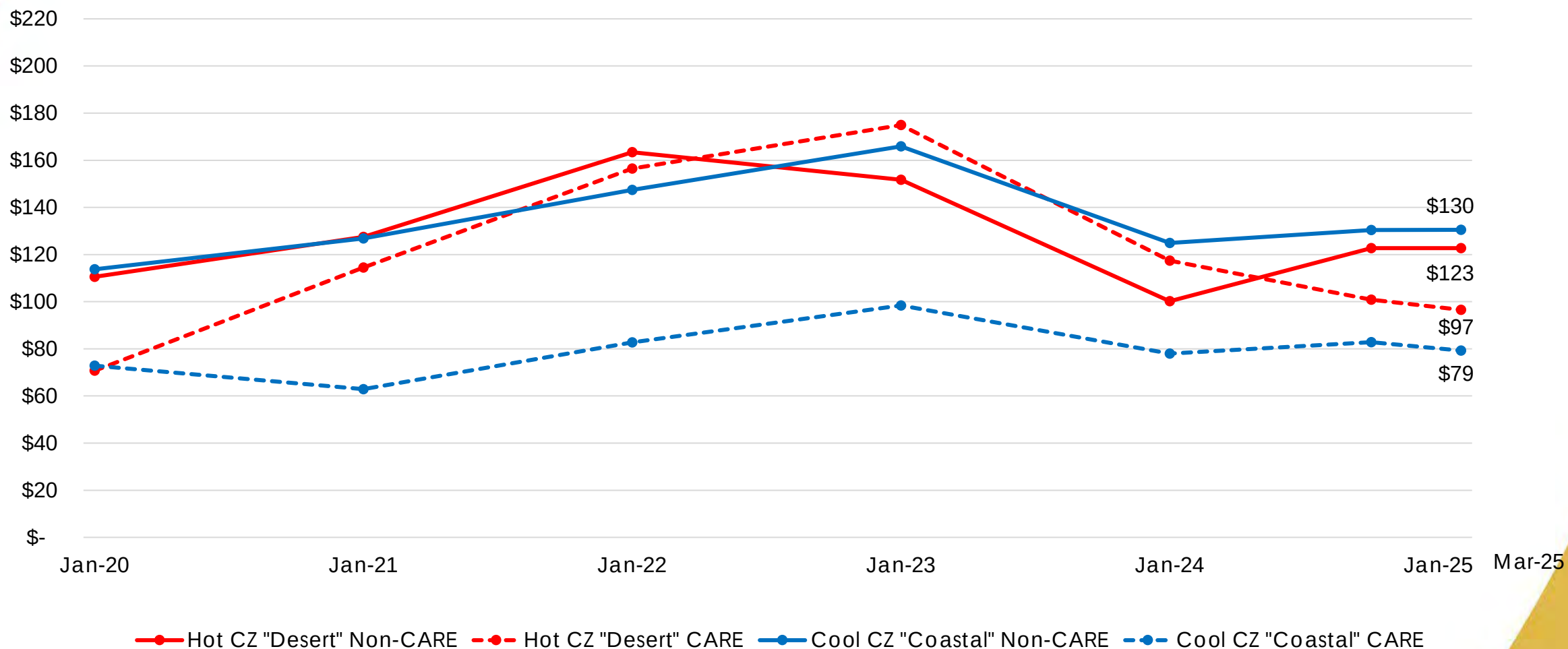


SCE's Average Monthly Electricity Bills for CARE & Non-CARE Customers in Hot and Cool Climate Zones



SCE's 15 hot climate zone has relatively high average usage of around 790 kWh monthly usage across Non-CARE & CARE customers. For Comparison, 6 cool CZ customers average around 385 kWh of monthly electricity usage.

SDG&E's Average Monthly Electricity Bills for CARE & Non-CARE Customers in Hot and Cool Climate Zones



SDG&E's Non-CARE customers in its Coastal Climate Zone use more electricity on average in the Winter season than Non-CARE customers in SDG&E's Desert Climate Zone.

More information

We develop recommendations to ensure that energy, water, and communications services provided by investor-owned utilities are affordable, safe, and reliable.

Visit our website at www.publicadvocates.cpuc.ca.gov

Contact us

- Mary Flannelly, Policy & Communications Advisor
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Appendix

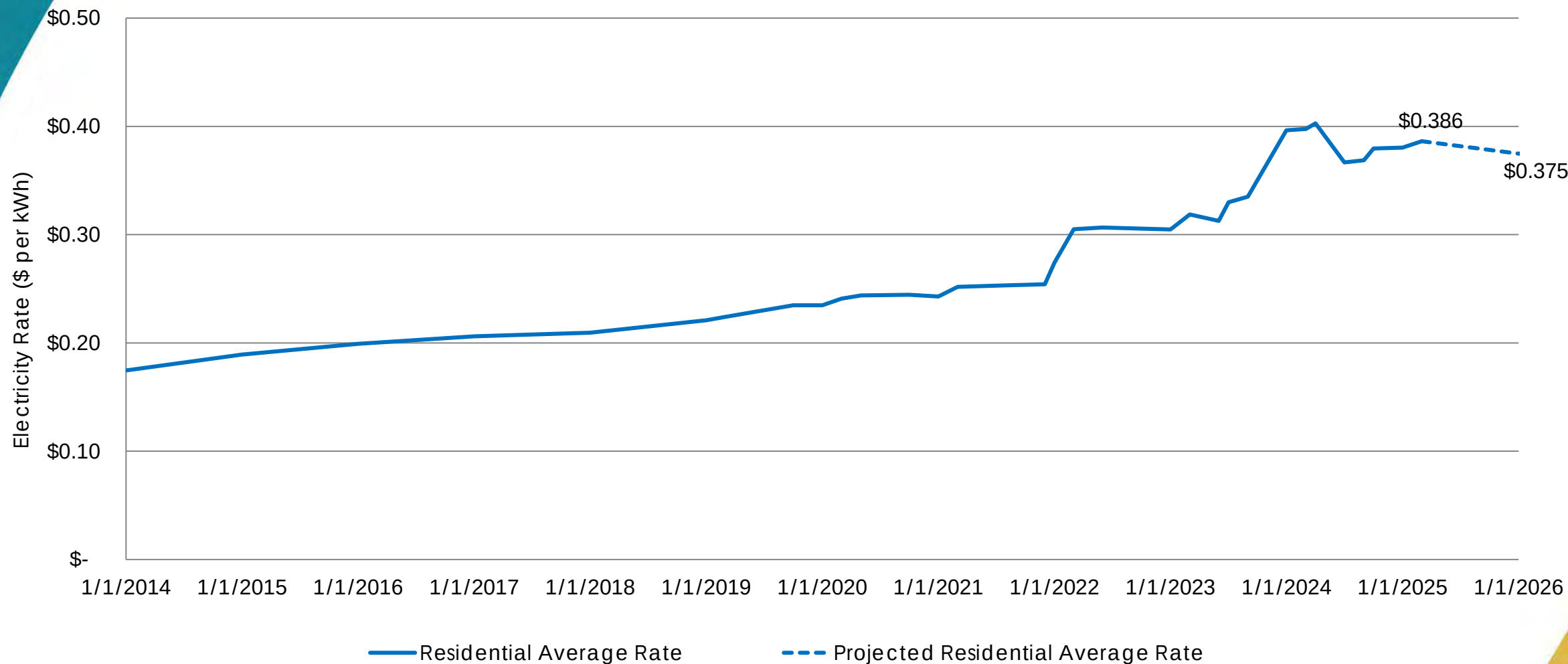
Assumptions & Additional Utility Data

Electric Vehicle (EV) Fuel Price Parity Assumptions (Slide 10)

- Internal Combustion Engine (ICE) MPG: 28
- EV MPGe: 100
- \$/Gallon Range: 4.60 – 6.00
- kWh/Gallon (EPA est.): 33.7

$((\text{EV MPGe} / \text{ICE MPG}) * \$/\text{Gallon}) \div \text{kWh/Gallon}$
= \$0.487 to \$0.636 \$/ kWh equivalent

PG&E Rate Change | Residential Average Rate



Expected rate decrease from 3/1/2025 to 1/1/2026 is due primarily to implementing PG&E's pending request for a \$2.38 Billion credit to ratepayers, from A.24-06-013.

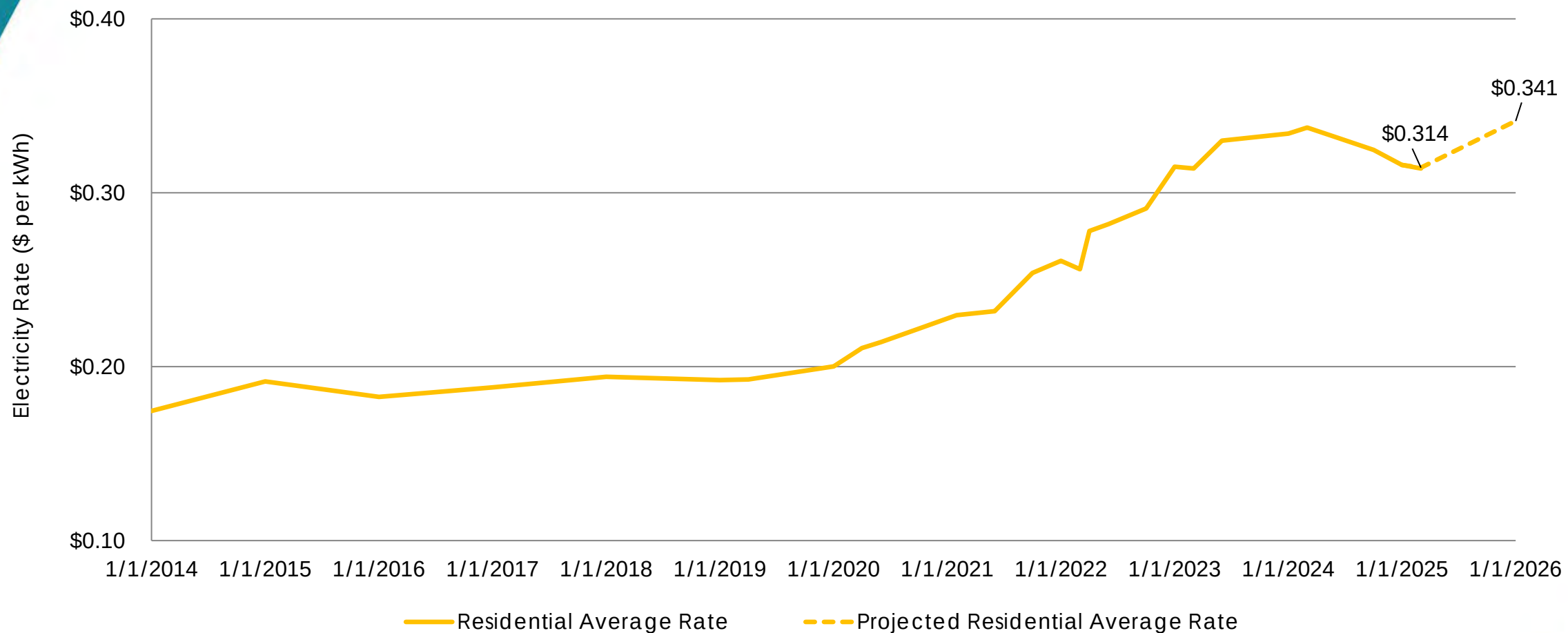
PG&E Q1 2025 Changes to Revenue Requirement

On February 26, 2025, PG&E submitted Advice Letter 7516-E, to update electric rates effective March 1, 2025. Noteworthy changes include:

- **2021 Wildfire Mitigation and Catastrophic Events (WMCE) Vegetation Management Balancing Account (VMBA)** – PG&E is implementing the approved total electric distribution revenue requirement of \$502.8 million in distribution rates over a 12-month period effective March 1, 2025.
- **End of Recovery of 2020 WMCE** – On February 2, 2023, the CPUC issued D.23-02-017, granting PG&E's request and authorizing recovery of \$1.038 billion in revenue amortized over 2 years. In this advice letter, PG&E is removing the 2020 WMCE annualized electric distribution revenue requirement as 2 years have concluded.

March 1, 2025, Rate Change: The authorized revenue requirement, sales forecast, and rate design changes resulted in a residential average rate (RAR) increase of approximately **1.6%** for bundled service customers relative to rates in effect on January 1, 2025.

SCE Rate Change | Residential Average Rate



Expected rate increase from 3/1/2025 to 1/1/2026 is due primarily to implementing SCE's 2025 GRC, from A.23-05-010.

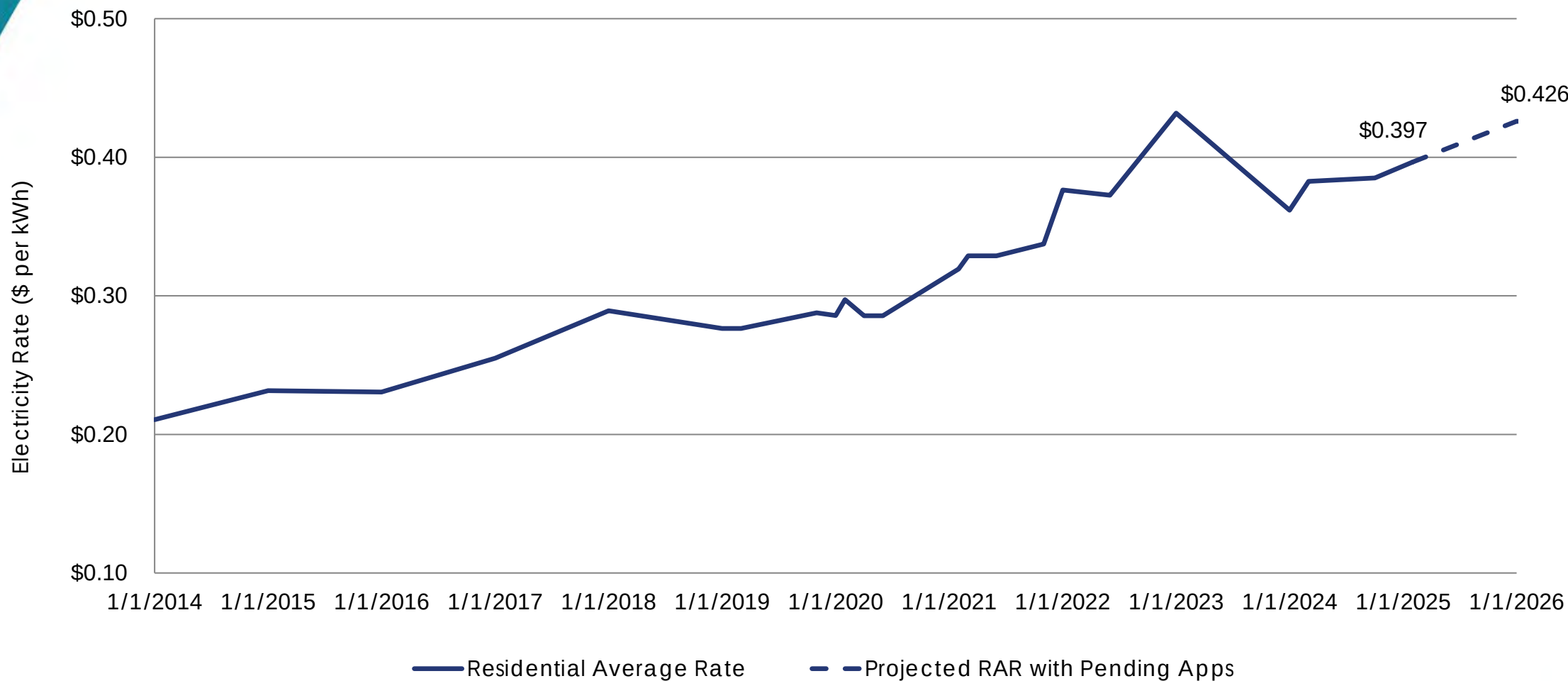
SCE Q1 2025 Changes to Revenue Requirement

On February 26, 2025, SCE submitted Advice Letter 5484-E, to update electric rates effective March 1, 2025. Noteworthy changes include:

- **Update to the 2021 GRC Track 2 O&M** – On December 3, 2021, in accordance with D.21-10-025, SCE submitted Advice Letter 4658-E to set the amortization period for recovering Track 2 of its O&M expenses totaling \$401 million. This implementation set a 36-month amortization period, which ended on February 28, 2025. As a result, SCE is removing \$135.162 million from its March 1, 2025, revenue requirement.
- **Update to the 2020 Incremental Uncollectibles** – The approval of Advice Letter 4558-E also set a 36-month amortization period for Track 2 of SCE's 2020 Incremental Uncollectibles expense totaling \$77 million, which ended on February 28, 2025. As a result, SCE is removing \$25.7 million from its March 1, 2025, revenue requirement.

*March 1, 2025, Rate Change: The authorized revenue requirement, sales forecast, and rate design changes resulted in a residential average rate (RAR) decrease of approximately **-0.8%** for bundled service customers relative to rates in effect on January 1, 2025.*

SDG&E Rate Change | Residential Average Rate



Expected rate increase from 2/1/2025 to 1/1/2026 is primarily due to implementing SDG&E's 2024 GRC, from D.24-12-074.

SDG&E Q1 2025 Changes to Revenue Requirement

On January 21, 2025, and January 29, 2025, SDG&E submitted Advice Letters 4588-E and 4588-E-A, to update electric rates effective February 1, 2025. Noteworthy changes include:

- **2024 General Rate Case (GRC)** – Updates to SDG&E’s electric revenue requirements from the approval of its 2024 GRC in D.24-12-074 will increase revenue requirements by \$295 million compared to October 1, 2024, revenue requirements.
- **Non-Fuel Generation Balancing Account (NGBA) Update** – Updates to SDG&E’s NGBA will increase revenue requirements by \$156.6 million compared to October 1, 2024, revenue requirements.

*February 1, 2025, Rate Change: The authorized revenue requirement, sales forecast, and rate design changes resulted in a residential average rate (RAR) increase of approximately **2.3%** for bundled service customers relative to rates in effect on October 1, 2024.*

Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas

Author: Michael Nicholas

Date: August 2019

Keywords: electric vehicles; charging infrastructure; United States

The rollout of electric vehicles is aided and enabled by a concurrent rollout of infrastructure at home and in public locations. Home charging provides most of the charging needed for most drivers, whereas public infrastructure improves the electric vehicle proposition for prospective buyers, increases the potential electric miles from electric vehicles, and provides charging for those without home charging. Exactly how much charging infrastructure will be needed and what it will cost are top questions for prospective electric vehicle owners, automakers, policy-makers, and electric utilities alike.

The need for much more electric vehicle charging infrastructure across the United States through 2025 is well established by a recent charging gap analysis.¹ Based on that analysis, about 4 times more public charging infrastructure than was in place in 2017 is needed by 2025 to match expected electric vehicle market growth. The

analysis finds that at least 100,000 public and workplace chargers will be needed across the 100 most populous U.S. metropolitan areas over 2019–2025. These chargers would help serve the 2.6 million new plug-in hybrid electric vehicle (PHEV) sales and battery electric vehicle (BEV) sales expected by 2025 in those 100 areas.

This paper analyzes the capital costs of the electric vehicle charging infrastructure needed for public, workplace, and home charging for the most populous 100 metropolitan areas in the United States from 2019 through 2025. We review charging equipment cost data, including installation and hardware, for chargers of various charging types and locations. These equipment costs are then applied to our recent estimation of public and workplace charging needs, along with home charging needs that are newly assessed here. Ultimately we quantify the infrastructure costs on a metropolitan-area basis. Excluded from this scope are charging costs outside the 100 largest markets, which is to say in smaller cities and fast-charging corridors linking the cities.

Charging cost by type and location

This section describes the types of electric vehicle charging infrastructure related to the charging location. Cost estimates and research studies were used to estimate installation and hardware-related costs for home and nonhome charging to obtain average hardware and installation costs. These installation and hardware costs are used to construct estimates by metropolitan area in the following section.

Three main categories of electric vehicle chargers are assessed in this paper: Level 1, Level 2, and direct current (DC) fast. Basic information regarding the different levels of chargers evaluated in this report is summarized Table 1. The voltage (V) column shows the voltage at which electricity is delivered to the electric vehicle, and the typical power in kilowatts (kW) is the rate of energy transfer. The associated electric vehicle miles of range per hour of charging and the typical charging locations are also shown. Generally, Level 1 is used in home charging, whereas Level 2 is used in a variety of charging conditions, and DC fast

¹ Michael Nicholas, Dale Hall, and Nic Lutsey, *Quantifying the electric vehicle charging infrastructure gap across U.S. markets*, (ICCT: Washington DC, 2019), <https://www.theicct.org/publications/charging-gap-US>

Table 1. Electric vehicle charging infrastructure specifications in the United States.

Charging level	Voltage	Typical power	Electric vehicle miles of range per charging hour	Location
Level 1	120 V AC	1.2–1.4 kW AC	3–4 miles	Primarily home and some workplace
Level 2	208 V–240 V AC	3.3–6.6 kW AC	10–20 miles	Home, workplace, and public
DC fast	400 V–1,000 V DC	50 kW or more	150–1,000 miles	Public, frequently intercity

Note: AC = alternating current; DC = direct current; kW = kilowatt; V = volt

charging is most commonly used at public charging stations.

For this paper's estimation of charging equipment costs across U.S. metropolitan areas through 2025, several simplifying assumptions are made regarding charger power requirements. Chargers are assumed to be 1.4 kW for Level 1, 6.6 kW for Level 2, and DC fast chargers include a combination of 50 kW, 150 kW, and 350 kW. We define chargers by these listed power levels rather than the number of outlets. For example, two outlets on the same pedestal providing 3.3 kW per outlet when two vehicles are connected are counted as one Level 2 charger, and a 13.2-kW Level 2 charger pedestal with two outlets is counted as two chargers.

Table 2. Per charger public and workplace charger hardware cost.

Level	Type	Chargers per pedestal	Per-charger cost
Level 1	Non-networked	One	\$813
Level 1	Non-networked	Two	\$596
Level 2	Non-networked	One	\$1,182
Level 2	Non-networked	Two	\$938
Level 2	Networked	One	\$3,127
Level 2	Networked	Two	\$2,793
DC fast	Networked 50 kW	One	\$28,401
DC fast	Networked 150 kW	One	\$75,000
DC fast	Networked 350 kW	One	\$140,000

PUBLIC AND WORKPLACE CHARGER HARDWARE COSTS

Public and workplace charging infrastructure hardware costs include the charger and its pedestal. The main cost drivers are the power of the unit, in kW; whether it requires a pedestal; and whether it is networked with communication or payment gathering capability. Table 2 summarizes the costs applied in this analysis, based on the average hardware costs from several studies² and manufacturer price quotes.³ For calculations, we determine an average cost per charger by level and type including mounting pedestal across all quotes and studies. As shown, Level 2 per-charger costs are lower when there are dual chargers, rather than one charger, per pedestal. Adding networking to a

charger more than doubles the cost of hardware. For DC fast charging, we use the single charger cost for all calculations. Costs are reported in 2019 dollars, and future-year hardware costs are assumed to decline over time at the rate of 3% per year.

Based on existing trends from our charging gap analysis, future workplace charging is assumed to be 15% Level 1 and 85% Level 2. Networking enables chargers to communicate by WiFi or cellular signal to report usage, charge customers, and collect payment information. These cost estimates are based on workplace Level 1 not being networked and 62% of workplace Level 2 being networked, corresponding to the percentage of workplace charging that is paid.⁴ Public charging is assumed to be 80%

2 Avista Utility, "Docket No. UE-160082 – Avista Utilities Semi-Annual Report on Electric Vehicle Supply Equipment Pilot Program" (2018), https://www.utc.wa.gov/_layouts/15/CasesPublicWebsite/CasItem.aspx?item=document&id=00044&year=2016&docketNumber=160082&resultSource=&page=&query=&refiners=&isModal=&omItem=false&doItem=false; Department of Energy, "Transportation Energy Futures Series, Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity and Retail Availability for Low-Carbon Scenarios" (2013), <https://www.osti.gov/biblio/1079728-transportation-energy-futures-series-alternative-fuel-infrastructure-expansion-costs-resources-production-capacity-retail-availability-low-carbon-scenarios>; Pierre Ducharme and Catherine Kargas, *Feasibility of a Pan-Canadian Network of DC Fast Charging Stations for EVs*, (Electric Vehicle Symposium 29: Montréal, Québec, Canada, June 19–22, 2016), <https://www.mdpi.com/2032-6653/8/1/1/pdf>; Josh Agenbroad, "Pulling back the veil on EV charging station costs," Rocky Mountain Institute, accessed Jan 5, 2019, <https://rmi.org/pulling-back-veil-ev-charging-station-costs/>

3 "Commercial EVSE: Public, Fleet, Workplace Charging," ClipperCreek, accessed February 1, 2019, <https://store.clippercreek.com/commercial/>; "Smart charging stations," Chargepoint, accessed February 1, 2019, <https://www.chargepoint.com/products/commercial/>

4 Gil Tal, Jae Hyun Lee, and Michael Nicholas, "Observed charging rates in California," (Research Report – UCD-ITS-WP-18-02, Institute of Transportation Studies: University of California, Davis, 2018), https://itspubs.ucdavis.edu/index.php/research/publications/publication-detail/?pub_id=2993

networked, and all fast charging is assumed to be networked, as these are typical practices. For Level 1 workplace chargers we assume 80% will be simply a wall outlet, but average costs presented above are for the 20% of dedicated Level 1 chargers.

PUBLIC AND WORKPLACE CHARGING INSTALLATION COSTS

Installation costs are composed of labor, materials, permits, taxes, and utility upgrades, as shown in Table 3. These are based on the most recent and detailed cost estimates among the various investigations into costs for nonresidential infrastructure.⁵ Notably, the Electric Power Research Institute (EPRI) studied 637 sites with 1,294 Level 2 charging units, including disaggregated costs for labor, materials, permits, and taxes. The EPRI study also shows how per-charger costs decline as more chargers are installed per site (i.e., sites with 3-5 chargers, and those with over 6 chargers). Costs are further disaggregated by sites within California versus those in the rest of the country and are applied as such in this analysis. For our analysis, based on the EPRI study, we assume workplace charging costs are 10% below,

Table 3. Installation costs for Level 2 public and workplace charger, by chargers per site.

		1 charger per site	2 chargers per site	3-5 chargers per site	6+ chargers per site
California	Labor	\$2,471	\$1,786	\$1,491	\$1,747
	Materials	\$1,235	\$958	\$1,014	\$908
	Permit	\$283	\$172	\$110	\$65
	Tax	\$156	\$121	\$128	\$115
	Total	\$4,148	\$3,039	\$2,745	\$2,837
Outside California	Labor	\$1,544	\$1,827	\$1,647	\$1,316
	Materials	\$1,112	\$1,039	\$1,272	\$874
	Permit	\$82	\$62	\$59	\$38
	Tax	\$96	\$89	\$110	\$75
	Total	\$2,836	\$3,020	\$3,090	\$2,305

and public Level 2 are 11% higher, than the average numbers shown in Table 3. Utility upgrades are included in the materials cost, based on upgrades incurred in southern California.⁶ In practice, part of these utility upgrade costs may be covered by the utility company. Typically, a utility provides the customer an upgrade allowance, above which the customer pays for the remainder of the upgrade cost.

Our DC fast charger installation costs, shown in Table 4, are based two sources.⁷ Data from the Rocky

Mountain Institute study are used to estimate costs for 50-kW chargers, and data from Ribberink et al. are used to project how costs scale for multiple chargers per site and for higher power stations. Similar to Level 2 charging, installation costs per charger fall as more chargers are installed per site. Also, costs do not rise proportionally with power so a charger with triple the power does not result in triple the cost. Hence, installation costs are mainly a function of the number of chargers per site.

Table 4 highlights the role power and multi-charger sites play in determining per-charger installation costs. For example, at a site with one 50-kW charger, installation costs are approximately \$45,000. Increasing the power by 7 times to 350 kW results in an installation cost of approximately \$65,000, reflecting higher material cost and the probability that switchgear and distribution lines may need to be upgraded. Although we show an approximately \$20,000 increase, this is highly variable and certain sites with 350 kW require very expensive upgrades whereas other sites require modest upgrades depending on factors related to charging site

5 Idaho National Laboratory, U.S. Department of Energy, Plug-in electric vehicle and infrastructure analysis (INL/EXT-15-35708), 2015, <https://indigitalibrary.inl.gov/sites/sti/sti/6799570.pdf>; NC PEV Taskforce, "Plug-in electric vehicle (PEV) roadmap for North Carolina" (2013), http://www.pluginnc.com/wp-content/uploads/2016/06/7-NCPEVRoadmap_April2014_v2.pdf; Ducharme and Kargas, "Feasibility of a Pan-Canadian Network"; Avista, Semi-Annual Report on Electric Vehicle Supply Equipment Pilot Program; Electric Power Research Institute, "Electric Vehicle Supply Equipment Installed Cost Analysis" (December 2013), <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002000577>.

6 Based on upgrades incurred in the Southern California Edison territory, \$36.99 is added to each Level 2 charging installation. See J.R. DeShazo, Overcoming Barriers to Electric Vehicle Charging in Multi-unit Dwellings: A Westside Cities Case Study, (2017), <http://innovation.luskin.ucla.edu/sites/default/files/Overcoming%20Barriers%20to%20EV%20Charging%20in%20Multi-unit%20Dwellings%20-%20A%20Westside%20Cities%20Case%20Study.pdf>

7 Hajo Ribberink, Larry Wilkens, Raed Abdullah, Matthew McGrath, and Mark Wojdan, "Impact of Clusters of DC Fast Charging Stations on the Electricity Distribution Grid in Ottawa, Canada," (Electric Vehicle Symposium 30: Stuttgart, Germany, October 9-11, 2017); Agenbroad, "Pulling back the veil on EV charging station costs", Rocky Mountain Institute, accessed Jan 5, 2019, <https://rmi.org/pulling-back-veil-ev-charging-station-costs/>.

Table 4. Installation costs per DC fast charger by power level and chargers per site.

	50 kW				150 kW				350 kW			
	1 charger per site	2 chargers per site	3-5 charger per site	6-50 chargers per site	1 charger per site	2 chargers per site	3-5 chargers per site	6-20 chargers per site	1 charger per site	2 chargers per site	3-5 chargers per site	6-10 chargers per site
Labor	\$19,200	\$15,200	\$11,200	\$7,200	\$20,160	\$15,960	\$11,760	\$7,560	\$27,840	\$22,040	\$16,240	\$10,440
Materials	\$26,000	\$20,800	\$15,600	\$10,400	\$27,300	\$21,840	\$16,380	\$10,920	\$37,700	\$30,160	\$22,620	\$15,080
Permit	\$200	\$150	\$100	\$50	\$210	\$158	\$105	\$53	\$290	\$218	\$145	\$73
Taxes	\$106	\$85	\$64	\$42	\$111	\$89	\$67	\$45	\$154	\$123	\$92	\$62
Total	\$45,506	\$36,235	\$26,964	\$17,692	\$47,781	\$38,047	\$28,312	\$18,577	\$65,984	\$52,541	\$39,097	\$25,654

readiness and electrical equipment. Location flexibility is paramount in reducing these costs. There is generally a site limit of 2.5 megawatts of power before a step change in costs. Therefore, the maximum number of chargers per site is 50, 20, and 10 for 50-, 150-, and 350-kW chargers, respectively. Finally, we note that there are some costs that may not be included in the installation costs above including signage, striping, lighting, and security cameras.

Trends in the number of chargers per site allow us to estimate overall future charging developments based on the preceding per-charger cost examples. Recent data on chargers per site from U.S. metropolitan areas with greater electric vehicle uptake serve as a guide for smaller markets. To determine the relationship between electric vehicle market development and chargers per site, markets are first categorized and binned by the status of the electric vehicle market development by metropolitan area at the end of each year from 2014 through 2018. The market development bins are defined by the electric vehicles per million population, ranging from 6,000 (in low electric uptake markets) up to 40,000 (high uptake). Then the associated charger locations and number of chargers per site were

analyzed by metropolitan area.⁸ These sites are grouped into four categories—one, two, three to five, and six or more chargers per site—to match the categories analyzed above. In areas with low numbers of electric vehicles per million population, sites with six outlets or more are rare but can still account for a large portion of a metropolitan area's chargers.

Figure 1 shows a trend toward more chargers per site in markets with greater electric vehicle uptake. The horizontal axis shows the relative electric vehicle market development in vehicles per million resident population in bins. The vertical axis shows the percentage of chargers per site size category, based on the charger data for all the metropolitan areas in each bin. For example, the lowest level of market development analyzed is 6,000 electric vehicles per million population, where approximately 30% of charging outlets are at sites with two chargers, 30% are with 3–5 chargers, 30% are with 6 or more chargers, and the remaining 10% are at sites with just one charger. Most metropolitan areas fall in the lower bins and the 40,000 electric vehicles-per-million bin is represented

by just one metropolitan area, San Jose, in 2018.

The implication of the trend shown in Figure 1, based on Table 3, is that as electric vehicle markets grow, the number of outlets per site increases, and the per-outlet cost drops. Cumulative sales in San Jose by the end of 2018 are what define the highest market penetration category, where there are 40,000 electric vehicles per million population, and 60% of total outlets are located at sites with six or more chargers. The lines in Figure 1 represent the natural log fit of these points (e.g., $y = 0.21 * \ln(x) - 1.57$ for six or more chargers per site), and the equations shown are applied to the infrastructure buildout cost analysis that follows in the cost scenario section.

Compared to Level 2 chargers, DC fast chargers do not show such a clear trend for chargers per site versus electric vehicles per capita. However, overall site size for new installations is growing year by year. To reflect a general increase in the number of chargers per site, we extrapolate the trend from 2014–2018 into the future. In 2018, the percentages of chargers at one, two, three to five, and six or more chargers per site were 11%, 20%, 17%, and 52%, respectively. The corresponding percentages for 2025 are 5%, 13%, 15% and 67%. These percentages are

8 Downloaded from Alternative Fuel Data Center (Alternative fuel stations - electric, Accessed Sept. 1, 2014; Jan 1, 2016; Jan 1, 2017; Jan 1, 2018; and Jan 1, 2019), https://afdc.energy.gov/data_download/

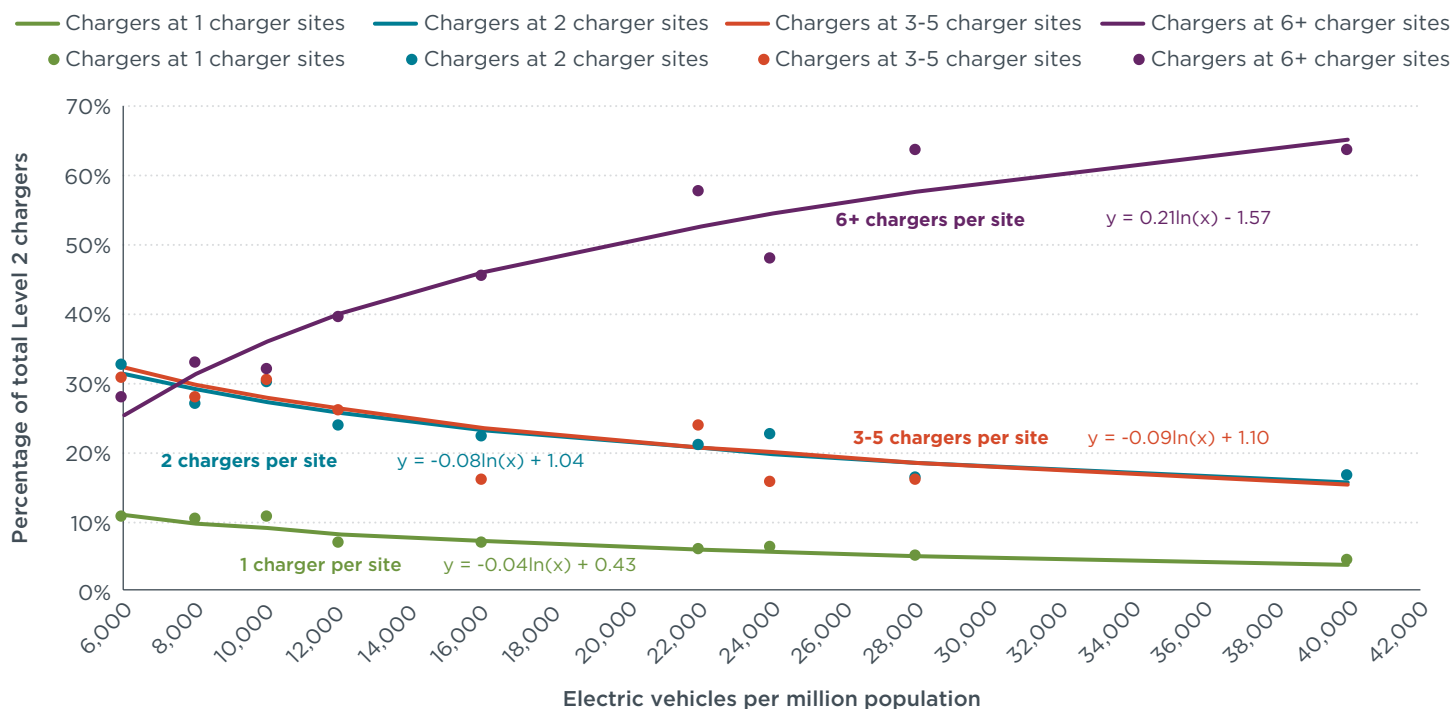


Figure 1. Percentage of public Level 2 chargers by site size as a function of electric vehicles per million population.

not applied as a function of market development, but rather by year across all metropolitan areas. We also assume the breakdown for the distribution of charger power is 44.4% for 50 kW, 44.4% for 150 kW, and 11.1% for 350 kW through our future year scenarios. This breakdown of DC fast chargers of varying power levels reflects our expectation of a continuing tradeoff between electric vehicle range and charger installation cost.⁹

HOME CHARGING HARDWARE AND INSTALLATION COSTS

Our charger cost analysis for home charging is similar to the previous discussion of public and home charging but accounts for varying cost by housing types. Home charging hardware and installation is typically less expensive than for public chargers. We separate the cost of home charging into charger level (Level 1 or Level 2) and housing type (detached house, attached house, and apartment). Hardware and installation costs are included, and installation is composed of labor, materials, taxes, utility upgrades, and permits. Some studies provide only installation cost, but not hardware costs, whereas others provide only hardware and installation

costs combined.¹⁰ We therefore represent the costs as combined costs for home charging estimates and average these across studies.

Average charger hardware plus installation costs applied to our analysis for 2019 are shown in Table 5. As

9 Wei Ji, Michael Nicholas, and Gil Tal, "Electric Vehicle Fast Charger Planning for Metropolitan Planning Organizations: Adapting to Changing Markets and Vehicle Technology," *Transportation Research Record*, 2015, 2502 (1): 134-143, <https://doi.org/10.3141/2502-16>; Michael Nicholas and Dale Hall, *Lessons learned on early electric vehicle fast-charging deployments*, (ICCT: Washington DC, 2018), <https://www.theicct.org/publications/fast-charging-lessons-learned>

10 Idaho National Laboratory, U.S. Department of Energy, Plug-in electric vehicle and infrastructure analysis; Electric Power Research Institute, "Electric Vehicle Supply Equipment Installed Cost Analysis"; NC PEV Taskforce, "Plug-in electric vehicle (PEV) roadmap for North Carolina"; California Air Resources Board, "California's advanced clean cars midterm review: Appendix B: Zero emission vehicles and plug-in hybrid electric vehicles" (California Environmental Protection Agency, Air Resources Board, 2017), <https://www.arb.ca.gov/msprog/acc/acc-mtr.htm>; California Air Resources Board, "California's advanced clean cars midterm review: Appendix D: Zero emission vehicle infrastructure status in California and Section 177 ZEV states" (California Environmental Protection Agency, Air Resources Board, 2017), <https://www.arb.ca.gov/msprog/acc/acc-mtr.htm>; DeShazo, *Overcoming Barriers*; Agenbroad, "Pulling back the veil on EV charging station costs."

shown, the costs vary depending on the electric vehicle home charging situation and the housing type. For the housing types, detached house signifies a house not connected to any others; attached house signifies a house with a shared wall of up to three housing units; and apartments are structures with more than 3 units. We use an average cost across all studies and apply a 3% per year reduction in hardware cost. To give examples of some of the underlying studies, the total installed costs ranged from \$650 in the Rocky Mountain Institute study to \$2,423 for a networked charger as assessed by Avista Utility. Higher costs for home charging upgrades generally correspond to a greater number of wall and floor penetrations, total circuit distance, or service upgrades. As indicated, attached homes and apartments typically are associated with higher cost upgrades.

Two types of upgrades are shown in Table 5: charger upgrades and outlet upgrades. Charger upgrades refer to new wiring and a charger, whereas outlet upgrades refer to only new wiring and a 120-volt wall outlet (Level 1) or a 240-volt dryer-type outlet (Level 2) with no additional charger. Most vehicle purchases come with a convenience charger that can be plugged into one or both of these outlet types and the convenience charger is not considered an additional infrastructure cost for this analysis. Categories of electric vehicle-owning households that have no additional home cost are also shown for context, as these are discussed in our overall average cost calculations.

The 3% per year hardware reduction is not shown, but as an example, total installed costs for a hardwired Level 2 unit in a detached house drop from \$1,445 in 2019 to \$1,317 by 2025 and from \$4,061 to \$3,933 in an apartment over the same period. Outlet

Table 5. Installation and hardware costs for home chargers by housing type.

Home charging category	Detached house	Attached house	Apartment
Level 1 outlet upgrade	\$400	\$500	\$600
Level 1 charger upgrade	\$700	\$800	\$900
Level 2 outlet upgrade	\$680	\$2,000	\$3,300
Level 2 charger upgrade	\$1,400	\$2,800	\$4,100

upgrades do not decrease in cost over the analysis period. Average outlet upgrade and Level 2 charger installation costs in attached houses are not detailed in any study and are therefore assumed to be the average of apartment costs and costs in detached houses. The Table 5 costs by home charging category and housing type are applied across the U.S. metropolitan area data in the cost assessment that follows.

Cost scenarios

Costs are estimated for home, public, and workplace charging for approximately 2.6 million new electric vehicle sales in the 100 most populous U.S. metropolitan areas over the 2019–2025 period. In modeling the overall vehicle fleet, which accounts for vehicle retirement, this amounts to a stock increase of 2.3 million vehicles, and a total stock of 3.2 million electric vehicles in 2025 in the top 100 metropolitan areas. This represents 88% of the estimated 3.6 million electric vehicles on the road in the United States in 2025. The cost scenarios presented below are shown in terms of the aggregated costs for all the metropolitan areas combined and on a per-electric-vehicle-sold per year basis.

HOME CHARGING

Home charging is an important part of the charging ecosystem. Its associated cost to support new electric vehicle sales in the top 100 most populous metropolitan areas for the years

2019–2025 is analyzed here. We apply electric vehicle charging dynamics and sales across the metropolitan areas and the areas' housing stock as in our previous analysis¹¹ to provide a breakdown of electric vehicles by home charging category and housing type.

Our overall U.S. estimates for the number of electric vehicle sales from 2019–2025 in each type of home charging situation, and across housing types, are summarized in Table 6. There are seven home charging categories, two vehicle types (BEV and PHEV), and three housing types. The first row shows drivers who do not use home charging, primarily relying on workplace and public charging. Level 1 users are divided into those who have an existing outlet with no upgrades needed, those who install a new upgraded 120-volt household outlet for their electric vehicle, and those who install a dedicated Level 1 charger (charger upgrade). Level 2 home charging has categories similar to Level 1, but includes those with existing 240-volt dryer-type outlets and upgrades for new outlets and new dedicated chargers (charger upgrade). Ratios for determining the outlets and upgrades by charging level were determined from the results of a California Air Resources Board survey.¹²

The categories in Table 6 have two broad classifications—those that

¹¹ Nicholas, Hall, and Lutsey, Quantifying the electric vehicle charging infrastructure gap.

¹² California Air Resources Board, "California's advanced clean cars midterm review: Appendix B."

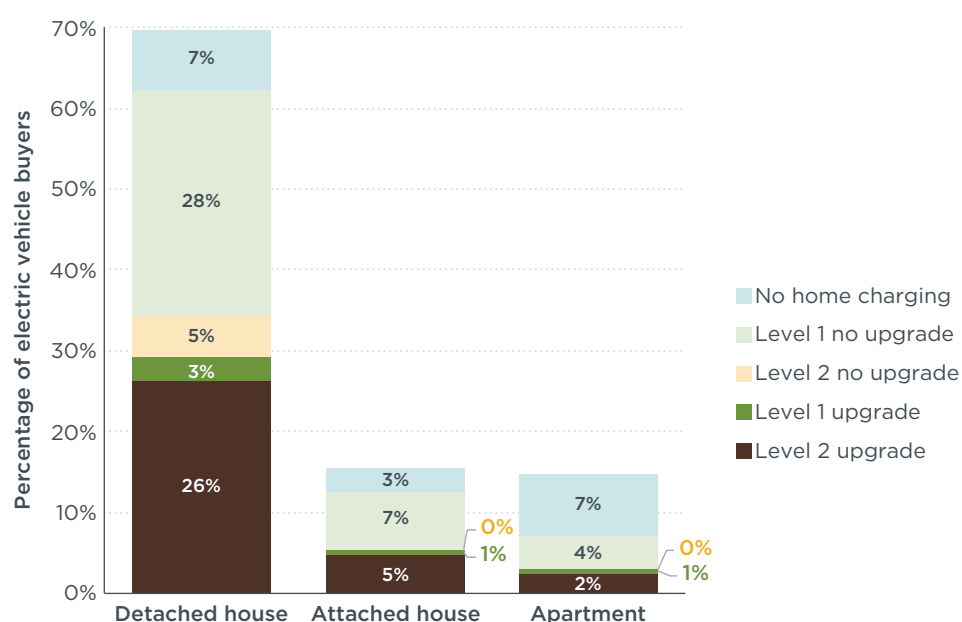
Table 6. California electric vehicle drivers by home charging category and housing type for 2019–2025.

Home charging category	Detached house PHEV	Detached house BEV	Attached house PHEV	Attached house BEV	Apartment PHEV	Apartment BEV	Totals
No home charging	124,429	67,272	46,129	30,467	102,185	89,171	459,653
Level 1 no upgrade	484,233	234,054	121,330	60,841	66,920	37,426	1,004,803
Level 1 outlet upgrade	36,228	18,606	6,709	4,824	5,905	3,364	75,636
Level 1 charger upgrade	8,296	10,927	2,236	4,020	3,543	3,154	32,177
Level 2 no upgrade	38,195	89,917					128,112
Level 2 outlet upgrade	48,644	180,114	12,281	44,473	5,200	16,212	306,925
Level 2 charger upgrade	132,960	312,477	23,026	43,375	12,712	27,731	552,282
Total	872,985	913,367	211,712	188,001	196,465	177,058	2,559,588

Note: BEV = battery electric vehicle, PHEV= plug-in hybrid electric vehicle

require electrical work and those that do not. As indicated, approximately 967,000, or 38%, of the 2.6 million electric vehicle owners are estimated to either need to install a dedicated charger or do an outlet upgrade. These include the four categories of Level 1 outlet upgrades, Level 2 outlet upgrades, Level 1 charger upgrades, and Level 2 charger upgrades. This also highlights that more than 1.1 million electric vehicle owners (or 44%) will use existing 120-volt or 240-volt outlets, and the remaining 18% either do not plug in or exclusively use workplace and public charging infrastructure.

In Figure 2, the data from Table 6 are represented graphically to show the fraction of electric vehicle drivers in our 2019–2025 analysis by home charging investments needed. The figure shows the percentage of electric vehicle drivers in three housing types (detached, attached homes, apartments) and home charging categories (No home charging, Level 1 home charging, and Level 2 home charging). The hashed bars indicate that there is no additional cost incurred for home charging for these drivers. For example, in the leftmost column, 70% of electric vehicle drivers in the analysis are in detached homes, and this includes 29% that are estimated to be complete home charging upgrades (26% Level

**Figure 2.** Percentage of new electric vehicle drivers by home charging access and upgrade.

2 and 3% Level 1) and 41% without any upgrades. Electric vehicle buyers in attached houses and apartments are less likely to use home charging than those in detached houses, likely reflecting challenging installations and lack of control over upgrades.

Based on Figure 2 the majority of electric vehicle drivers will not be installing additional home infrastructure given current trends. Approximately 39% will simply use existing Level 1 (28% in detached houses, 7% in attached houses, and

4% in apartments), and 5% will use existing Level 2 charging (i.e., dryer outlet, largely in detached houses). The approximately 18% of all drivers not using home charging includes 5% of electric vehicle drivers rarely charging at all (primarily using PHEVs as hybrids) and the remainder relying on public and workplace charging.

Costs for the above electric vehicle driver, housing, and home charging calculations include the charging equipment costs from Table 5 and Table 6 for the 100 metropolitan areas.

The total cost for the 38% of customers assumed to undertake upgrades including upgraded outlets and installed chargers totals \$1.3 billion. Averaged over all the new electric vehicle drivers, this represents \$520 per new electric vehicle, decreasing from about \$540 to \$510 over the 2019–2025 period. A weighted average over only those electric vehicle drivers that had an upgrade at their residence results in \$1,400 per vehicle. If costs are calculated separately for electric vehicles by housing type, and once again assigned only to those undergoing upgrades, we estimate \$1,100 for those in detached houses, \$2,100 for those in attached houses, and \$3,100 for those in apartments.

PUBLIC AND WORKPLACE CHARGING

Total public and workplace charging infrastructure costs across the 100 metropolitan areas over the 2019–2025 period are estimated from the per-charger costs from Table 2, Table 3, and Table 4 and the distribution of outlets per site shown in Figure 1. Although overall costs are tallied based on the specific needs across the 100 areas, the results are presented here for all the areas combined to inform the overall charging infrastructure costs, the primary underlying cost components, and the costs on a per-electric-vehicle basis.

Figure 3 shows the overall 2019–2025 costs for workplace, public Level 2, and DC fast charging disaggregated by labor, materials, permits, taxes and hardware. The vertical axis shows the total costs for that charger category, which are approximately \$190 million, \$360 million, and \$390 million for workplace, public Level 2, and DC fast, respectively. As indicated, hardware costs are the largest cost component in each case, representing 43%, 40%, and 68% of the total costs, respectively, for

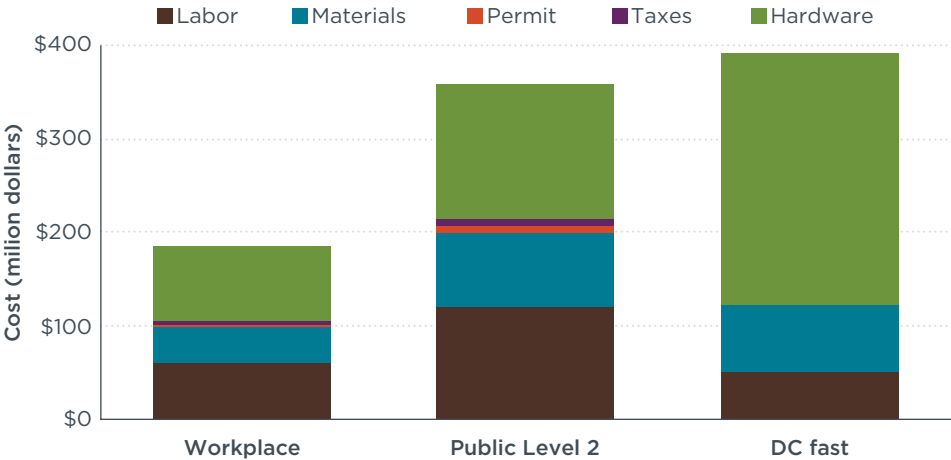


Figure 3. Workplace, public Level 2, and DC fast charger costs from 2019 through 2025.

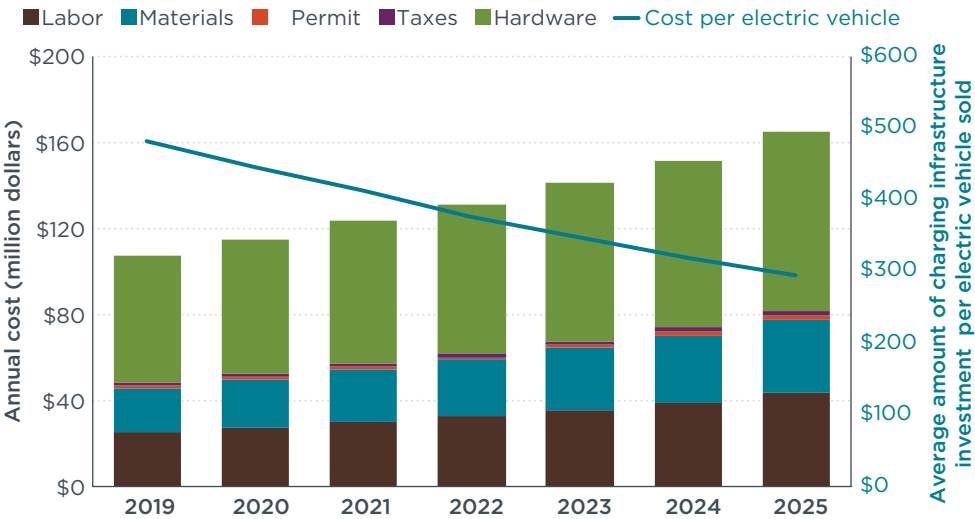


Figure 4. Total cost of public and workplace infrastructure and associated average aggregate charger cost per new electric vehicle sold for 2019 through 2025.

the three charging types. Workplace chargers and public Level 2 charger costs are similar in terms of the breakdown by cost component, but DC fast charging hardware is more expensive, especially for the highest power stations driving a relatively high hardware cost, as indicated on a per-charger basis in Table 2. Summing the costs by cost component, hardware costs are about \$490 million, followed by labor at \$230 million, materials at \$190 million, taxes at \$12 million, and permits at \$9 million.

Figure 4 shows how annual charging infrastructure costs increase over time with higher electric vehicle sales volumes, and also how average charging costs for additional charging needed in each year decline on a per-electric-vehicle-sold basis. This decline is due to three factors. First, higher utilization of chargers, in terms of hours of active charging per day per charger, results in fewer chargers needed per electric vehicle. Second, installation costs decline as the number of chargers per site increases with growing market penetration. Third, we

assume a 3% decline in per-charger hardware cost per year. The figure shows the installation and hardware costs increase from approximately \$110 million to \$165 million dollars in 2025. The blue line (right vertical axis) shows the average cost per electric vehicle, calculated by dividing public and workplace charging costs in each year by the number of electric vehicles sold in that year, and declines from \$480 in 2019 to \$300 in 2025.

To provide a more detailed understanding of how the charging infrastructure costs differ by electric vehicle type, Figure 5 shows the average cost of home and nonhome infrastructure separately for BEVs and PHEVs. The nonhome costs include workplace, public Level 2, and DC fast charging. The figure shows the average cost per new electric vehicle in the year sold and according to the year in which costs are incurred. Per BEV, the average home charger cost declines from \$760 to \$720 over 2019–2025, and the average nonhome charger cost declines from \$690 to \$420. Per PHEV, the average home charger cost declines from \$320 to \$300 over 2019–2025, and the average nonhome charger cost declines from \$260 to \$180. The BEV nonhome line includes DC fast charging cost whereas the PHEV nonhome line does not.

DC fast charging adds a significant cost to the average nonhome costs for BEVs. This is largely driven by the high cost of 150 kW and 350 kW hardware as shown in Table 2. Although a 3% cost reduction per year is applied to all nonhome charging hardware costs, the higher power DC fast charging hardware is relatively new and its cost may decrease faster as suppliers recoup development costs and move to higher production volume. Home costs are also greater for BEVs because more of the BEVs upgrade to Level 2 rather than use existing Level 1.

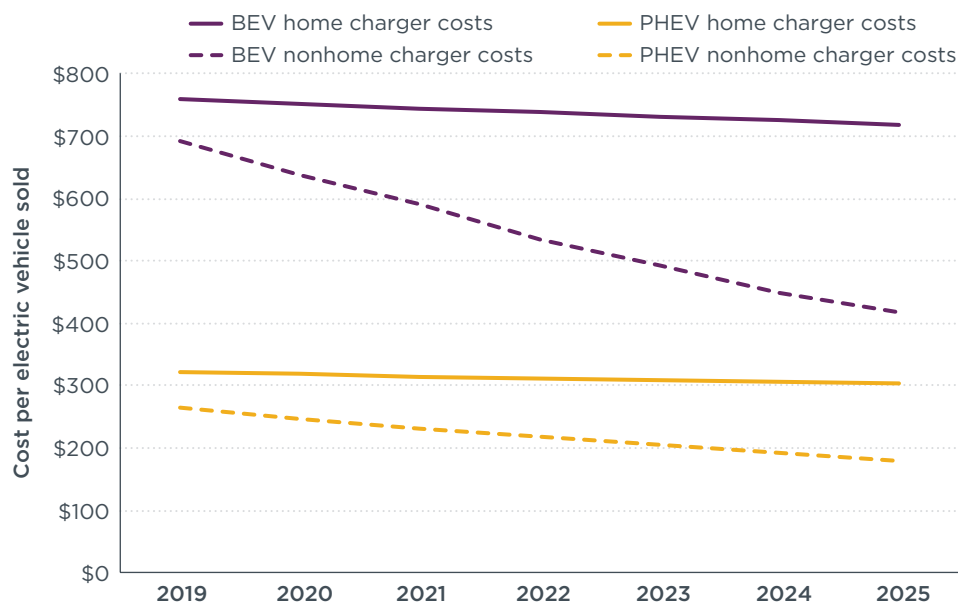


Figure 5. Average home and nonhome charger costs for BEVs and PHEVs.

Table 7. Summary of needed charging infrastructure and associated costs across 100 U.S. metropolitan areas over 2019–2025, by charging category.

Charging category	Chargers	Total 2019–2025 cost	Average 2019–2025 capital cost per charger
Home Level 1 no upgrade	1,005,000		
Home Level 1 outlet upgrade	76,000	\$33 million	\$440
Home Level 1 charger upgrade	32,000	\$24 million	\$735
Home Level 2 no upgrade	128,000		
Home Level 2 outlet upgrade	307,000	\$339 million	\$1,104
Home Level 2 charger upgrade	552,000	\$948 million	\$1,716
Workplace	48,000	\$186 million	\$3,880
Public Level 2	66,000	\$359 million	\$5,440
DC fast charging	5,000	\$392 million	\$81,818

Table 7 summarizes the total home, workplace, and public charging needed and the associated costs for the 2.6 million new electric vehicles in the 100 most populous U.S. metropolitan areas over 2019–2025. The home charging needs are shown by charging category (i.e., availability of Level 1 and Level 2) in the top six rows. Nonhome charging is shown in rows seven to nine. Counts refer to the number of new chargers in that category. As shown, the analysis finds that 5,000 DC fast, 66,000 public Level 2, 48,000

workplace, and 967,000 home charger upgrades will be needed from 2019–2025. In addition, within this analysis there are 1.1 million electric vehicle drivers who will use existing home charging outlets. Although not shown, there are another 460,000 electric vehicle drivers in this analysis who do not have home charging and will rely on public and workplace charging.

The costs in Table 7 show the relative contributions of the various charging types to the overall charging

infrastructure costs for the major U.S. electric vehicle markets. The home charging costs ultimately result in more than half of the overall costs (\$1.3 billion of \$2.3 billion), followed by DC fast charging (\$392 million), public Level 2 (\$359 million), and workplace charging (\$186 million). As indicated by the far right column, the average cost per charger is much higher for the DC fast charging (\$81,818), followed by public Level 2 (\$5,440), workplace (\$3,880), and various home charging types. Home charging costs are a weighted average across housing types, and cost differences for those housing types are detailed in Table 5. Nonhome charging costs are similarly averaged across all years and metropolitan areas. This summary reinforces that there is a significant number of new electric vehicle buyers who will not need home upgrades.

In addition to the preceding summary analysis, similar results for two specific metropolitan areas are provided as examples of underlying analysis on charging infrastructure needs and the associated costs evaluated across the 100 metropolitan areas. Table 8 summarizes the home, workplace, public, and DC fast chargers needed over 2019–2025 and the associated estimated charger costs for the Portland and San Francisco metropolitan areas. These two examples are chosen because they represent large and growing electric vehicle markets and also are areas where there are many utility, state policy, and city activities to actively fill the charging needs.

In the Portland area, our scenario has the total electric vehicle stock increasing by 75,000 electric vehicles from 2019–2025. As shown in Table 8, the associated Portland area charging costs for home, DC fast, public Level 2, and workplace charging are \$43 million, \$13 million, \$10 million, and \$6 million, respectively. In the San Francisco area, our scenario has the

Table 8. Example results for amount of needed charging infrastructure and associated costs over 2019–2025 by charging category for two metropolitan areas.

Charging category	Portland area		San Francisco area	
	Charger outlets	Total 2019–2025 cost	Charger outlets	Total 2019–2025 cost
Home Level 1 no upgrade	29,000		90,000	
Home Level 1 outlet upgrade	2,000	\$1 million	7,000	\$3 million
Home Level 1 charger upgrade	1,000	\$1 million	3,000	\$2 million
Home Level 2 no upgrade	5,000		13,000	
Home Level 2 outlet upgrade	10,000	\$10 million	32,000	\$37 million
Home Level 2 charger upgrade	19,000	\$32 million	57,000	\$101 million
Workplace	1,600	\$6 million	4,300	\$17 million
Public Level 2	2,000	\$10 million	5,400	\$30 million
DC fast charging	160	\$13 million	440	\$36 million

Note: Metropolitan areas are the core-based statistical areas and represent populations of approximately 2.5 million residents in the Portland area and 4.7 million in the San Francisco area.

total electric vehicles increasing by 220,000 vehicles from 2019 to the end of 2025. The respective San Francisco area home, DC fast, public Level 2, and workplace charging costs are \$143 million, \$36 million, \$30 million, and \$17 million, respectively. These two cases provide examples and local-level context for the level of investment this analysis implies for electric vehicle owners, electric utilities, governments, and private charging providers.

Conclusions

In this analysis, we evaluate the capital costs, including installation and hardware, for a scenario with 2.6 million new electric vehicle sales in the top 100 U.S. metropolitan areas over the 2019–2025 period. Our basic findings here are that home charging costs to support these electric vehicles total \$1.3 billion, whereas new workplace, public Level 2, and DC fast charging costs total \$940 million.

The home and public charging costs analyzed here exclude several major aspects of a comprehensive charging ecosystem. This analysis excludes the necessary charging infrastructure for fast-charging corridors to link cities, which has been the early focus of some

auto industry efforts.¹³ The 100 metropolitan areas analyzed here represent 88% of all new electric vehicles sold and 75% of the overall U.S. vehicle market, but smaller markets are outside the scope of this analysis. Also excluded from this analysis are the project management and land-related costs, which can be highly variable and location-specific. Finally, charging infrastructure for the potential increased electrification of ride-hailing services is not included in these cost estimates. Nonetheless, the estimates provided here are important to provide capital cost estimates to inform the scale of infrastructure investment needed in major markets.

We also note that investments are underway for substantial fractions of the necessary charging buildout. Electric utility charging infrastructure activities are proliferating and

¹³ For example see “Charge on the Road,” Tesla, accessed June 11, 2019, <https://www.tesla.com/supercharger>; “About Ionity,” Ionity, accessed June 11, 2019, <https://ionity.eu/en/about.html>; General Motors, “General Motors to collaborate with EVgo, ChargePoint and Greenlots to enhance the charging experience for customers,” news release January 9, 2019, <https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2019/jan/0109-charging.html>

increasingly including direct support for infrastructure to partially fill charging gaps.¹⁴ For example, three California utilities received approvals in 2018 to invest \$738 million in charging infrastructure although some of it is dedicated to heavy duty vehicle infrastructure and items outside the scope of this report.¹⁵ Volkswagen dieselgate settlement funds are also substantial. Volkswagen's Electrify America funding has allocated \$360 million for fast charging corridors, \$330 million for public and workplace charging, and \$14 million for home charging.¹⁶ In addition, up to 15% of the settlement's \$2.7 billion environmental mitigation funding can be spent by states on charging infrastructure.¹⁷

However, this analysis of charging indicates there remains a need for charging infrastructure funding to support electric vehicle growth trends in the United States through 2025. We make the following conclusions regarding our analysis of electric vehicle charging infrastructure costs in the 100 most populous U.S. metropolitan areas.

Substantial charging infrastructure investments are needed to fill the charging gap. Our findings indicate

that, to serve the growing electric vehicle market, necessary investments in workplace, public Level 2, and DC fast charging infrastructure would increase from approximately \$110 million in 2019 to \$270 million in 2025, amounting to a total of about \$940 million. In addition, home charging investments of \$1.3 billion are needed, largely for the upgrades and installation of Level 2 charging in houses and apartment buildings. These charging infrastructure costs are approximately 25% for hardware, 50% for labor, 20% for materials, and 5% for permits.

Infrastructure costs are relatively modest—and steadily decrease—on a per-electric-vehicle basis. Costs for public charging infrastructure decrease substantially on a per-electric-vehicle basis. This is due to public chargers becoming more heavily utilized, the shift to more outlets per charging site, and decreased hardware costs as the market grows. The result is that the total public infrastructure costs per electric vehicle decline from \$480 per electric vehicle in 2019 to \$300 in 2025. Averaged over all electric vehicles, some of which need home charging upgrades, home infrastructure costs are around \$510–\$540 per electric vehicle sold.

Investing in home charging will remain important. More than half of electric vehicle owners are expected to continue using their existing home charging options without home upgrades. Around 38% of electric vehicle owners are expected to have upgrades to improve their home charging, with an average cost of \$1,400 to install home outlets or chargers. However, this average includes charging costs that are typically much higher in apartments. Incentives such as off-peak electricity rates and smart charging could remain important as the market expands to ensure more charging at apartment complexes and ensure home charging is mutually beneficial to drivers and utilities. Although

many will utilize Level 1 charging with existing 120-volt outlets, higher power Level 2 charging at home will become increasingly important as battery size and vehicle range increase.

Based on these findings, charging infrastructure buildout is a strong candidate for large-scale federal funding. Although state-level utility support is growing, city and state funding for charging is generally limited. Cost-sharing federal and local funding would help leverage limited funding to help fill the charging gap and allow local authorities to align the federal support with their own action plans. Federal grants, perhaps directed at cities that demonstrate high electric vehicle uptake, comprehensive electric vehicle action plans, and city policies (e.g., streamlined infrastructure permitting, aggressive electric vehicle-ready building codes) could also be effective.

Many related questions remain. These charging infrastructure costs, clearly substantial, are presented here in the absence of vehicle electrification benefits. Follow-on analysis of how electric vehicle costs decline and fuel-saving and emission benefits increase, would likely show a strongly positive case for charging infrastructure investments.¹⁸ Determining the lowest-cost pathways for a sufficient charging ecosystem will require persistent tracking of developments with electric vehicle charging speeds, electric range, charging preferences, and charger utilization. Finally, if the electrification of ride-hailing fleets were to ramp up, this would greatly increase the need for charging infrastructure investments.

14 Smart Electric Power Alliance, "Utilities and electric vehicles: Evolving to unlock grid value," (March, 2018), <https://sepapower.org/resource/utilities-electric-vehicles-evolving-unlock-grid-value/>

15 Decision on the transportation electrification standard review projects, California Public Utility Commission May 31, 2018, <http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M215/K380/215380424.PDF>

16 The Electrify America funds are referred to as "Appendix C" funds per the settlement. "Our Investment Plan," Electrify America, accessed April 25, 2019, <https://www.electrifyamerica.com/our-plan>

17 These are "Appendix D" environmental mitigation funds. See U.S. District Court, Northern District of California, San Francisco Division, Case No: MDL No. 2672 CRB (JSC), Third Partial and 3.0L Second Partial and 2.0L Partial and Amended Consent Decree, retrieved from <https://www.epa.gov/enforcement/third-partial-and-30l-second-partial-and-20l-partial-and-amended-consent-decree>

18 Previous analysis with much higher electric vehicle costs than today indicated as much, with benefits many times greater than the infrastructure costs. See National Research Council, *Transitions to Alternative Vehicles and Fuels* (Washington, DC: The National Academies Press, 2013), <https://doi.org/10.17226/18264>

Title Page

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Principal investigator: Dr. Catherine Brinkley

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Prepared for the California Air Resources Board and the California Environmental Protection Agency

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

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Abstract

Through this contract, California became the first state to offer comprehensive, searchable, public-facing plan databases of both General Plans and Climate Action Plans. The overall aim of assembling and hosting planning data is to improve plan making, allowing community members to search for policy approaches that are already being piloted in comparable communities. With community-based organizations across the state, this contract enabled demonstrations of these online tools with a focus on three California Air Resources Board climate readiness priorities: zero-emission vehicle (ZEV) uptake, reducing vehicle miles traveled (VMT), and decarbonization of buildings. To inform the workshops, this contract assessed the current state of city and county planning approaches. We find that interest in climate policy adoption is growing. Yet, there are policy approach mismatches between state goals and local actions. Further, few plans explicitly consider equitable approaches. This report detailed equitable policy approaches for the three priority areas as models to inform further policy adoption and implementation.

Executive Summary

Background: To meet state climate goals, local jurisdictions must update plans for physical and social infrastructure. Learning from advances in other jurisdictions will help better inform local policymakers. To survey the many approaches to improving climate readiness across the state, this project created and launched landmark planning tools. Prior this contract, no state had a comprehensive, public database of General Plans or Climate Action Plans (CAP). Through this contract, California became the first state to offer such databases as planning tools for spurring civic engagement. The research team partnered with community-based organizations (CBOs) across the state to demonstrate these tools while providing locally tailored climate readiness workshops in relation to three California Air Resources Board climate readiness priorities: zero-emission vehicle (ZEV) uptake, reducing vehicle miles traveled (VMT), and decarbonization. CBOs were compensated for this collaboration.

Objectives and Methods: The overall objective of this contract is to advance climate readiness. To achieve these aims, the research team created a database of General Plans and CAPs, conducted assessment of both plan types for the priority topics, reviewed existing literature, and supported CBOs in conducting a series of evidence-informed workshops for other partner organizations. Together, the plan evaluations and literature review helped identify discrepancies between state, local, and research climate change emphases. CBOs then tailored the findings to local priorities and immediate policy discussions and hosted workshops with attendees representing over 155 organizations across California. The research team gathered feedback from participants and CBO staff from these workshops to identify barriers and opportunities for future climate readiness planning.

Results: We find that, as of January 2023, 23 of 58 counties (40%) and 230 of 482 cities (48%) have created a CAP, while 25 counties (43%) and 182 cities (43%) refer to CAPs in their General Plans. The cross-referencing of General Plans and CAPs highlights how these plan types work in tandem. Of jurisdictions with CAPs, many prefer a non-California Environmental Quality Act (CEQA) certified CAP. This non-binding planning product can be used to celebrate and set intentions that are later infused into and referred to in the General Plan. For other jurisdictions, the term “climate” is not as favored, and approaches effectively influence climate goals without labeling the action as such (e.g., aiming to improve air quality). In comparison to voluntary plans like CAPs and other alternative documents, all jurisdictions are required to create a General Plan that guides zoning and is CEQA certified. Thus, climate readiness planning often happens in and through the General Plan which can help socialize concepts and allow lead-up organizing around issues of consensus. With such variation at play, we find more fulsome attention to climate readiness policy in CAPs across all three CARB priority topics. We also find that General Plan and CAP planning vehicles are both associated with implementation as evidenced by statistical regression of plan mentions of “electric vehicle” and the siting of charging stations. We found no statistical difference in population nor geographic variation to explain which jurisdictions choose to use CAPs for climate readiness planning. Instead, CBOs note that communities employ a variety of policy approaches, and the state should support diverse pathways to climate planning.

The literature review highlights further recommendations for improving strategic goal setting and technical assistance. To start, we note terminology mismatch that creates confusion in policy dialogues where interested parties talk past one another. For example, while the term “building decarbonization” is common in state policy documents, only one county mentioned “decarbonization” in its General Plan. Scholarly literature also prefers synonyms to “decarbonization” (e.g., carbon neutral). This mismatch should not be confused with an absence of local planning effort. We provide recommendations and methods for state agencies to review policy terminology in local plans before setting state guidelines.

Our comprehensive General Plan and CAP assessments also indicate a lack of local climate readiness effort and weak policy commitments. Even where plans set intentions, most do not commit to actions. Planning scholarship recommends that plans include benchmarks for measuring progress, timelines for reaching deliverables, identified funding sources, and dedicated staff. For example, we found that of the 64 ZEV policies in county General Plans, 20 mention public ZEV use and 35 mention private ZEV use, giving shorter shrift to public ZEV goals compared to private. Even where timelines are included, local plan scoring indicates that California will fall short of its state goal for transit agencies to purchase only zero-emission buses (ZEBs) after 2029, with a goal for full transition by 2040. To explain the broad omission of policy benchmarks, CBOs state that a lack of understanding of available state funding limits their capacity to craft feasible policy that aligns with state goals and funding opportunities.

While attention to climate readiness in both General Plans and CAPs is nascent but growing, we also note a lack of attention to equity in policies. For example, 12 counties (20%) and 126 cities (26%) mention “electric vehicles” in their General Plans, but only six cities address equity considerations, including siting e-bike and electric vehicle charging stations (Alameda City, 2021 General Plan), electric vehicle charging for affordable housing (City of Arcata, 2008 General Plan), and converting public fleets to all-electric (City of East Palo Alto, 2016 General Plan). This finding underscores a need for greater equity planning support, including strong equity guidelines.

Conclusions: To encourage greater progress, CBOs recommend that state agencies consider celebrating planning advances through annual awards and pre-qualification programs for implementation funding based on equitable policy commitments in General Plans or CAPs. They also recommended sustained support for CBOs to ensure that climate readiness planning is ongoing, implemented, and reflects local priorities and targeted efforts to build capacity for equitable climate planning. Targeted CBO support is especially needed in underserved communities that have not yet crafted environmental justice policies. These recommendations rely on local-to-local learning about successful planning approaches. To facilitate such peer learning, we recommend that CARB, Governor’s Office of Land Use and Climate Initiatives, and Housing and Community Development, the state agencies that provide guidance for General Plan development, consider adopting planning data guidelines that require plans to follow FAIR standards such that plans are easily Findable, Accessible, and Interoperable, while being provided in a format that is Reusable (e.g. a machine-readable PDF). For plans to be easily located and reviewed, they must contain sufficient metadata on a cover page, including a unique and persistent identifier, and the data must be registered or indexed in a searchable resource. This requirement would bring public planning documents into compliance with federal Americans

with Disabilities Act (ADA) guidelines. Further, CBO partners recommend that CARB offer a jurisdiction-specific template that is pre-filled with greenhouse gas (GHG) inventories. This template can be used by local jurisdictions to estimate the reductions planned over a specific time horizon, helping advocates and state agencies evaluate progress. We provide an example in the appendix.

Introduction

The Best Practices and Capacity Building for Local Government Implementation of Climate Action Policies (Climate Readiness) project's primary goals are to identify best practices for local governments to implement climate planning with a focus on the three priority areas: reducing vehicle miles traveled (VMT), zero-emission vehicle (ZEV) readiness, and building decarbonization. This project seeks to simultaneously inform communities and state agencies about effective methods to address climate readiness planning challenges and implementation barriers at the local level. In May 2022, the California Air Resources Board (CARB) contracted the University of California, Davis (UCD) Center for Regional Change to lead the two-year project.

To meet these goals, this project created novel, public-facing databases of Climate Action Plans (CAPs) and General Plans along with additional materials to support local government climate efforts. Through plan evaluation, the research team scored plans and compared them to local ordinances to identify jurisdictions implementing climate action policies and the policy types best suited for different types of jurisdictions. The information gathered and additional information from CARB, including funding opportunities through CCI, were used to foster statewide capacity building sessions on resources and the priority policies. Sessions were co-hosted with community partners to leverage trusted networks of local leaders and translate state policy and research findings to the local context and priorities. Findings are documented in training materials, informational guides, and the final report, including recommendations for how CARB and CCI can best support climate readiness efforts. The training materials created in this project seek to inform a broad constituency and include a focus on equitable planning.

Background

California can only move development and planning standards forward by understanding regional and local climate planning and implementation approaches. Currently, the state requires local jurisdictions to meet various goals around climate, housing, and the environment. For example, cities and counties with an identified “disadvantaged community” that revise two or more General Plan elements concurrently are required to incorporate environmental justice (EJ) into their General Plans (Gov. Code, § 65302(h)) such that environmental hazards and mitigation costs do not fall disproportionately to historically disadvantaged communities. Further, since the California Legislature passed a suite of housing policies in 2017, there are added opportunities for local governments to receive additional funding and guidance for collectively addressing the housing and climate crisis to reduce vehicle miles traveled and decarbonize buildings while meeting demands for affordable housing.

Such state-level goals and support for environmental justice and climate action may be achieved unevenly as local jurisdictions have different planning priorities and vary widely in capacity and funding for planning and implementing these policies. Further, local jurisdictions often face planning capacity challenges, as evidenced by the many plans that are out of date, with more than half of California's General Plans being older than 15 years, according to the Governor's Office of Planning and Research (2022), an administrative office that changed title in 2024, becoming the Governor's Office of Land Use and Climate Initiatives (LCI). With added funding

for planning and additional tools and guidance, there is an opportunity to bring more local jurisdictions up-to-date in both planning for and implementing climate actions.

The project is conducted by the University of California, Davis Center for Regional Change (CRC), an applied policy-oriented research center dedicated to informing the building of healthy, prosperous, sustainable, and equitable regions. To meet these goals, the CRC brings expertise from engaged partnerships in rural and urban communities and a legacy of work focused on environmental justice in addressing the inequalities in land-use, housing and transportation planning, policies and funding. With extensive expertise collaborating with community partners to develop interactive web-based mapping platforms and training programs (e.g., Putting Youth on the Map: training in youth participatory action planning), the CRC has close ties to communities facing the greatest health challenges due to air quality and related environmental health indicators that are located outside the largest and most resource-rich urban areas in California. The platforms CRC has created in past projects are used by leaders in the business, government, nonprofit, and philanthropic sectors to target funding opportunities and support the creation of sustainable, socially responsible development.

Materials and Methods

This project incorporated stakeholder feedback in developing project deliverables. For example, the General Plan and CAP databases provide searchable tools that jurisdictions can use to examine specific language in comparable jurisdictions, such as those in the same region or with a similar population size or demographic composition. Through demonstrations, these public tools were refined so that these resources could better bridge gaps in capacity. For example, jurisdictions with fewer resources are often at a disadvantage when applying for state and federal funding allocated through competitive processes because of a lack of readily available data for benchmarking progress and making comparisons.

To center equity, the project team specifically engaged CBOs representing vulnerable, marginalized, and otherwise disadvantaged populations. Through this contract, the following CBOs were funded to support capacity building workshops: the Bay Area Climate Action Network (BayCAN), Climate Action Campaign, Los Angeles Regional Collaborative for Climate Action and Sustainability (LARC), Robert Redford Conservancy for Southern California Sustainability, and Sierra Business Council. Community engagement included iterative and mutually beneficial co-design of climate capacity building workshop materials, with the project team incorporating input and feedback from stakeholders to improve the tools, as well as the companion materials and media developed to best support broad dissemination, education, and adoption of the findings and recommendations. Such genuine engagement is critical to the long-term goal of this project, which is to identify and disseminate equity-focused policies at the city and county levels for use in capacity-building workshops. The theory of change that was used considered that available data and identification of supporting policies can better allow communities to consider plan updates, including proven policies that have worked in nearby jurisdictions. The project aimed to create communities of learning as cities and counties update plans and learn from policies that have worked in neighboring jurisdictions.

Limitations

While this project focused on a review of planning and policy to support equitable climate readiness, future iterations of this work could be augmented with the following steps: supports for additional CBO partnerships across the state with the option for extension, technical support for CAP and General Plan database updates and maintenance, and interviews with local planning officials and planning boards. Future work could further investigate implementation of plan policies by following VMT reductions on a jurisdictional basis.

Community Based Organization Partnerships

The process for selecting community partners emphasized a fair and balanced approach to prioritize established organizations with track records of success and rising organizations; nonprofits, community groups, and regional/local government organizations. The selection also sought to contract with a range of organizations that work from local to statewide. The contractor worked collaboratively with the CARB contract manager to select five of the selected community partners as compensated subcontractors.

The selection process was designed to provide commensurate funding for the level of time and skill each organization will bring to the collective partnership and the number of capacity-building workshops to be co-hosted. This partnership model aimed to foster equitable distribution of resources to established nonprofit, public institutions, and smaller grassroots organizations. The community partners and their missions are as follows:

The Bay Area Climate Adaptation Network (BayCAN), serving the Bay Area region, is a collaborative effort among local government staff and partner organizations to address climate change impacts, such as water supply, sea level rise, wildfires, and public health, by focusing on equitable adaptation strategies and enhancing existing initiatives.

With 23 staff members, The Climate Action Campaign (CAC) is a coalition of major environmental, justice, and public health organizations working together to push for science-based federal climate action, aiming to reduce pollution, accelerate clean energy transitions, and promote justice, jobs, health, and quality of life for all.

The Los Angeles Regional Collaborative for Climate Action and Sustainability (LARC), with 7 staff, established in 2007, is a network of governments, agencies, nonprofits, businesses, and academics working together to advance climate mitigation and adaptation in LA County through cross-jurisdictional collaboration, peer knowledge sharing, and cutting-edge research, while optimizing regional resources and outcomes.

Founded in 2012 and named in recognition of Robert Redford's dedication to environmental advocacy and service on Pitzer College's Board of Trustees, the Robert Redford Conservancy for Southern California Sustainability at Pitzer College works to promote socio-ecological justice and sustainability in local communities and beyond.

With 19 team members, Sierra Business Council is a nonprofit dedicated to fostering community vitality, economic prosperity, environmental quality, and social equity in the Sierra Nevada by

supporting local economies, enhancing climate resilience, and addressing rural issues through innovative, on-the-ground programs and projects.

The CRC also welcomed additional partners without a compensated subcontract by making training materials cost-free and publicly available online.

The CRC project team worked closely with CARB staff and partner organizations to co-create presentations and materials to be covered at the capacity-building sessions (please see Appendices 2 and 3). These materials aim to explain in clear and accessible language:

1. State-level policies and goals;
2. CARB priority strategies for local climate action;
3. Examples of policies implemented by local jurisdictions, including sample ordinances and language;
4. Strategies identified to overcome barriers associated with local action planning and implementation; and
5. Sources of funding for implementing climate projects, including CCI.

Training and outreach materials aimed to foster ongoing learning through the General Plan and CAP databases. As such, the CRC worked with CARB staff to develop media and collateral materials with the broadest audience of stakeholders, including handouts, videos, and guides (Appendix 3.) for local government, advocacy organizations, and community organizations. The purpose of these materials is to educate local jurisdiction staff and local advocates on available tools and CARB priority strategies. The materials were further informed by community-identified successes and barriers to be used in workshops and beyond the project. Community partners also informed the development of training materials to ensure cultural compatibility and efficacy. The CRC translated materials into Spanish and worked with community partners to target other languages for translation to ensure greater access to research and policy products.

The CRC project leads consulted throughout partner-led climate readiness workshops. Initially, these workshops were designed for CBOs to present materials, building from existing, local, trusted relationships to ensure that questions, feedback, expertise, and empowerment continued to be fostered locally. At the request of multiple partners, CRC project leads and CARB were invited to attend and present at several workshops. The CRC debriefed with partners after each workshop through a short survey. At the conclusion of all workshops, the CRC hosted an informal debriefing for partners to share and compare experiences.

Building tools for informed planning

The idea behind building public-facing online tools for climate readiness planning is that, in part, greater data access and analytics can inform and celebrate more efficient and equitable practices. As part of the Climate Readiness project, this team created two public-facing data platforms. One is focused on California's city and county General Plans. The other is focused on California's local Climate Action Plans (CAPs). To create these tools and predict their long-term impact, this section details similar efforts and outcomes.

Similar planning data democracy efforts are underway across the nation as several states and federal agencies innovate new forms of data infrastructure, the digital platforms necessary for promoting data sharing and use. For example, in 2018, the New York State Division of Homeland Security and Emergency Services and the Federal Emergency Management Agency (FEMA) produced the nation's first web-based State-wide Hazard Mitigation Plan in partnership with Dr. Catherine Lawson (MitigateNY, 2021) to urge counties to update hazard plans to be eligible for federal funding during disasters. The online map of local plans highlights that over half of the New York counties do not have up-to-date plans and many lack a focus on hazards of interest. The tool aims to help advocates urge for plan updates while assisting local jurisdictions by making planning approaches easy to find and assimilate. Similarly, the National Zoning Atlas is a federated data project focused on land use planning through zoning ordinances. The UC Berkeley's Othering and Belonging Institute and UC Davis Center for Regional Change are assembling zoning data from each California jurisdiction, with initial analysis demonstrating that the majority of land is zoned for single family housing with implications for affordable housing supply and CARB's goals to reduce VMT through compact development approaches. Each tool allows the public to consider regional and state-wide implications for equity and climate planning as they engage in local policymaking.

Surveys of developers and consultants involved in planning, design, and impact assessment attest to the importance of such spatial data infrastructure in creating and tracking planning progress in order to meet planning goals (e.g., Campagna and Craglia, 2012). Though such databases are broadly useful, there is good reason for why they have yet to be assembled. The effort to gather and evaluate plans is labor-intensive. Though public documents, like plans, are often physically accessible under sunshine laws like the American Freedom of Information Act, immense labor is involved in assembling plans for comparison, particularly where plans must be translated. Some plans are just scanned documents. Not all are in machine-readable PDF formats. Such varied formatting is an issue and labor-intensive to resolve. The result is that there are few plan evaluation studies overall (Talen, 1996). In their meta-analysis of plan evaluation, Berke and Godschalk (2009) note only 16 plan evaluation studies over a 20-year period from 1997-2007. In addition, most studies compare tens of plans (33 plans in Berke and Conroy, 2000; 34 plans in Conroy and Berke, 2004; 47 plans in Mui et al., 2021). In explanation, many plans are over 2,000 pages in length; qualitative coding or even a simple tally of search terms across plans is only recently available with text mining via computer-based information retrieval. With modern cloud-based storage and advances in machine learning, some of these barriers can be overcome, and plans assembled for one purpose can also be evaluated for other topical areas of interest. The creation of a General Plan search engine and public-facing CAP database can help further such

accountability and monitoring—not only for state agencies, but also for nonprofit organizations working toward climate, equity, and broader planning goals. Next, we detail current state requirements for plan access and review.

California goals and local planning efforts

Multiple California state agencies rely on local plans to deliver state goals. As a result, several state agencies provide guidance for land-use plan development. LCI is required by Government Code Section 65040.2 to adopt and periodically revise the State General Plan Guidelines (LCI, 2021b) which provides a technical how-to” for preparing a General Plan in California. In statute, the general plan is required to address the following "elements" or topic chapters: land use, circulation, housing, conservation, open space, noise, safety, environmental justice, and air quality, each addressing a specific aspect of community development and planning (Gov. Code §65302). These elements guide land use, transportation, housing needs, natural resource conservation, public safety, and pollution reduction, with examples from cities and counties linked throughout the General Plan Guidelines. LCI also serves several important functions in the administration of the California Environmental Quality Act (CEQA; Public Resources Code Section 21000) that requires state and local government agencies to inform decision-makers and the public about the potential environmental impacts of proposed projects and plans, and to reduce those environmental impacts to the extent feasible. As such, LCI provides technical planning assistance for meeting CEQA and other state General Plan mandates and also manages the State CEQA Clearinghouse where many, but not all, plans are submitted for state level review and made available to the public. To assist with the land use and air quality elements of General Plans, the California Environmental Protection Agency and CARB provides guidance through their “Land Use Handbook” (CARB, 2005). Similarly, the state Housing and Community Development (HCD) agency offers a comprehensive housing-element guide (HCD, 2021a). In addition, HCD is empowered to review the housing element, which is updated every 3-8 years (Article 10.6 of Chapter 3 of Planning and Zoning Law, commencing with Government Code Section 65580).

The state does not currently require that cities and counties report planned development in a standard format—nor that plans be maintained in a central repository. Yet, state agencies are moving toward such precedents to enable more timely assessment of local progress toward state goals. For example, with the 2017 Legislative Housing Package (Cal. Gov. Section 65585), HCD now requires that housing elements or amendments adopted on or after January 1, 2021, shall be submitted to HCD electronically using forms pursuant to SB 6 (Chapter 667, Statutes of 2019) in order to standardize reporting on the number of planned housing units.

Similarly, state laws require local plans to meet a variety of accessibility standards. For example, local government documents must be compliant with Section 202 of the Americans with Disabilities Act (42 U.S.C. §12132) which seeks to ensure that public documents are accessible to hearing and visually impaired individuals with formatting that allows screen readers, refreshable Braille displays, alternative text describing images, and resizable text. The Brown Act (Gov. Code § 54950-54963) seeks to guarantee the public's right to attend and participate in meetings of local legislative bodies. Through this legislation, the public is entitled to copies of contracts, settlement agreements, and other documents approved by the public body and subject

to any of these reporting requirements (Gov. Code § 54957.1(b)). As part of accessibility requirements, a federated, central repository of plans will help public engagement across jurisdictions. This project aims to meet such mandates and demands.

The lack of an aggregated and complete dataset of plans as well as an inability to search across plans hinders both state agencies and CBOs in climate readiness planning. To work around these limitations and regularly assess implementation, LCI conducts an Annual Planning Survey (APS) and Annual Progress Reports (APRs) each year per Government Code Sections 65400 and 65700. Notably, the results of such data gathering efforts are incomplete. Only 59% of California cities and counties (319 of the 540) returned the Annual Planning Survey in 2023, leaving many questions unanswered or marking responses as “unsure” regarding survey questions about what policies the General Plan contained. Similarly, HCD found that many cities have not updated their plans in accordance with state mandates as noted through their Housing Element Implementation Tracker (HCD, 2023b).

In response to these data infrastructure concerns and to foster informed community-driven climate planning, this contract developed the first statewide comprehensive database of California’s 482 city and 58 county General Plans in addition to the creation of a comprehensive California CAP database. In addition to being first for the state of California, these public-facing data products are the first for any state—or nation. In the following section, we detail the data assembly and design of each product.

General Plan data visualization tool

Following Chen et al. (2020), we engaged in a platform development effort that centered equity through an “iterative process [that] requires peer-review, discussion and edits within the community.” First, we examined the current state of data infrastructure for plans in California by studying state-level mandates for land-use planning data infrastructure in California and qualitatively examining the structure and formatting of plans from all cities and counties in California. Second, we designed and tested a pilot database and platform for archiving, searching across, and visualizing the contents of California plans. At each step, we checked our understanding of the current state of planning and the problems with information discovery and accessibility needs with state agencies, policy advocates, and community-based nonprofit organizations (see Poirier et al., 2024). At each stage of the process, the research team presented findings to state agency representatives and nonprofit members with an EJ focus on climate readiness planning. CARB convened meetings with state agencies. The CRC convened meetings with non-profits and partners.

We center state agencies and EJ stakeholders in an intentional effort to build equity and accessibility into the analysis and platform design with partners that are involved in real-time technical planning efforts. Many EJ CBOs were involved in efforts to help motivate the state legislature to pass SB 1000 (Leyva) in 2016 (Cal. Gov. Code, § 65302(h)). This law requires local governments to identify disadvantaged communities (DACs) in their local planning area, engage with communities in developing their plans, and adopt EJ policies that address equity, such as reducing air pollution exposure and promoting local clean energy economies. EJ is further defined in California law as “the fair treatment and meaningful involvement of people of all races, cultures, incomes, and national origins with respect to the development, adoption,

implementation, and enforcement of environmental laws, regulations, and policies” (Cal. Gov. Code, § 65040.12, subd. (e)). Each partner, state and nonprofit, seeks greater plan data infrastructure to allow 1.) monitoring of local jurisdiction compliance with state mandates, and 2.) informed updates to their technical planning toolkit based on the discovery of model EJ policies and best practices in the development of in General Plans. We also sought pilot platform development input from the LCI, HCD, and CARB, state agencies that provide guidance for General Plan development. These early efforts helped take the original platform to its third version through this contract.

Data collection

Most California General Plans are publicly available on city websites, but there are no centralized locations for archiving plans nor standards regarding where such plans should appear on the sites. In 2017, Dr. Brinkley’s team collected PDFs of General Plans for 421 of California’s 482 cities via their websites (Brinkley and Stahmer, 2021). At that time, we were missing plans for 61 cities, having not been able to locate them on city websites. A second round of data collection was initiated as part of this contract to locate previously missing plans and to incorporate county plans. In addition to reviewing municipal websites, this round involved emailing or calling city planning offices to inquire about plans. By the end of 2022, we obtained plans for every California jurisdiction. While most plans were available as PDFs, some were published as Word documents, html files (e.g., City of Ontario), or text files. In these cases, we converted the documents into a PDF, using Adobe Acrobat.

Plan format analysis

We took a random sample of 100 city plans and documented the availability of certain metadata descriptors such as the plan’s creator, when the plan was created, and when the plan was last updated. In providing an overview of current plan structures, this analysis laid the foundation for piloting a platform for federating and searching across General Plans (see Poirier et al., 2024). We found that in a sample of 100 city plans, none of the plans included structured metadata and less than half listed unstructured metadata such as who created the plan, who to contact with questions, or the resolution number. Of note, most plans did not follow standard formatting to enable text recognition nor did any plans provide text for all images per ADA guidelines. As a result, even when the public can access a plan, it can be difficult to discern when the plan was produced, when it was last updated, what it contains, and who to contact with questions. In a few cases, though different elements of the General Plan were adopted or revised in different years, all elements were compiled into a single document. Further, due to local variation in the formatting and naming of plan elements, classifying plan “types” is difficult. For example, some communities refer to their CAP as a “Sustainability Plan.” With some General Plans dating back to the 1960s, many PDFs of older General Plans are scanned to city and county websites from typed documents with non-machine-readable text, low contrast, and low image quality. Many existing optical content recognition tools and text extraction packages are limited in their ability to accurately recognize and parse words in such documents. Based on these findings, we recommend that the state of California provide guidelines for plan formatting that include requirements for plans to be accessible as machine readable PDFs with a standard template cover

page that details plan metadata and a digital object identifier (DOI). A DOI is a unique, persistent identifying number for an online document which remains the same even if the document's location on the Internet changes. A summary of recommendations for local and state actions can be found in Appendices 4 and 5.

General Plan Platform Development

The pilot platform was first developed in R and later redeveloped in Python. Because planning language is constantly in flux and relies on specialized phrases, the search engine required sophisticated indexing. For example, California jurisdictions discuss “homelessness,” “the unhoused,” and “unsheltered.” Indexing for accurate search capabilities requires a large vocabulary of terms and phrases to capture synonyms. Thus, we redesigned the platform using Python packages optimized for quickly extracting information directly from PDF documents and ElasticSearch to allow multi-word and phrase search queries (see Banginwar et al., 2023). The resulting search engine for General Plans won the California American Planning Association Award for Academic Excellence in 2023, indicating its welcome reception by practicing planners across the state.

Climate Action Plan database

The California Climate Action Plan Database (CCAP Database) was started in 2010 by Professors Michael R. Boswell and Adrienne Greve of California Polytechnic State University, San Luis Obispo. The purpose of the database was to support research on the nascent field of climate action planning. The database has periodically been made available to researchers and public officials, but for the first time through this contract, it was made widely available with a GIS-based interface and a complete web-based library. The database is regularly updated, and further updates can be submitted by email to: mboswell@calpoly.edu.

The CAP Database includes CAPs with the following criteria:

1. Must be based on a community-wide greenhouse gas (GHG) emissions inventory.
2. Must address community-wide emissions, not just municipal emissions.
3. Must substantially address issues of climate change (may address other areas of sustainability/environment).
4. Should be structured as a plan with standard introductory, background, and policy- type sections (e.g., not just ideas on a webpage).

There is some gray area in interpreting these standards, so some additional clarifications and caveats are specified. For example, the CAPs do not need to be stand-alone documents to be included and can be embedded in other policy documents (e.g., General Plans, Sustainability Plans, Energy Plans) if the criteria above are generally met. There are a few “energy action plans” in California cities and counties. Some of these plans focus narrowly on energy issues and are not consistent with the criteria above, thus are not included. Others, which are included in the database, are based on GHG inventories and have GHG reduction targets, though they often only focus on energy policy. Ideally the CAPs have been formally adopted by the jurisdictions, but this is sometimes difficult to determine, so they are included regardless of their adoption status (unless they were formally rejected). Some regions prepare regional CAPs but then leave the

individual cities and counties to finish the process and formally adopt/accept the CAP. This can be confusing. The CAPs prepared under regional initiatives that appear in this database have been examined for their status and only included if there is evidence of formal action by the individual jurisdiction. Mere participation in the regional effort was not sufficient for inclusion. Of note, the database does not include the nine Priority Climate Action Plans (PCAPs) prepared under the EPA Climate Pollution Reduction Grants (CPRG) program. All the CAPs included in the database address GHG emissions reduction and/or mitigation. They can include adaptation and resilience content as well, but plans that only include adaptation are not in this database, though efforts are underway to add them. For these reasons, we recommend a standard template cover page identifying CAP adoption date, GHG inventory, expected emission reductions over the planning horizon, and CEQA certification.

The CAP database can be accessed at the following:

- CCAP Database Homepage: <http://climateactionplanning.com/ccapdbase/>
- ArcGIS Online map interface: <https://arcg.is/mSXv0>
- CAP Library with summary Excel database (via Dropbox): <https://bit.ly/CCAPLibrary>

Recommendations for furthering equitable planning

In the process of developing the General Plan database and platform (PlanSearch) and CCAP, we reflected on the challenges of archiving and searching across plans given the current state of data infrastructure for California planning. There is a great deal of variation in the formatting of CAPs and General Plan documents from city to city and county to county. Some plans are thousands of pages long, while other plans are fewer than 50 pages. Some cities divide required elements into separate documents while others compile all of the elements into a single document. Some General Plans signpost required elements via text headings, while others reference required element policies throughout the General Plan text. Some plans will include separate sections or PDFs for planning themes such as Recycling, Youth and Education, Recreation, and Agriculture, while others do not. Required content, like the Housing Needs Assessment, may be written in paragraph text, formatted in a table, or summarized in an image, making it difficult to extract affordable housing unit numbers across plans in a standardized manner. Most California General Plans include elements that are more than 15 years old. Even where there are state mandates for basic data infrastructure requirements, like plan updates, many local jurisdictions do not adhere.

Our findings highlight where and how the state of California can help local jurisdictions with planning templates and data management to further equitable planning and state climate action goals alike. For example, a template for formatting a GHG cover page in the General Plan or CAP can help with regional assessments of planning progress toward state goals. Importantly, there are precedents and guidelines for such initiatives. For example, FAIR guiding principles emphasize the need to make data: Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016).

- **Findable:** For data to be findable there must be sufficient metadata; there must be a unique and persistent identifier; and the data must be registered or indexed in a

searchable resource. The PlanSearch tool and CAP database aim to improve the ability of the public to easily find, read and compare plans.

- Accessible: To be accessible, metadata and data should be readable by humans and by machines, and it must reside in a trusted repository. A plan that is in a machine-readable PDF format allows users to search for key terms rapidly. This format is also useful for visually impaired reading software.
- Interoperable: Data must share a common structure, and metadata must use recognized, formal terminologies for description. This can be accomplished with a standardized cover page that allows readers to see immediately when the plan was adopted, who created the plan, and whether there are newer versions.
- Reusable: Data and collections must have clear usage licenses and clear provenance, and meet relevant community standards for the domain. This could be achieved by registering plans with a DOI with a timestamp.

Guidelines for improving the ‘FAIR’-ness of data emphasize the importance of indexing data in a searchable repository, describing the creation, contents, and management of data with rich metadata, and ensuring that links to the data will persist over time. There are currently no such FAIR guidelines for California General Plans or CAPs. We recommend creating such standards.

In addition, we recommend creating standardized cover page templates (see Appendix 7) for use in plan creation. These templates can be voluntarily adopted and partially pre-filled by the state and ready for editing by local jurisdictions. Based on feedback from CBO partners, these templates should include the following information:

- Date plan was adopted;
- Date plan is updated;
- CEQA certification. Many CAPs are not CEQA certified or do not provide information on CEQA certification;
- Jurisdiction with shapefile attributes;
- Plan authorship, information about the firm that prepared the plan or authors of the plan;
- DOI.

Plan Evaluation

We used a comparative plan evaluation to understand the prevalence of terms and planning goals. This information is compared with state goals to understand: alignment and gaps (Berke & Conroy, 2000; Conroy & Berke, 2004); future trends (e.g., Grafakos et al., 2020); and promising policies across plans (e.g., Mui et al., 2021).

Plan Evaluation Methods

In comparing plan contents for the three priority areas, we follow a post-hoc plan evaluation protocol (Berke & Godschalk, 2009; Baer, 1997). We followed standard methods developed in previous studies by categorizing policy strength based on strength of policy language, identified funding, dedicated staffing, and benchmarks for implementation (Berke & Godschalk, 2009). To achieve these goals, one team of coders evaluated General Plans, with an intercoder reliability score of 94% to ensure standard coding across coders. The CAP scoring relied on an individual coder.

To be scored, a policy needed to show commitment. Efforts to explore approaches or set intentions were not scored. A score of “1” indicates that a policy within the plan met one of the three requirements for committed funding, benchmarked timeline for implementation, or dedicated staff. A score of 3 indicated that the plan contained all three levels of commitment (Berke, 1996; Berke & French, 1994). A plan can contain multiple policies, each varying in strength. Similarly, a plan could address the topic or term, but with weak policy language resulting in a score of 0.

Importantly, the strength of policy language is predicated on the presence of enabling language. For example, weak policy language suggested, but did not require action, using words like: “encourage”/ “may”/ “should” / “promote” / “explore” / “continue”. As an example: Shasta County (2014) included the following policy: “6.4.4 Policy E-j The County should continue to implement plans to convert more of its vehicle fleet to hybrid or alternative fuels that meet or exceed air quality standards.” This policy did not mention timeline, funding, nor personnel and would have scored a 0 as a policy as it lacked any benchmarks for success. Conversely, strong policies included enabling language such as: “will”/ “shall” / “must”/ “participate” / “Require” / “Update or review the code to allow for ...” / “processing or permitting priority” / “Develop requirements” / “adopt an ordinance.” As an example, Solano County (2008) included the following policy: “Implementation Program RS.I-42: Replace existing County vehicles with alternative fuel vehicles such as electric, hybrids, natural gas, and fuel cell powered vehicles. New County vehicles must be alternative fuel vehicles.” This policy included a timeline, identified funding (the general fund), and detailed committed personnel (the Department of General Services). As a result, this policy would have scored a 3. To compare planning language with policy strength, we also include term mentions.

Our scoring method helps indicate where plans mention terms of interest (term counts), and where they follow California Department of Justice best practice guidelines (2023). Per these guidelines, “local governments *should* include metrics to help assess the effectiveness of their engagement efforts and evaluate their progress towards implementing their environmental justice

policies. Metrics, such as timelines for implementation or measures of success, should allow for the community to be able to track and assess progress” (CDJ, 2023, p. 8).

For the county plan score evaluations, all counties with CAPs as of January 2023 were included in the analysis. For city evaluations, a sampling strategy was used. First, as in the General Plan analysis, all city CAPs key term mentions, such as “VMT” and “energy,” were noted. The first draw of the city CAP sample was then determined by taking the top 10 term mentions in CAPs; in the case of a tie score, both cities were drawn. The method is meant to score a sample of the plans that mention the search terms the most using the premise that term mentions, and the strength of policy scores will correlate. The second draw on the city sample was taken by using the top 10 term frequency cities for the General Plan analysis. The premise tested in this method is that jurisdictions that mention the term most in their General Plan, were also expected to include strong related policies that will score highly in their CAP. In several cases, cities did not have CAPs so those were obviously excluded from CAP policy scoring. In combination, these methods yield sample city CAP score samples for each search term: the highest “VMT” is 20, “energy” is 17, and “EV” is 20.

As previously noted, counties and cities organize their General Plan and CAP in various ways. For example, the Tulare County 2012 General Plan includes goals, policies, and implementation measures that apply to specific policies. Not all policies are covered in an implementation measure. Of the two ZEV policies (AQ-1.6 and AQ-1.10) in this plan, policy AQ-1.10 was not included in an implementation measure and therefore did not receive points for timeline, funding, or personnel. Similarly, the Marin County General Plan (2007) includes goals and implementing programs that do not necessarily correspond with a specific policy, making assessment of policies difficult. In comparison, the Mono County General Plan (2009) includes goals, objectives, policies, and actions - all of which are directly connected. In some cases, actions or goals containing search terms and resembling policies were treated as policies. For instance, Action CON-3.D was coded as a policy because it contained the term “alternative fuel,” even though Albany City (2016) did not have this “action” labeled as a “policy” in its plan.

Limitations

It is important to note that many jurisdictions are currently working toward plan updates. Thus, the plan score and term assessments will likely offer an undercount of efforts. Differences between what the adopted plan covers and what is part of a current, but not yet realized, planning effort are perhaps best illustrated through equity considerations. The Annual Planning Survey (APS) from 2023 found that 20% of reporting jurisdictions are addressing “racial equity” and 35% are addressing “climate adaptation and resilience” in their plans or efforts. With an APS response rate of 59%, the information is incomplete. Yet, we also note that there is very little evidence within plans of such progress. For example, only two cities (0.4%) and three counties (5%) use the term “racial equity” in their General Plans. Similarly, only 46 cities (9.5%) and 13 counties (22.4%) mention “climate adaptation” in their General Plans despite state goals to meaningfully address this topic in every jurisdiction. Clearly, both plans and current efforts are well behind state goals but plans seemingly lag further behind planner-reported efforts to address state priorities.

In the following plan evaluation sections, we will first address plan scores in general plans, followed by those of CAPs.

ZEV plan evaluation results for counties

The ZEV composite score is a sum of the number of strong policies for the following terms: “alternative fuel” and “electric vehicle”, with the following terms scored under “electric vehicle”: “zero-emission vehicle”, “plug-in electric vehicle”, “battery-electric vehicle”, and plug-in hybrid electric vehicle” (Table 1).

Table 1. ZEV-related term mentions in city and county General Plans

Zero-emission Vehicle Terms	# of City General Plans that mention “electric vehicle” (out of 482)	# of County General Plans that mention “electric vehicle” (out of 58)
Alternative Fuel	142	28
Electric Vehicle	109	11
Zero-emission Vehicle (ZEV)	5	0
Plug-in Electric Vehicle (PEV)	1	0
Battery-electric Vehicle (BEV)	0	0
Plug-in Hybrid-electric Vehicle (PHEV)	0	0

The total ZEV score for county general plans ranged from 0-16, with 34 of California’s 58 counties scoring a 0. The average score was 2.6 and the median was 0.0. The top three scoring counties are Yolo, San Luis Obispo, and San Joaquin. The majority of counties with a score over 0 tended to be populous counties of central and coastal California.

The top scoring county overall for ZEV policies was Yolo County with a total score of 16. The 2009 Yolo County General Plan contained 11 policies: two policies used strong policy language, three mentioned a timeline, none mentioned funding, and three mentioned personnel. Here is an example of a policy with weak language, a timeline, and personnel:

“Action PF-A79 Include incentives for alternative fuel vehicles as part of new County facility development, including charging stations and preferred parking. (Policy PF-12.3)” Timeline: Ongoing. Personnel: County Administrator's Office. (The policy PF-12.3 is mentioned within this action, however that policy itself did not contain the search term, so it was not separately coded.)

The second highest scoring county was San Luis Obispo with a total score of 15. San Luis Obispo (2010) included seven ZEV policies. None used strong policy language or mentioned funding, but four policies had implementation strategies with timelines and personnel. The following is an example of a policy with an implementation strategy:

“Policy AQ 2.6 - Alternative fuel incentives: Support and seek funding for incentives to residents, fleet operators, school districts, and employers to purchase and use alternative fuel vehicles as local, state, or federal funding sources become available. Implementation Strategy AQ 2.6.3 - Vehicle Charging in New Development: Encourage new construction to include vehicle access to properly wired outdoor receptacles to accommodate zero emission vehicles (ZEV) and/or plug-in electric vehicles (PHEV).” Timeline: Ongoing, start time immediately. Personnel: County Department of Planning and Building, San Luis Obispo County Air Pollution Control District.

The third highest score was San Joaquin County at 12 points. The San Joaquin County 2016 General Plan contains six ZEV policies, all written with strong policy language, and two policies mentioning both timelines and personnel. Here is an example of a policy with strong language, a timeline, and personnel:

“Implementation NCR-J: Government Automobiles. As vehicles come up for replacement, the County shall evaluate the feasibility of replacing them with hybrids, alternative fuel, or smaller and more energy-efficient vehicles.” Timeline: Ongoing. Personnel: Public Works, General Services.

These findings compare to CAP county-level scores. Total ZEV scores for county CAPs ranged from 0-37, with an average score of 10. From this, we see stronger policies occurring in CAPs. The three highest scoring counties were Butte (37), San Diego (31) and Los Angeles (28). Thus, we note that inclusion of strong policies in general plans does not neatly match CAP contents. One explanation may be that plans are updated and adopted step-wise, with newer plans offering bolder policies. For example, five of the 23 counties with CAPs (21%) had no ZEV policies in their CAP, though they were adopted from 2010-2014 thus predating much of the attention to ZEVs.

Policy Approaches

Policy approaches included priority parking for ZEV, charging infrastructure, and encouragement of public (government-owned or neighborhood electric vehicles) or private ZEV use. Neighborhood Electric Vehicles (NEVs) are small, low speed electric vehicles, like golf carts. Considerations for private fleet ZEV uptake outweighed those for public efforts. For example, of the 64 total ZEV policies in county General Plans across all counties, 20 mention public ZEV use and 35 mention private ZEV use.

Example of priority parking ZEV policy:

Napa County 2019: “Policy CIR-29: As a major employer, the County of Napa shall demonstrate leadership in the implementation of programs encouraging the use of transit, walking, and bicycling by its employees, as well as the use of alternative fuels. Example programs may include: Preferential carpool parking and other ride sharing incentives; Flexible working hours or telecommuting where consistent with job duties and customer service needs; A purchasing program that favors hybrid, electric, or other non-gasoline vehicles; Assisting in the development of demonstration projects for alternative fuel

technologies such as ethanol, hydrogen, and electricity; Secure bicycle parking; and Transit incentives.” This policy did not mention timeline, funding, or personnel.

Example of charging infrastructure policy:

Humboldt County 2017: “E-P4 Transportation Energy Conservation and Alternative Fuels Substitution: Support revitalization and infill projects within Urban Development Areas as a means to reduce long-term vehicle miles traveled as an energy conservation strategy. Support the development and implementation of Electric Vehicle (EV) charging stations and other alternative fueling infrastructure.” Timeline: 2-5 years. Funding: TBD. Personnel: Redwood Coast Energy Authority.

Example of public ZEV uptake:

San Joaquin 2016: “GOAL IS-3 To increase efficiency of County facilities, services, and operations to conserve resources and reduce greenhouse gas emissions. IS-3.5 New Fleet and Equipment Purchases: The County shall purchase lower-emission and/or electric vehicles and energy efficient equipment when purchasing new fleet vehicles and maintenance/construction equipment.” Timeline: Annual, ongoing. Funding: None. Personnel: General Services, Public Works.

Example of private ZEV uptake:

Calaveras County 2020: “Goal PF 3: Wide use of alternative energy sources; cost-effective integrated solid waste management and systems emphasizing waste reduction and recycling PF 3.1 Support the development of new energy generating technologies and facilitate the incorporation of these technologies into new development while retaining community character. (IM PF-3A, PF-3B, PF-3E and PF-3F) Implementing Measure PF 3B Alternative Fuel Vehicles Infrastructure and Incentives Amend the zoning code to recognize and permit infrastructure necessary to support alternative fuel vehicles (e.g., charging stations) and encourage their use through the provision of incentives provided in the zoning code. Implements: Policy PF 3.1.” Timeline: None. Funding: None. Personnel: Planning Department.

In these findings CAPs contained stronger policy language. Of all the policies examined, 50% used strong language such as “shall” or “will.” Los Angeles and Marin counties had the highest number of strong policies. Five of the 21 counties had more than 75% of their total policies characterized as strong.

Example of strong policy:

Los Angeles County 2024: “T6.3—Require all new development to install EVCSs through a condition of approval/ordinance. Residential development must install EVCSs; nonresidential development must install EVCSs at a percentage of total parking spaces.”

Note that EVCS refers to Electric Vehicle Charging Stations.

Equity-focused Approaches

No counties included explicitly equity-focused approaches to a ZEV policy in their county General Plans. Such approaches would have considered priority parking for vulnerable populations, siting of charging stations in DACs, or additional funding and support for low-income community members to lease or own ZEVs.

This compares to CAPs, where four counties clearly showed a focus on equity in their policies.

Example of equity policy:

Los Angeles County 2024: “T6.4—Install EVCSs at County facilities and properties for public, employee, and fleet use, prioritizing locations in frontline, BIPOC (Black, Indigenous, and people of color), and disadvantaged communities. Complete an assessment of EV charging locations, identifying gaps in publicly accessible stations for frontline, BIPOC, and disadvantaged communities. Provide EV purchase incentive information in multiple languages to frontline communities.”

Timeline

Most timelines for ZEV policies in county General Plans were marked as “ongoing.” When counties used “short-term” and “long-term,” their definitions varied. For example, Mono County 2015 marked their policy as “Within the 10-year short-term time frame of this plan” and Marin County 2007 marked one of their policies as “Long term (over 7 years).” Such variance made it difficult to predict state-level ZEV achievement goals on the basis of local planning efforts alone. Where timelines are included, local plan scoring indicates that California will fall short of its state goal for transit agencies to only purchase zero-emission buses after 2029, with a goal for full transition by 2040.

The lack of timeline metrics to benchmark progress is echoed in CAPs. Of all the policies examined in county-level CAPs, 45% had a timeline or prioritization for implementation. Butte, Santa Barbara, San Diego, and San Francisco counties state specific years for implementation, while others use the short/medium/long-term convention.

Example of CAP policy with specific timelines:

San Francisco City/County 2021: “TLU.7-2 Expand publicly available EV charging across the city that is financially and geographically accessible to low-income households and renters.

- a) By 2022, complete an evaluation framework to develop curbside charging pilots
- b) By 2023, expand charging to 10% of spaces in municipally owned parking lots
- c) By 2023, expand charging to 10% of spaces within privately owned large commercial garages

d) By 2023, create three “fast-charging hubs” with one serving a disadvantaged community within San Francisco.

e) By 2025, install charging to 10% of SFO-owned parking stalls supported by load management software.”

Funding

Only seven counties identified funding sources or potential funding sources for their county-level General Plan ZEV policies. The most common sources listed were “Planning and Building Department Budget” (San Luis Obispo 2010, three out of six of their ZEV policies) and General Fund (Solano 2008 for their only ZEV policy, and San Luis Obispo 2010, two out of six of their ZEV policies). The only county that listed a specific grant was Madera County 1995: “Air pollution control district grants.” No counties listed an amount, indicating the difficult and uncertain funding landscape for achieving ZEV transitions.

The lack of identifying funding resources is echoed in CAPs. Of the 18 counties that included ZEV policies in their CAPs, only 3 included funding sources for their policies. This finding, combined with climate readiness workshop feedback that funding is a limiting factor for local planning, highlights how state guidelines and mandates should explicitly point local jurisdictions to readily available funding sources.

Staff and Personnel

The identification of dedicated personnel, where listed, provides valuable information about coordinating climate ready ZEV policy. Common personnel identified as responsible for county-level General Plan ZEV policies include: planning departments, public works departments, air districts, general services departments, and the county administrator’s office. Less common personnel identified and mentioned just once include: the board of Supervisors, Department of Health, the Central Coast Clean Cities Coalition, and the Transportation Authority of Marin. Similarly, just over 50% of county-level CAP policies included an assignment to a specific department or agency for implementation, such as community development or public works. These are usually listed in an implementation table and not discussed in detail.

State agencies hoping to convene working groups and spur implementation of ZEV policy would do well to convene those listed as responsible at the local level in future climate readiness planning efforts.

ZEV plan evaluation results for cities

Next, we look to city-level ZEV policies in General Plans and CAPs. Based on term mentions, state policy-making language and use of ZEV terminology is less common at the local level, where jurisdictions more commonly refer to “alternative fuel” and “electric vehicle” (Table 1). Figure 1 shows jurisdictions that mention “electric vehicle” in their general plan. In this spirit, the sample of city-level CAPs was scored for the following terms: “electric vehicle” and “EV.” With the prevalence of terminology in mind, state agencies may wish to change their messaging to reach broader audiences.



Figure 1. City and county jurisdictions that mention “electric vehicle” in their General Plan. As of 9/26/2024, 135 out of 482 cities mention “electric vehicle, ” and 19 out of 58 counties mention "electric vehicle." There is no clear geographic pattern across urban and rural jurisdictions in the North, Central and South on the coast and inland. Image created on PlanSearch.

City General Plan ZEV composite scores ranged from 0-25, with 285 cities scoring a 0 (60%). The strongest scoring cities all scored 21 and were: Agoura Hills, Aliso Viejo, Artesia, and Pinole. Similarly, only 125 cities mention “electric vehicle” in their General Plan (26%) demonstrating nascent ZEV policy uptake at the local level. This indicated that about 40% of California jurisdictions use General Plans to move ZEV policy forward by setting intentions and crafting policy commitments. It should be noted that many jurisdictions mention terms without including strong policies, instead referring to additional planning efforts outside of the General

Plan. For example, the City of Alameda (2021) includes the following effort to prepare a separate plan for ZEV uptake:

“Goal 2: Reduce the community’s greenhouse gas emissions which are contributing to global warming, climate change, and environmental and social impacts. Policy CC-6 Climate-Friendly Vehicles and Equipment: Reduce transportation greenhouse gas emissions by promoting, and when appropriate, requiring the use of low and zero emission vehicles and equipment and supporting the use of micro-mobility devices to reduce energy use and carbon emissions from personal vehicles. Action g. EV and Micromobility Action Plan: Partner with Alameda Municipal Power to prepare and adopt an Electric Vehicle Plan that provides a path forward for increased EV and micromobility adoption in Alameda with a focus on renters and low-income residents, increasing charging availability on City owned lots and in multifamily housing, enhancing community awareness, and expanding incentives and rebates for the purchase of a range of EVs, including micromobility devices, and for the installation of chargers.”

Further, while many ZEV plans were connected to GHG emission reduction, many others use alternative motivators. As the state continues to develop goals, it will be important to translate these goals into local motivators. Below is an example of strong policy from the City of Commerce (2008) General Plan that motivates conversion of the public fleet to alternative fuels based on both state goals and clean air:

“8.3.3 Issue: Alternative Fuels: A cornerstone of the state and local clean air strategy involves the development and use of alternative fuels. Towards this end, the city supports these efforts through the following policies. Air Quality Policy 3.6. The city of Commerce will manage the city's transportation fleet fueling standards to achieve the greatest number of alternative fuel vehicles in the city fleet.”

Further, many policies within plans refer to municipal code updates and CAPs. For example, the City of Elk Grove (2021) General Plan refers to both municipal code and a CAP for further policy action:

“Action 1.7 Building Code Update. Review and update Elk Grove Municipal Code Title 16 - Buildings and Construction as needed to incorporate the goals and policies of the General Plan into the City’s building code. This should also include any updates that are required by the 2019-2020 update to the California Green Building Standards Code (CALGreen). The following items shall be reviewed and amended: • Update the building code to incorporate higher standards for green building as required by the City’s Climate Action Plan (CAP) • A requirement for new single-family residential development to pre-wire for plug-in electric vehicles.” Timeline: FY 18/19-FY 19/20. Funding: None. Personnel: Development Services - Planning, Development Services - Engineering, Public Works, Strategic Planning.”

These findings compare to city-level CAPs where total scores for “electric vehicle” ranged from 0-55, with an average score of 18. Two cities had no ZEV policies in their CAP; one was from 2018, which is surprising, but the other is from 2013 thus predating much of the attention to ZEVs. Again, local jurisdictions are more emboldened to take strong policy stances in their

CAPs—though many CAPs are not CEQA certified (59%) and lack the same legal basis as the General Plan thereby questioning how such strong policy statements ultimately lead to implementation.

The three highest scoring cities were San Carlos (55), San Mateo (44) and Burbank (39). Again, the strongest scoring CAPs do not match the strongest scoring General Plans, indicating the variance in which plan-making approach local jurisdictions emphasize, a topic further explored in Climate Readiness workshops. In addition, all three of the strongest scoring CAP jurisdictions include municipal ZEV reach codes, municipal codes that go beyond state requirements. Of the strongest scoring General Plans, only Agoura Hills has a ZEV reach code. This finding may be due to the relative ease and speed of one planning vehicle over the other. Municipal codes are shorter policy prescriptions, and more likely to be passed and updated more quickly than a General Plan, which can take several years of community input to revise and update a single chapter.

Policy approaches

ZEV policy approaches included priority parking for ZEVs, siting charging infrastructure, and encouragement of public (government-owned or NEV) or private ZEV use. Similar to county-level policies, considerations for private ZEV transitions were more numerous than efforts toward public fleets. Of the 455 total ZEV policies identified across all city general plans, 141 mention public ZEV use and 273 mention private ZEV use. This finding indicates a need for greater state support toward local public fleet conversion policies.

An example of example of public ZEV use from the City of Santa Rosa (2020) General Plan underscores the need for greater planning and implementation data infrastructure to celebrate the motivation of local leadership in climate action:

“OSC-J Take appropriate actions to help Santa Rosa and the larger Bay Area region achieve and maintain all ambient air quality standards. OSC-J-2 Budget for clean fuels and vehicles in the city’s long-range capital expenditure plans, to replace and improve the existing fleet of gasoline and diesel powered vehicles. Initiate a policy to make its fleet among the cleanest in the North Bay by: • Purchasing alternative fuel vehicles, such as natural gas, as the existing diesel-powered fleet is replaced. Alternatively, purchase diesel vehicles only if they meet or exceed emission specifications for available natural gas fuel vehicles.”

This finding is similar to CAP ZEV scores. Of all the policies examined, 62% used strong language such as “shall” or “will.” San Mateo and San Carlos had the highest number of strong policies. Nine of the 20 cities had more than 75% of their total policies characterized as strong.

Examples of strong policy from city-level CAPs:

City of Dublin CAP 2020: Measure SM-1: Adopt an Electric Vehicle Charging Station Ordinance. The City of Dublin will adopt an electric vehicle (EV) charging station ordinance for multifamily and commercial buildings to increase access to charging stations and promote the use of electric vehicles.

City of Encinitas CAP 2020: CAP Measure CET-5: Require Commercial Electric Vehicle Charging Stations. Stating in 2018, require installation of EVCS at 8% of the total number of parking spaces. For 1) all new commercial buildings, including the commercial portion of mixed-use projects, 2) commercial building modifications, alterations, and additions that require building permits with square footage larger than 10,000 sq. ft.

City of Del Mar CAP 2016: “Goal 17: Increase Number of Preferential Parking Spaces for Clean Vehicles

STRATEGIES

- Set aside 10 percent of all on-street parking spots on Camino del Mar and in City-owned lots for high-efficiency and clean vehicles by 2020
- Explore modifying the Del Mar Municipal Code parking standard requirements to incentivize stalls designed for micro-vehicles and to provide a credit toward parking requirements for providing parking stalls for electric vehicles and charging station.”

Equity-focused Approaches

In contrast to the counties, six cities listed notable equity-focused ZEV policies within their General Plans. The six cities were Alameda, Arcata, East Palo Alto, Folsom, Lathrop, and Milpitas. It is important to note that five out of the six policies are from General Plans adopted within the last five to six years, suggesting the increasing focus on equity at the local and state level within recent years. The identified equity-focused initiatives to ZEV policy focused on creating dense and affordable housing and infill projects that include transportation infrastructure, working to promote increased access to alternative modes of transportation, and prioritizing the development of electric vehicle charging stations at multi-family residential units.

Examples of equity-focused policy approaches from General Plans:

City of Alameda 2021: LU-13 Green Economy. Promote a green economy that reduces greenhouse gas emissions generated by Alameda businesses. Action b. Green Business Practices. Encourage Alameda businesses and industries to become more sustainable and continue to make positive contributions to the community by, for example, hiring locally, supporting telecommuting, utilizing solar power, reducing waste, and prioritizing active transportation, transit, and electric vehicles. This includes providing electric vehicle and e-bike charging stations, long-term bike parking options, and a variety of transit options.

City of Arcata 2008: Goal B. Housing Quantity - It is the goal of the City of Arcata to provide housing opportunities for people of all income levels through the development of

a wide range of housing types and the preservation of existing housing. Policy HE-13 Support affordable housing and greenhouse gas emissions reduction by prioritizing high-density, mixed-income, infill housing projects that improve alternative transportation infrastructure. Affordable housing and infill projects that include public and/or private infrastructure for public transit, bike and other ride share programs, electric vehicles, and other transportation demand management strategies or alternative transportation modes will receive incentives including deferred fees and reduced development standards, including but not limited to reduced parking, setbacks, or landscaping requirements. (Reference Implementation Measures: 11, 12 and 20)

City of East Palo Alto 2016: Goal HE-10. Improve respiratory health throughout the City and strive to reduce incidence of asthma and other respiratory illnesses. Policy 10.6 Electric vehicle fleet. Improve air quality and respiratory health through City programs and operations such as converting to a clean-air and primarily electric fleet.

City of Folsom 2018: Policy M 4.2.4 Electric Vehicle Charging Stations Encourage the installation of electric vehicle charging stations in parking spaces throughout the city, prioritizing installations at multi-family residential units.

City of Lathrop 2022: Goal Cir-4, Plan for the future of transportation to ensure accessibility for all, reduce the environmental impacts of transportation, and improve the quality of life. Policy CIR-4.4 Electric Vehicle Charging. Support the creation of electric vehicle charging stations at multifamily residential, commercial, government.

City of Milpitas 2021: CIR 6-6 Work with stakeholders to encourage the development of electric vehicle charging stations and other alternative fuel infrastructure at publicly-owned locations, near businesses, and employment sites.

The focus on equity in city-level General Plans is not proportionally greater than the focus on equity in CAPs where two of the 20 sampled cities with the most mentions in CAPs and General Plans clearly showed an equity focus in their CAP policies.

Example of CAP ZEV equity policy:

City of Escondido 2021: “Measure T-1.3: Adopt an Ordinance to Require Electric Vehicle Charging Stations in Developments. Adopt an ordinance, effective in 2023, that requires Level 2 or better EV charging stations to be installed in a minimum of 10 percent of total parking spaces provided in new multi-family and new and existing commercial developments.”

Includes the following performance measure:

“Establish a “Clean Energy Equity Plan” to improve equitable access to clean and sustainable energy in priority investment neighborhoods (“PINs”) to increase EV ownership, EV car-sharing, installation of EV chargers in existing multi-family projects, etc.”

Timeline

Like county-level general plans, few city-level general plans supplied strong timelines for action. This compares to the sample of CAPs with relatively stronger policy scores. Of all the ZEV policies examined in city-level CAPs, 78% had a timeline or prioritization for implementation. Of note, Escondido had specific “target years” for specific performance metrics in each policy.

Example of policy with specific timelines:

City of Escondido 2021:“Measure T-1.4: Require Electric Vehicle Charging Stations at New Model Home Developments. Adopt an ordinance, effective in 2021, requiring new developments to encourage EV charging station installation in new homes by:

- Installing at least one EV charging station (wall mount or pedestal) in new single-family model homes and multifamily model homes with private garages (e.g. townhouse);
- Including EV charging stations as an add-on option at no cost to new homebuyers in new home subdivisions; and
- Working with the City to waive permitting and installation fees for EV charging stations in these subdivisions.

The City should consider incentives to offset participant costs of the measure’s implementation. The detail and scope of the incentives should be discussed at the time of the ordinance’s adoption.

Performance Metric

2021 Adopt an ordinance requiring EV charging station installation in new single family homes and townhouses.

2030 Install 200 EV charging stations in new single-family homes and townhouses by 2030

2035 Install 300 EV charging stations in new single-family homes and townhouses by 2035.”

Funding

By far, the most common source of funding cities identified to enact their ZEV policies was the city’s General Fund, being cited by cities 15 times out of the 23 total cities that specified funding sources in their General Plans. Additional sources of funding listed by cities consisted of a variety of local fees and grants, namely fee revenues, development fees, the Assembly Bill 2766 Subvention Fund, sales tax revenue, the gas tax fund, and funds allocated and generated by the capital improvement program. Similar to the counties, no cities explicitly identified specific funding amounts allocated to their policy and implementation strategies in their General Plans. Again, this finding signals to state agencies a need to help local jurisdictions match policymaking will with available external funding sources.

Similarly, of the 20 CAP cities scored, nine included funding sources for their policies. This compares to none of the county CAPs listing funding sources for ZEV policy. The City of Burbank (2022) has an impressively detailed appendix (Appendix E) on potential funding of the CAP. This example is too long to reproduce in the report, but we encourage readers to explore this appendix as a model approach.

CAP examples of funding approach:

City of Dublin 2020 (summarized from Table 8-1): “Measure SM-1: Adopt an Electric Vehicle Charging Station Ordinance” “The City would use the general operation budget to develop this ordinance. Staff would promote incentives for EV ownership as well as adopt building reach codes to increase the installation of new EV charging stations.”

“Measure SM-2: Develop an Electric Vehicle Infrastructure Plan

“The City would use the general operation budget to develop the plan. Incentives and grant funding opportunities may be available for infrastructure and planning efforts. Collaborate with third party businesses to site charging facilities. City and privately-owned facilities could possibly obtain grant funding from Bay Area Air Quality Management District, PG&E, EBCE, or other sources.”

Staff and Personnel

Findings reflect the county-level plan evaluations and signal to ZEV policy advocates and state agencies which responsible local staff and departments to include in outreach for policymaking updates, available funding, and implementation guidance. In reference to city personnel and capacity, the majority of personnel identified as responsible for city ZEV policies in General Plans include various city departments, including planning, public works, city manager’s office, and community development. Personnel were often listed as responsible for an entire policy, not assigned a specific task. Less frequently identified personnel include the Transportation Management Association, fleet division, and the building division. In addition, implementation strategies were not specific enough in assigning certain personnel, teams or departments to specific tasks. For example, the following policy shows all relevant personnel that would be involved in implementation, but their specific role is vague:

City of Los Angeles 2021: “Policy 1: continue to encourage energy conservation and petroleum product reuse. Program 3: alternative fuel and energy sources research and use.” Timeline: None mentioned. Funding: None mentioned. Personnel: Department of Water and Power in cooperation with other agencies that produce alternative energy (e.g., Bureau of Sanitation) and/or operate facilities that have the capability of being converted to alternative energy use.

In the 20 sampled city-level CAPs, just over 74% of ZEV policies included an assignment to a specific department or agency for implementation, such as community development or public works. These are usually listed in an implementation table and not discussed in detail.

Unique Approaches Across Cities and Counties

Examples of unique terms that appeared in city and county planning documents during the search for “zero-emission vehicles” include:

Renewable Energy Vehicle: Chico City General Plan 2017 - Policy CIRC-8.2 (Parking Improvements): Ensure that new parking facilities and renovations are designed to be safe, efficient, and pedestrian-friendly. Action CIRC-8.2.2 (Public Parking Facilities): When designing new public parking facilities, incorporate preferred parking for renewable energy vehicles and assess the need for electric vehicle charging stations. Timeline: None. Funding: None. Personnel: None.

Properly wired outdoor receptacle: Belvedere City 2010 - Policy SUST-9.1: Encourage use of electric vehicles. Actions: SUST-9.1.1: Encourage new commercial construction to include vehicle access to properly wired outdoor receptacles to accommodate zero-emission vehicles (ZEVs) and/or plug in electric hybrids. Timeline: None. Funding: None. Personnel: None.

Chino City 2010 - Policy P1. The City shall encourage new construction to include vehicle access to properly wired outdoor receptacles to accommodate zero emission vehicles and/or plug in hybrids. Timeline: None. Funding: None. Personnel: None.

Fueling stations for alternative fuel vehicles: Calabasas City 2021 - IV-39 Promote the use of alternative energy sources such as solar energy, cogeneration, and non-fossil fuels. Ways in which alternative energy can be promoted include, but are not limited to, incorporation of solar panels on structures and provision of fueling stations for alternative fuel vehicles. Timeline: None. Funding: None. Personnel: None.

Alternative fuel/recharging facilities: Corning City 2015 - ENERGY Goal: Reduce reliance on non-renewable energy sources in existing and future development and improve the delivery of energy to existing and future users. Policy E-(5): Amend the zoning ordinance to require alternative fuel/recharging facilities in Commercial, Industrial, and Industrial Light districts subject to appropriate standards. Timeline: None. Funding: None. Personnel: None.

Electric plug in recharging stations: Menlo Park City 2013 - Goal OSC4 — PROMOTE SUSTAINABILITY AND CLIMATE ACTION PLANNING: Promote a sustainable energy supply and implement the City’s Climate Action Plan to reduce greenhouse gas emissions and improve the sustainability of actions by City government, residents, and businesses in Menlo Park. This includes promoting land use patterns that reduce the number and length of motor vehicle trips, and encouraging recycling, reduction and reuse

programs. Policy OSC4.4: Vehicles Using Alternative Fuel. Explore the potential for installing infrastructure for vehicles that use alternative fuel, such as electric plug in recharging stations. Timeline: None. Funding: None. Personnel: None.

Electric Vehicle plugs: Oakdale 2013 - PF-5.9 New Residential Development. Require new residential development to incorporate rewiring for solar or other renewable energy systems, and offer optional features that would allow for increased energy efficiency in homes (e.g., electric vehicle plugs, zoned heating and cooling, automated lighting and heating/cooling systems). (RDR, NR-IP5) Timeline: None. Funding: None. Personnel: Community Development & Services, Public Works.

Cleaner-burning fuels: San Leandro City 2016 - Policy EH-3.9 Alternative Fuel Vehicles. Promote the development of infrastructure which supports the use of alternative fuel (i.e., electric) vehicles, including electric charging stations and preferential parking for electric vehicles. Action EH-3.9.A: Replacement of City Vehicle Fleet: Pursue the gradual replacement of the City's passenger vehicle fleet with vehicles using cleaner-burning fuels, such as natural gas and electricity. Timeline: None. Funding: None. Personnel: None.

Recharging Station: San Marcos 2012 - Policy M-3.8: Work with regional agencies, such as SANDAG, to install appropriate recharging stations to support the use of electric vehicles. Work with developers to install recharging stations, employment, and transit centers to support electric vehicle use. Timeline: 2012-2014, Ongoing. Funding: General fund, private development, grants. Personnel: City Manager, Development Services, Public Works.

Low-emission vehicles: Cotati City 2015 - GOAL CI 3 - Reduce Vehicle Miles Traveled (VMT) in Order to Reduce Congestion and Help Achieve Regional Efforts to Reduce Greenhouse Gas (GHG) Emissions. Policy CI 3.3 - Work with major employers and representatives from Sonoma State University to implement Transportation Demand Management (TDM) programs. Examples of TDM programs may include (but are not limited to) subsidized transit passes, guaranteed ride home, carpool matching, telecommuting, alternative work schedules, car sharing, employer-sponsored vanpools, priced workplace parking, and preferential parking for carpools and/or low-emission vehicles. Timeline: None. Funding: None. Personnel: None.

Clean vehicles: Marin County 2007 - GOAL AIR-3 Reduction of Vehicle-Generated Pollutants. Reduce vehicle trips and emissions, and improve vehicle efficiency, as means of limiting the volume of pollutants generated by traffic. Policy AIR-3.1 Institute Transportation Control Measures. Support a transportation program that reduces vehicle

trips, increases ridesharing, and meets or exceeds the Transportation Control Measures recommended by BAAQMD in the most recent Clean Air Plan to reduce pollutants generated by vehicle use. Implementing Program AIR-3.c Consider Model Clean Vehicle Requirements. Research and consider adoption of an ordinance or standards that provide a set of voluntary measures to incorporate clean vehicles in fleets and promote the use of clean alternative fuels. Timeline: Long term (over 7 years). Funding: None. Personnel: Department of Public Works.

Alternative fuel filling stations: Yolo County 2009 - GOAL CI-3 Service Thresholds. Balance the preservation of community and rural values with a safe and efficient circulation system. Policy CI-3.19 The Dunnigan Specific Plan shall incorporate a maximum of 44 vehicle miles of travel (VMT) generated per household per weekday through implementation of all feasible actions including but not limited to specifications contained in Policies CC-3.3 through CC-3.6. As part of the specific plan implementation, the VMT performance shall be monitored at each phase. If VMT performance exceeds the threshold in this policy, then additional actions shall be implemented and may include, the following actions: Action N. Consider unique transportation incentives such as free bikes, recharging stations for electric vehicles, alternative fuel filling stations, plug-in hybrid car-sharing, and carpool concierge services. Timeline: None. Funding: None. Personnel: None.

Decarbonization plan evaluation results for counties

Similar to ZEV policy scoring in the previous section, the decarbonization composite score is based on the strength of policies within the plan. A score of 1 indicates that a policy within the plan met one of the three requirements for committed funding, benchmarked timeline for implementation, or dedicated staff. A score of 3 indicates that a policy within a plan contained all three levels of commitment (Berke, 1996; Berke & French, 1994). A plan could have multiple policies, each varying in strength, yielding a composite score when summed. Similarly, a plan could address the topic or term, but with weak policy language resulting in a composite score of 0.

Strength of policy language was determined by the presence of enabling language. For example, weak policy language suggested, but did not require action, using words like: “encourage”/ “may”/ “should” / “promote” / “explore” / “continue.” For example, Lake Forest (2020) included the following: “Goal PF-6 Energy Management: A community with adequate power, provided through economically and environmentally sustainable means. Policy PF-6.6 Public-Private Partnerships. *Investigate* the opportunity to engage in public-private partnerships on energy efficiency, energy storage, and microgrid development to achieve cost savings, reduce energy use, and improve energy reliability.” No timeline, funding, or personnel were mentioned. This policy would score a “0”. In comparison, Port Hueneme (2021) provides an example of a strong-scoring policy with the following: “4.1 Policy CAP 2-1: Increase electric/alternative fuel vehicle and equipment uptake to 10% by 2030, and 15% by 2045. Action Number CAP 2-1.1: Adopt EV Charging Reach Code for Commercial and Multifamily Buildings that require all new commercial and multifamily buildings to exceed minimum CALGreen standards for “EV Ready” charging spaces and infrastructure. Anticipated Reduction (MT CO₂e) - 2030: 3,555; 2045: 4,635.” While no funding or personnel were identified, the policy did include a timeline for benchmarking progress.

It is important to note that only one county mentioned the terms “decarbonization,” “reach code,” or “microgrid” (Table 2). the underrepresentation of in local planning of such state-level goals indicates a policy and language mismatch between state and local efforts. As a result of this mismatch, the following more prevalent decarbonization terms were selected for scoring counties: “energy”, “heat pump”, and “carbon neutral”. Because of the large number of “energy” terms in city general plans, the following terms were scored for city general plans: “decarbonization”, “heat pump”, “reach code”, “microgrid”, and “carbon neutral”. For CAPs, all 23 counties with CAPs were scored for the terms “energy” and “decarbonization”, and a sample of city-level CAPs were scored for the same terms. This sample was selected from the 10 city-level General Plans with the most mentions of “energy” in combination with 10 CAPs with the most mentions of “energy.” We note that adopted plans may lead municipal code adoption, or plans may lag and not mention adopted reach codes.

Table 2. city and county decarbonization-related General Plan term mentions

Term	# of city General Plans that mention search term (out of 482)	# of county General Plans that mention search term (out of 58)
Decarbonization	1	1
Heat pump	8	3
Solar	370	54
Reach code	3	1
Energy	413	57
Energy storage	9	4
Energy efficiency	373	54
Microgrid	2	1
Carbon neutral	4	2
Green building	318	47

Policy Approaches

County General Plan decarbonization scores had an average of 52 and median of 37, indicating skewing toward a few counties scoring more highly and lifting the average. This is similar, but less pronounced for the 23 county CAPs with a median plan decarbonization score of 23 and average of 28. County General Plan decarbonization scores ranged from three counties with a score of zero to the counties with the strongest decarbonization scores in their General Plan policies included Marin (176), Solano (156) and Ventura (143)—which are all coastal counties. This compared with county-level CAPs ranging from two CAPs with no score to the strongest scoring counties: Butte (162), Contra Costa (138), and Santa Barbara (134). As with ZEV scoring, strong scores in general plans do not neatly correlate with strong scores in CAPs indicating a mismatch across local jurisdiction policy approaches where one plan may be selected over another for moving climate policy forward. Next, we review policy approaches.

Three counties mention “heat pump” in their General Plan: San Luis Obispo 2010 (one mention), Shasta County 2007 (one mention), and Siskiyou County 1993 (36 mentions). This policy approach compared with the seven county-level CAPs (30%) that mention the term “heat pump”, indicating relatively greater heat pump policy coverage in CAPs. The highest scoring county for “heat pump” was Shasta County with 5 points, the next highest was Siskiyou County with three points, and San Luis Obispo had zero points (mentioned the term once but did not include the term in a policy). Shasta County’s General Plan (2007) “heat pump” policy scored strongly across all categories. Consider, for example, the following policy:

“Program 65. The County Housing Department will explore opportunities to apply for a CDBG technical assistance grant and other Federal and State grants to establish continuing programs to provide information and assistance to property owners seeking to obtain funding for construction related to energy conservation programs available in Shasta County, including, but not limited to: a. CDBG funds b. USDA Rural Development-Farmers Home Administration funds c. Energy Commission funds d. Self-Help Home Repair Program e. Heat pump energy savers.” Timeline: Continuous. Funding: Building permit administrative fees. Personnel: Department of Resource Management, Building Division/Department of Housing.

Relatedly, Siskiyou County’s 1993 General Plan includes a section on “geothermal energy,” and sets policy supporting its utilization with heat pumps, although it did not use strong language nor include implementation plans. Here’s an example of one policy:

“Policy 12. The County supports utilization of geothermal resources, either with heat pumps, direct applications, or for purposes of generating power. However, such support is conditioned on a determination that the proposed use can be developed in a timely, orderly, and environmentally-sound manner, and that adequate protection of the resource is provided so as to ensure its continued availability and productivity over time.” Timeline: none. Funding: none. Personnel: none.

Similarly, two counties mention “**carbon neutral**” in their General Plans: Marin County 2007 (5 mentions) and San Luis Obispo County 2010 (one mention). This compared with 11 county-level CAPs addressing this term (50% of county CAPs), with San Mateo County mentioning this term the most (23 times), and nearly three-times more than the counties with the next most mentions of “carbon neutral” in their CAPs: Butte (7 mentions) and San Francisco (7 mentions). Again, CAPs show greater attention to climate ready terminology.

When comparing mentions to plan scores, we note that term mentions do not correlate neatly with the creation of strong policy language. For example, Marin County’s 2007 General Plan scored five points and San Luis Obispo County scored zero points (mentioned the term once but not in a policy). Marin County had three policies that mention “**carbon neutral**,” all of which identified a timeline, funding source, and committed personnel, as seen in the below example:

“Implementing Program 1.h Promote Resource Conservation. (EN-1.b-f, EN-3.a, EN-3.e-i and EN-3.k) Continue to promote development and construction standards for new and rehabilitated dwellings that encourage resource conservation through materials selection, water conservation, community design, energy efficiency, and the use of renewable energy through the following: c. Evaluate the feasibility of carbon neutral construction for new single-family dwellings.” Timeline: Ongoing. Funding: Local resources. Personnel: Community Development Agency.

Marin County’s (2007) three policies mentioning “carbon neutral” involved new construction of buildings and carbon neutral transportation technologies.

In comparison to the scantily mentioned term “decarbonization,” a total of 57 out of 58 counties mentioned the term “energy”—highlighting the topical representation of energy planning at the

local level and a need for state agencies to align messaging. Below is an example of a Marin County policy with strong language and implementation measures:

“1.h Promote Resource Conservation. (EN-1.b-f, EN-3.a, EN-3.e-i and EN-3.k) Continue to promote development and construction standards for new and rehabilitated dwellings that encourage resource conservation through materials selection, water conservation, community design, energy efficiency, and the use of renewable energy through the following:

- a. Adopt green building requirements for new single-family and multi-family residential construction projects, additions, and remodels that require compliance with energy efficiency and conservation requirements that exceed State standards. Require verification of these measures.
- b. Consistent with the Countywide Plan, adopt Leadership in Energy and Environmental Design (LEED) Gold certification requirements for development and major remodels of public buildings where feasible.
- c. Evaluate the feasibility of carbon neutral construction for new single-family dwellings.
- d. Continue to enforce the Single-Family Dwelling Energy Efficiency Ordinance that requires new residential projects, additions, and remodels to exceed Title 24 requirements by a minimum of 15%.
- e. Explore a program consistent with AB 811 that provides to homeowners loans repayable through the property tax bill for energy efficiency, water conservation, and renewable energy generation upgrades.
- f. Work with the Marin Housing Authority to provide applicants for rehabilitation loans for upgrading their residences with green materials and energy conserving measures.
- g. Continue to provide free technical assistance to architects, developers, green businesses, homeowners, and other agencies.”

Timeline: Ongoing; Funding: Local resources; Personnel: Community Development Agency

Energy:

County policies generally incorporated one or more of the following approaches: enforcing or encouraging standards above Title 24, promoting energy efficiency programs for residential appliances, and energy conservation. The following is an example of a strong policy with implementation from Placer County 2013:

“Goal H: To increase the efficiency of energy use in new and existing homes with a concurrent reduction in housing costs for Placer County residents.

G-1 mPOWER PLACER

The County shall continue to encourage investments in energy efficiency through the mPower Placer program for commercial and multi-family properties, which provides special assessment financing for energy efficiency and renewable energy projects. The County shall continue to pursue resolution to conflicting directives from the Federal Home Finance Agency to ensure that homeowners have the same opportunities as commercial property owners.” Timeline: Ongoing; Funding: General Fund; Personnel: Community Development Resource Agency.

Decarbonization policies frequently referenced reach codes but did not capture state language for technology uptake. We explore the connection between General Plans, CAPs, and municipal reach codes further in the city-level analyses.

Equity-focused Approaches

Many equity-focused policies containing the term “energy” focused on housing programs targeting low-income households. Here’s an example from Kings County General Plan (2016) with strong policy language and implementation measures:

“1.2 Housing Rehabilitation Program: In collaboration with a housing partner, the City will continue providing rehabilitation loans to lower income households, including very-low- and extremely-low-income persons. Initiated in 1988 with CDBG funds, the Housing Rehabilitation Program will provide loans for up to \$190,430 for most types of housing repairs, energy conservation improvements, and handicapped accessibility devices.” Timeline: Ongoing; Funding: CDBG, HOME, CAL-HOME; Personnel: Community Development Department and Self-Help Enterprises.

Of the 23 count-level CAPs scored, nine counties (40%) clearly showed an equity focus in their policies. This finding suggest that state agencies should continue to provide equity guidance, supportive funding, and reward progress through repeated monitoring of local initiatives if equity-focused goals are to be established and realized.

Example of equity policy from Contra Costa County CAP, 2015:

“Measure EE-1: Energy Efficiency Retrofits – Residential Buildings

Provide opportunities for residential buildings to become more energy efficient.

Action items:

3. Increase participation in the existing low-income weatherization program and seek additional program funding.
4. Identify disadvantaged individuals and households for increased participation in energy efficiency programs.”

Policy Strength

Of all the policies examined, 48% used strong language such as “shall” or “will.” Butte and San Mateo counties had the highest number of strong policies in their CAPs. Only 4 of the 23 counties had more than 75% of their total policies characterized as strong, indicating a need to support metric-focused policy creation at the local level.

Example of strong policy:

Butte County 2021:

“4f. Require on-site solar PV systems and/or energy storage for nonresidential buildings 10,000 square feet or greater.”

PV refers to PhotoVoltaic.

Timeline

A majority of the timelines for decarbonization topics in General Plans were “ongoing.” For example, Marin County’s 2007 General Plan was the only plan to score points for a timeline for “carbon neutral,” as each of its three policies included a timeline with a 4-9 year horizon. For example, see:

“Policy EN-3.k: Evaluate Carbon Neutral Building Incentives. Evaluate the feasibility of incentives and regulations to achieve carbon neutral buildings.”

Example of General Plan policy with specific timelines, Butte County 2021:

“Time Frame: The year by which a strategy should be effective by fiscal year’s end. The exact status of a strategy will vary based on its actions, and many strategies will be ongoing through and beyond 2030. An effective strategy is one that will be actively on track to achieve its targeted GHG emission reductions, support adaptation to climate change effects, or achieve long-term resilience. For a strategy to be effective, the necessary programs and efforts should be active, and any infrastructure or other capital improvements should be in place. The effective year is not the end year, as many of the strategies are programs that are intended to remain in effect for the foreseeable future, and so they do not have end dates. Time frames for effectively setting up the strategies are described as follows:

--Immediate

--Near-Term (by 2023)

--Mid-Term (by 2025)

--Long-Term (by 2030)”

Similarly, of all the CAP policies examined, 73% had a timeline or prioritization for implementation. Butte, Santa Barbara, San Diego, and San Francisco counties state specific years for implementation, while others use the short/medium/long-term convention that makes benchmarking policy progress a fuzzy concept.

Example of CAP policy with specific timelines, San Francisco City/County 2021:

“BO.1-1 By 2021, require newly constructed buildings to be efficient and all-electric with no on-site carbon emissions.”

Funding

Reliance on local funding, such as general funds, to meet state-level decarbonization is evident in the few mentions of supporting funding Goals. All three Marin County “carbon neutral” General Plan policies contained a funding source, identifying either the existing budget or local resources. Most of the funding sources listed for “energy” were either the “general fund” or “existing fund.” Other funding sources included: grants, Community Development Block Grants, or HOME funds, and permit fees. HOME is the largest federal block grant to state and local governments designed exclusively to create affordable housing for low-income households.

Of the 23 counties with CAPs, only three included funding sources for their policies. No counties have details on funding sources for each policy. Instead, the few that address funding at all provide a list of potential funding sources. Alameda County provided an exemplary funding strategy and list of potential funding sources. San Francisco City/County developed a funding approach to implement their CAP, as shown below.

Example of funding approach, San Francisco City/County CAP 2021:

“Overall, recommended next steps include:

1. Create an interdepartmental climate finance working group to assess the economic, social, political, and administrative viability of securing new funding sources.
2. Develop a detailed cost estimate for implementing CAP actions (beyond high-level estimates in the CAP).
3. Identify all opportunities to fund CAP strategies from existing funding sources and approved measures.
4. Assess which CAP strategies are not funded or partially funded to identify funding gaps.
5. Investigate a new tax (carbon tax, food tax) and/or increase existing taxes (sales tax, property tax) as a major contributor to reducing funding gaps.
6. Seek out and apply for relevant federal, state, and local grant opportunities which can serve as important seed funding for implementing CAP strategies or other supporting activities such as community engagement or technical analysis.”

These findings point to best practices at the local level, but also indicate that there is a need for greater support at the local level for identifying feasible funding opportunities and aligning policies.

Staff and Personnel

For the term “energy” the most common personnel listed in county-level General Plans were community development, planning, public works, housing, and boards of supervisors. For example, Shasta County’s “heat pump” policy committed personnel: Department of Resource

Management and Building Division/Department of Housing. Similarly, all three Marin County “carbon neutral” policies contained personnel: Community Development Agency, Marin County Transit District, and Transportation Authority of Marin.

These identified agencies in General Plans are similar to those found in CAPs, but differ slightly from responsible departments in ZEV implementation. For example, about 65% of CAP policies included an assignment to a specific department or agency for implementation, such as community development or public works. These departments are usually listed in an implementation table and not discussed in detail. Notably, Alameda County conducted a detailed assessment of staffing needs for implementing their CAP; see the example below.

Example of CAP section discussing staffing, Alameda County 2014:

“STAFF TIME FOR CAP IMPLEMENTATION

The successful implementation of the CAP will, in great part, be achieved through voluntary programs that will be managed and overseen by County staff. The emphasis on voluntary programs was a result of feedback from County staff, community members, and local professionals that the CAP should limit the number of mandates imposed on the community. Consequently, many measures require staff time to develop programs, implement outreach campaigns, and oversee policy development such as ordinances. The cumulative staff requirements for each Action Area were assessed, with the results shown in the table below. Since there are many potential synergies in measure implementation (i.e., energy efficiency and solar programs for residences may have joint implementation as the target audience of that suite of measures is the same constituency). Furthermore, as the implementation of many measures only requires staff time (with, for instance, no capital cost requirement), the total staff time requirement and associated cost is aggregated at the level of the Action Area. See Appendix C for more details on the costs and savings analysis. It should be noted that these staff requirements do not necessarily represent additional County hires; the staff time requirements to implement the CAP could potentially be included in an existing staff member’s job description.”

This emphasis on volunteers to meet decarbonization goals creates policy vulnerability as economic downturns or public health crises may shift the ready supply of able and qualified volunteers. These findings not only indicate where advocates and state agencies should conduct outreach for more meaningful climate readiness capacity building, but also where funding could be aligned with staffing needs to carry out decarbonization policies at the local level.

Decarbonization plan evaluation results for cities

Unlike ZEV policies, decarbonization policies were less discrete, offering room for a greater variety of policy approaches as well as greater difficulty in comparing across approaches. For example, decarbonization could include changing insulation in all public buildings. Or decarbonizing the built environment could include a heat pump rebate program. As a result, city General Plans were not scored. Instead, plan evaluation for city-level General Plans was focused on identifying unique policy approaches. To understand policy strength for decarbonization, we rely on total scores for the terms “**energy**” and “**decarbonization**” in a sample of 17 CAPs

drawn from: the seven cities with the most mentions of “energy” in their city-level General Plan (3 cities with the most mentions in their General Plans lacked a CAP) and the 10 city-level CAPs with the most term mentions of “**energy**.” This CAP scoring resulted in a range from 6-172, with an average score of 48. The three cities with the highest scoring CAPs were San Jose (172), Taft (120) and Sacramento (64).

We also compare these results with the presence of energy efficiency reach codes found in 74 cities (20%). Of the 230 cities with CAPs, 55 also adopted energy efficiency reach codes in 2019 and 2022. Reach codes “reach” beyond state requirements to achieve additional reductions. Thus, the presence of a CAP correlates with adoption of reach codes. For the most common decarbonization terms in General Plans “green building” (occurring in 318/482 city General Plans), “solar” (370), “energy efficiency” (373), and “energy” (413) (Table 2), we also see a strong relation with reach code creation. Of the 318 jurisdictions with city-level General Plans that mention “green building,” 193 have CAPs and 69 include reach codes. Of the 370 jurisdictions with city-level General Plans that mention “solar,” 206 include CAPs and 69 include reach codes. Of the 373 jurisdictions with city-level General Plans that mention “energy efficiency,” 207 include CAPs and 69 include reach codes. It is not until we consider the full 470 jurisdictions that mention “energy” in their city-level General Plan, that we encompass all 74 jurisdictions that include energy efficiency reach codes. And still, this selection includes 227 jurisdictions with CAPs, and leaves three jurisdictions that create CAPs, but do not address “energy” in their General Plan nor include reach codes. Together, these results do not neatly fit into a Venn diagram of climate readiness policy making. Nor can they be explained by the relatively simplified passage of municipal code in comparison to the more involved creation of a CAP or even more involved creation of a General Plan. Instead, we explain these findings based on the varied approaches taken regionally to decarbonization. Some approaches are better enacted in municipal code, others in CAPs, and still others require robust consensus building and more stringent CEQA review offered through the General Plan process. We explore these concepts in the following sections.

Policy Approaches

Similar to county General Plans, many state policy terms for decarbonization are underrepresented in city General Plans. For example, only one city mentioned the term “**decarbonization**” (Table 2). Relatedly, term mentions do not neatly map onto strong policies. For example, though the City of Port Hueneme (2021) General Plan mentioned the term “**decarbonization**” four times, it was not included in any policies. This finding may hint that state agencies should shift to using terminology that is more policy-relevant and will align better with actionable changes.

Next, we review discrete technology-relevant terms. For example, the term “**heat pump**” is used in eight city General Plans: Waterford 2016 (three mentions), Turlock City 2016 (two mention), Folsom City 2018 (one mention), Lathrop City 2004 (one mention), Los Angeles 2013 (one mention), Port Hueneme City 2021 (one mention), Ukiah city 2016 (one mention). Heat pump policy approaches include increasing community awareness through targeted outreach and engagement and the creation of financial rebate and exchange programs to provide incentives for households to switch to more environmentally friendly models. This term refers to a technology

that is readily implementable, like ZEV charging stations. Yet, while mentioned in city-level General Plans, only two cities included a policy specifically about heat pumps:

Folsom City General Plan 2018: “PFS-23 High-Efficiency or Alternatively-Powered Water Heater Replacement Program: Provide educational material and information on the City’s website, as well as through the permit and building department, on the various high-efficiency and alternatively-powered water heat replacement options available to current homeowners considering water heater replacement; develop appropriate financial incentives, working with energy utilities or other partners; and, streamline the permitting process. Replacement water heaters could include high-efficiency natural gas (i.e., tankless), or other alternatively-powered water heating systems that reduce or eliminate natural gas usage such as solar water heating systems, tankless or storage electric water heaters, and electric heat pump systems.”

Los Angeles General Plan 2013: “82. Incentives to Conserve Energy: Provide financial rebates and appliance exchanges of old appliances for new energy-saving models. Under the Refrigerator Turn-In and Recycle (RETIRE) program, provide rebates for old refrigerators and freezers. For low-income qualifying households, provide a program where residents can exchange older refrigerators with new more energy efficient models. Rebates also exist for Energy Star Windows, Cool Roofs, Room and Central Air Conditioners, Heat Pumps, Whole House Fans and Variable/Multi-Speed Pool Pumps and Motors. For a limited time, incentives of up to \$8,000 are available through Southern California Gas Company and Energy Upgrade California for LADWP customers who conduct whole home energy efficiency retrofits. Distribute Compact Fluorescent Light Bulbs (CFLs). Disseminate information and encourage participation in rebate and incentive programs offered by other agencies, including the Southern California Gas Company and the South Coast Air Quality Management District.” Timeline: none. Funding: LADWP Public Benefit Program. Personnel: LADWP, Southern California Gas Company.

This compares to 75 of the 230 CAPs which address “**heat pump**” policy. As in previous sections, CAPs offer more climate ready policy coverage.

Similar to the above, the term “**reach code**” is mentioned in only three city General Plans though 73 cities adopted energy efficiency reach codes in the 2019 or 2022 cycles. Reach code policy approaches include adopting reach codes focused on promoting housing development and exceeding minimum standards for charging spaces and infrastructure. As an example, the City of Port Hueneme (2021) mentioned “**reach code**” twice and included one policy with a specific timeline, but has not adopted a ZEV nor energy efficiency reach code according to the Statewide Reach Codes Tracking Program. The General Plan policy relating to the City of Port Hueneme reads:

“4.1 Policy CAP 2-1: Increase electric/alternative fuel vehicle and equipment adoption to 10% by 2030, and 15% by 2045. Action Number CAP 2-1.1: Adopt EV Charging Reach Code for Commercial and Multifamily Buildings that require all new commercial and multifamily buildings to exceed minimum CALGreen standards for “EV Ready” charging spaces and infrastructure.” Timeline: Anticipated Reduction (MT CO₂e) - 2030: 3,555; 2045: 4,635. Funding: none. Personnel: none.

Similarly, the City of Arcata 2019 General Plan mentioned “**reach code**” four times and had one policy with strong language and an implementation plan. Notably, Arcata has a CAP, but has not committed to a municipal reach code:

“Implementation Measure 24: The City will Evaluate the economic impact on the feasibility of housing development resulting from the REACH Code. Prior to adoption of a REACH Code, the City must demonstrate implementation of the code will be cost effective to the end users. There is no requirement to evaluate whether the extended energy code affects housing development. Action Required: Evaluate the impact on financial feasibility of housing development using a variety of methods, including pro forma for typical project, pro forma for actual projects to the extent available, and effect on housing production if detectable. Result: Determination whether REACH Code is a constraint to housing production and measures to remove or limit the impact of the additional energy code requirements.” Timeline: December 2021. Funding: General Fund. Personnel: Community Development Department.

The City of San Luis Obispo 2020 mentioned “reach code” twice but did not provide any policies with the term, yet has adopted a municipal reach code. Such variance in term mentions, the creation of strong policy, and adoption of reach codes acknowledge that the climate readiness planning landscape is varied with intentions and potential lags in policy enactment and implementation.

The same finding is true for “microgrid” policies with only two cities addressing this term in their General Plans. Both jurisdictions provided exploratory policy language without including implementation actions. See, for example, the City of Lake Forest (2020):

“Goal PF-6 Energy Management: A community with adequate power, provided through economically and environmentally sustainable means. Policy PF-6.6 Public-Private Partnerships. Investigate the opportunity to engage in public-private partnerships on energy efficiency, energy storage, and microgrid development to achieve cost savings, reduce energy use, and improve energy reliability.” Timeline: none. Funding: none. Personnel: none.

and the City of Morro Bay General Plan (2021):

“GOAL C-6: Energy available to Morro Bay residences, businesses, and public buildings is renewable and sustainable. POLICY C-6.4: Partnerships. Support public/private partnerships to implement energy efficiency, energy storage, and microgrid development to achieve cost savings, reduce energy use, and improve energy reliability.” Timeline: none. Funding: none. Personnel: none.

This compares to the 45 city-level CAPs that address “**microgrid**,” demonstrating the forward-thinking efforts in CAPs to move climate readiness policy less conservatively than General Plans. Microgrid policy approaches focused on expanding and building upon existing public and private partnerships to advance microgrid development while also promoting cost savings and energy reliability. As discussed in the literature review, such policy discussions are complicated

by the financial and regulatory landscape, but term mentions in plans indicate growing local interest that can be matched by supportive state policies.

Like the above terms, “**carbon neutral**” is also under-represented in city General Plans with only four cities mentioning the term: Hermosa Beach 2017, Port Hueneme 2021, San Mateo 2015, Santa Clara 2010. None provided policies. This compares to 92 city-level CAPs which mention “**carbon neutral**.”

Other approaches focused on siting low-carbon energy production. For example, the City of Hayward General Plan (2014) offered the following goal:

“GOAL CS-5 Prepare the Hayward community for future emergencies and disasters to minimize property damage, protect and save lives, and recover as a resilient community. CS-5.7 Energy Assurance Plan The City shall develop, maintain, and implement a citywide Energy Assurance Plan that documents the energy needs of critical City and community facilities and functions, establishes goals and actions to increase energy resiliency during disasters, and prioritizes the use of renewable energy or other sustainable technologies to reduce dependency on the grid during power outages.”

Adelanto City, 2014: “GOAL PF 8 Sustainable Public Facilities. Policy PF 8.1 Encourage new municipal construction to achieve Leadership in Energy & Environmental Design (LEED) certification and all existing municipal facilities to achieve LEED certification wherever feasible.”

Hemet City, 2012:

“GOAL CSI-5 Facilitate the provision and maintenance of adequate systems to provide and conserve natural gas, electricity, and telecommunications systems.

CSI-5.8 Agency Coordination: Provide early notification to utility companies regarding new development to ensure that services will be available in a timely manner, and encourage developers of large scale or complex developments to contact local utilities early in the process to insure (sic, ensure) that projected energy and utility demands will be able to be accommodated.”

Hayward City, 2014:

“GOAL NR-4 Reduce energy consumption through increased production and use of renewable energy, sustainable energy purchasing, and improved energy efficiency.

NR-4.13 Energy Use Data: The City shall consider requiring disclosure of energy use and/or an energy rating for single family homes, multifamily properties, and commercial buildings at certain points or thresholds. The City shall encourage residents to voluntarily share their energy use data and/or ratings with the City as part of collaborative efficiency efforts.”

Cathedral City, 2009:

“Policy 1.C. The City shall ensure that new and rehabilitated housing is efficient in its use of energy and natural resources. Program 1.C.2 A list of known incentives for energy and water conservation measures shall be maintained by the Community Development Department and made available for developers and property owners at the City’s reception desk.”

Dublin City, 2017:

“12.3.2 WATER CONSERVATION AND EFFICIENCY IN EXISTING DEVELOPMENT A. Guiding Policy 1 . Increase water conservation efforts and strive to maximize water use efficiency in existing residential, commercial, and industrial buildings and grounds. 2 . Support DSRSD in extending recycled water service to established areas of Dublin . **B. Implementing Policies 3.** Continue collaborative efforts and programs with outside organizations such as the California Youth Energy Services (CYES), which trains and employs local youth to provide resource conservation audits and water/energy retrofits to local residences (“Green Home Audits”).”

Unique approaches were also noted in CAPs as seen below.

City of Arroyo Grande CAP 2013:

“TL-7.2: Develop a form-based zoning code for the central business district/downtown. Form-based codes emphasize building form rather than use. This increases flexibility for a variety of complementary uses to be permitted in the same area, and the potential for mixed-use development, which helps to reduce vehicle miles traveled.”

Term mentions and lack of corresponding strong policy language or enacted municipal code can help redirect advocacy and state agency messaging to better align with local policy discussions. Indeed, the term “decarbonization” encompasses a wide array of policy and technology interventions that will vary from region to region. In general, we find that Northern California jurisdictions discuss “**heat pumps**” more often than southern jurisdictions though heat pumps are an appropriate technology outside of colder climates. Conversely, “**whole house fan**” is a term mentioned in 14 city General Plans for jurisdictions that can best make use of coastal and Delta breezes. As a last example, 79 out of 482 cities and 37 out of 58 counties mention “**biomass**” in their General Plans. Most of these communities are located in forested regions of the state, and seek to use forestry biomass for low-carbon energy and heating. Unlike ZEV policy support, decarbonization policy supports will need to employ a region-specific approach that encourages and introduces relevant and appropriate technologies based on local climate and available resources.

Equity-focused Approaches

Only one city’s General Plan contained an explicit equity-focused decarbonization policy. The City of Los Angeles’ specifically supports qualifying low-income households with rebates for purchasing and installing various systems that aim to decarbonize the built environment. Similarly, Hayward City included a suite of policies focused on equity and decarbonization.

The Los Angeles General Plan (2013) equity-focused decarbonization policy is as follows: “82. Incentives to Conserve Energy: Provide financial rebates and appliance exchanges of old appliances for new energy-saving models. Under the Refrigerator Turn-In and Recycle (RETIRE) program, provide rebates for old refrigerators and freezers. For low-income qualifying households, provide a program where residents can exchange older refrigerators with new more energy efficient models. Rebates also exist for Energy Star Windows, Cool Roofs, Room and Central Air Conditioners, Heat Pumps, Whole House Fans and Variable/Multi-Speed Pool Pumps and Motors. For a limited time, incentives of up to \$8,000 are available through Southern California Gas Company and Energy Upgrade California for LADWP customers who conduct whole home energy efficiency retrofits. Distribute Compact Fluorescent Light Bulbs (CFLs). Disseminate information and encourage participation in rebate and incentive programs offered by other agencies, including the Southern California Gas Company and the South Coast Air Quality Management District.”

Hayward City, 2014:

“GOAL NR-2. Improve the health and sustainability of the community through continued local efforts to improve regional air quality, reduce greenhouse gas emissions, and reduce community exposure to health risks associated with toxic air contaminants and fine particulate matter. NR-2.6 Greenhouse Gas Reduction in New Development. The City shall reduce potential greenhouse gas emissions by discouraging new development that is primarily dependent on the private automobile; promoting infill development and/or new development that is compact, mixed use, pedestrian friendly, and transit oriented; promoting energy-efficient building design and site planning; and improving the regional jobs/housing balance ratio.”

Hayward City, 2014:

“GOAL HQL-9 Build a foundation for community resilience to future threats and challenges to help ensure the City of Hayward will be able to respond and recover as quickly as possible to such threats and challenges. HQL-9.6 Energy Resiliency The City shall continue to encourage residents and businesses to use less gasoline for transportation, and improve energy efficiency in and renewable energy generation from buildings and industry processes to reduce impacts from rising oil and energy prices.”

Hayward City, 2014:

“Housing Element Implementation Program 1. Housing Rehabilitation Loan Program (HRLP). The City shall continue to provide below market-rate rehabilitation loans to qualified lower-income homeowners to make repairs (costing more than \$5,000) to correct major health and safety deficiencies and make needed accessibility modifications. The City shall disseminate information to homeowners who participate in the Housing Rehabilitation Loan Program regarding rehabilitation standards, preventative maintenance, and energy conservation measures.”

Hayward City, 2014:

“Housing Element Implementation Program 2. Minor Home Repair Grant (MHRP). The City shall continue to provide rehabilitation grants up to \$5,000 to qualified lower-income elderly and/or disabled homeowners to make minor home repairs in order to address health and safety problems, correct code deficiencies, and improve the outward appearance of homes. Priority will be given to work that corrects health and safety issues, and to accessibility modifications for people who have disabilities. The City shall disseminate information to homeowners who participate in the Housing Rehabilitation Loan Program regarding rehabilitation standards, preventative maintenance, and energy conservation measures.”

Six of the 17 cities with scored CAPs clearly showed an equity focus in their policies.

Example of equity policy, City of Pleasanton 2022:

“P2. Existing Building Electrification Plan

Equitable implementation will represent property owners and tenants with lower incomes in all implementation phases, have protections in place to avoid increased costs and other negative impacts, and support local installers.”

In addition, the following table (Table 9 from the City of Pleasanton 2022 CAP) includes the following scoring:

Table 9. CAP 2.0 focus areas for equitable implementation and applicable actions

	Fair distribution of benefits over time	Financial burden	Community engagement
P2. Existing Building Electrification Plan	●	●	●
P5. Create and implement a Zero Emissions Vehicle (ZEV) Infrastructure Plan	●	●	●
P10. Increase transit ridership	●		
S2. Community energy efficiency upgrades		●	●
P15. Water efficiency and retrofits		●	●
S9. Wildfire preparation, prevention, and education	●		●

Policy Strength

Of all the policies examined across the sampled 17 CAPs, 56% used strong language such as “shall” or “will.” Redondo Beach and San Jose had the highest number of strong policies. Only seven of the 17 cities had more than 75% of their total policies characterized as strong indicating a need for additional guidance in crafting actionable planning policies.

Example of strong policy, City of Rancho Cucamonga CAP 2021:

“Strategy 3.1: Zero Net Electricity for New Residential Buildings

Measure(s): Adopt an ordinance or update development code requiring that new single- and multi-family residential development to meet a standard of zero net energy (i.e., on-site generation of energy is equal to on-site energy consumption).”

As previously mentioned, only two cities, Arcata and Port Hueneme, listed policies related to reach codes in their General Plans. Arcata’s 2019 General Plan had a particular strong policy, earning a score of 5. The policy focused on exploring the impact of the reach code on encouraging or constraining housing development. The policy contained strong language, timeline (December 2021), funding source (general fund), and personnel (community development department). For reference, here is the identified policy:

Implementation Measure 24: The City will Evaluate the economic impact on the feasibility of housing development resulting from the REACH Code. Prior to adoption of a REACH Code, the City must demonstrate implementation of the code will be cost effective to the end users. There is no requirement to evaluate whether the extended energy code affects housing development. Action Required: Evaluate the impact on financial feasibility of housing development using a variety of methods, including pro forma for typical project, pro forma for actual projects to the extent available, and effect on housing production if detectable. Result: Determination whether REACH Code is a constraint to housing production and measures to remove or limit the impact of the additional energy code requirements.

Similarly, only two city General Plans, Folsom 2018 and Los Angeles 2013, contained policies related to heat pumps. Both policies from each city were equally strong, both earning a total score of four. Folsom’s policy focuses on community outreach and education in regard to the city’s high-efficiency or alternative-powered water heater replacement program. Contrastingly, Los Angeles’ policy focuses instead on the provision of financial rebates and appliances exchanges for households that shift from older appliances to new energy-saving models. The two respective policies are listed below:

Folsom City 2018:

“PFS-23 High-Efficiency or Alternatively-Powered Water Heater Replacement Program: Provide educational material and information on the City’s website, as well as through the permit and building department, on the various high-efficiency and alternatively-powered water heat replacement options available to current homeowners considering water heater replacement; develop appropriate financial incentives, working with energy

utilities or other partners; and, streamline the permitting process. Replacement water heaters could include high-efficiency natural gas (i.e., tankless), or other alternatively-powered water heating systems that reduce or eliminate natural gas usage such as solar water heating systems, tankless or storage electric water heaters, and electric heat pump systems.”

Los Angeles 2013:

“82. Incentives to Conserve Energy: Provide financial rebates and appliance exchanges of old appliances for new energy-saving models. Under the Refrigerator Turn-In and Recycle (RETIRE) program, provide rebates for old refrigerators and freezers. For low-income qualifying households, provide a program where residents can exchange older refrigerators with new more energy efficient models. Rebates also exist for Energy Star Windows, Cool Roofs, Room and Central Air Conditioners, Heat Pumps, Whole House Fans and Variable/Multi-Speed Pool Pumps and Motors. For a limited time, incentives of up to \$8,000 are available through Southern California Gas Company and Energy Upgrade California for LADWP customers who conduct whole home energy efficiency retrofits. Distribute Compact Fluorescent Light Bulbs (CFLs). Disseminate information and encourage participation in rebate and incentive programs offered by other agencies, including the Southern California Gas Company and the South Coast Air Quality Management District.”

No cities had policies related to decarbonization or carbon neutrality in their General Plans. No city policies focused on microgrids (i.e. policies from the Cities of Morro Bay and Lake Forest) were strong, each policy only earning a score of one. These findings help make the argument for state enabling legislation that is better aligned with current local policy discussions. For example, state agencies can review plans to understand where and how local jurisdictions are addressing building decarbonization in order to build onto ongoing momentum at the local level.

Timeline

Very few policies in General Plans included time-sensitive goals related to building decarbonization, microgrids, carbon neutrality, or reach codes; furthermore, even fewer cities include timelines related to the existing policies. Only one city, Folsom, provided a timeline for its heat pump policy, and that was “continuous” with the General Plan horizon. Similarly, of all the policies examined in the 17 sampled city-level CAPs, 59% included a timeline or prioritization for implementation. Stockton has an extensive analysis of costs and benefits that support some discussion on financing; though unique, it is now dated as the CAP is from 2014. Similarly, Taft and Rancho Cucamonga have performance metrics at regular intervals but the implementation timeline to support the measures is not clear. These vague policy benchmarks make assessments of plans and planned implementation difficult.

Funding

Arcata’s “reach code” General Plan policy is the only policy that listed a funding source, the general fund. No other policies mentioned funding for identified decarbonization, heat pump, microgrid, and carbon neutral policies. Similarly, of the 17 sample cities with CAPs, only six

included funding sources for their policies. Only a few have details on funding sources for each policy and most just provide a list of potential funding sources. Of note, San Jose includes an extensive discussion of funding options but does not directly connect them to implementation.

Example of funding approach, City of Dublin 2020 (summarized from Table 8-1):

“Measure EE-1: Achieve All-Electric New Building

Staff will implement and enforce electric preferred building codes. All electric buildings may create construction and occupant operations cost savings. EBCE will provide \$10,000 in 2020 to offset costs for staff time to develop electric preferred building codes for possible adoption.”

Together, this lack of identified funding and timelines for benchmarking progress indicate local policy will but confusion over feasible timelines and available funding to support policy realization.

Staff and Personnel

About 59% of the sampled city-level CAP policies included an assignment to a specific department or agency for implementation, such as community development or public works. These are usually listed in an implementation table and not discussed in detail. Similarly, the cities of Folsom City and Los Angeles list personnel for their heat pump policies as community development department and Los Angeles Department of Water and Power and Southern California Gas Company, respectively. Arcata lists personnel for their reach code policy as the community development department. The reliance on the community development department for implementation of decarbonization policies indicates that messaging, support and outreach should make staff contacts with community development departments across California a top priority in order to realize ambitious state-level goals.

Vehicle Miles Traveled - plan evaluation results for counties

Methods

Similar to previous plan evaluation sections, plans were scored based on policies that addressed VMT and compact development (Table 3). If a policy's purpose is to comply with standards that the jurisdiction already must meet, then the strength is a 0. For example:

Mono County 2020 - Action 23.A.1.d. Comply with Mammoth Air Basin SIP requirements for vehicle miles traveled – see the Regional Transportation Plan in the Circulation Element and RTP Objective 7.C.2.

A stronger approach would be specific language detailing how the jurisdiction plans to meet or exceed the standard.

As with previous sections, all county-level CAPs were scored, and a subset of city CAPs were scored based on top term mentions in both general plans and CAPs. This methodology allows us to see where and how general plans and CAPs are aligned.

Table 3. City and county General Plan VMT-related term mentions

Term	# of City General Plans that mention search term (out of 482)	# of County General Plans that mention search term (out of 58)
Vehicle miles traveled	244	47
Compact development	146	34

Policy Approaches

Policy approaches to VMT reductions include promoting dense, compact, and infill development, the construction of complete streets, establishing Transportation Demand Management (TMD) systems, working with employers to provide incentives for the use of alternative transportation methods, and increasing public transit safety and efficiency. The majority of VMT policies also focus on the production of co-benefits, such as improving local air quality, public health and safety, reducing greenhouse gas emissions, and promoting economic development. Recognizing such values can help state agencies align state and local motivations for policy change.

Policy example of promoting dense, compact, and infill development:

El Dorado County, 2019:

“MEASURE LU-Q Promote Infill Development: The program shall be linked to land-use, housing, air quality, transportation and circulation strategies that support

development within existing communities, reduce vehicle miles traveled, increase energy efficiency, and encourage the development of affordable housing.”

Policy example of promoting complete street construction:

“**Sacramento County, 2017:** GOAL: Provide mobility for current and future residents of Sacramento County through complete streets and through a balanced and interconnected transportation system which includes all modes of travel - automobile, transit, pedestrian and bicycling. CI-5. Land use and transportation planning and development should be cohesive, mutually supportive, and complement the objective of reducing per capita vehicle miles traveled (VMT).”

Policy example of establishing Transportation Demand Management systems:

Imperial County, 2008:

“6. Transportation Demand Management

a. Objective. The transportation system envisioned for the County is a balanced system, incorporating the needs of all groups, as well as making provisions for many Planning & Development Services Department (County of Imperial) Circulation and Scenic Highways Element (Revised 3-8-07) (Revised 01-29-08) different modes of transportation. To accomplish this, it is necessary to implement policies encouraging a range of transportation opportunities while reducing the dependency upon automobiles.

b. Policies The County shall encourage the reduction of vehicle miles, reduction of the total number of daily peak hour vehicular trips, and provide better utilization of the circulation system through development and implementation of Transportation Demand Management and Transportation Systems

Management programs. These may include implementation of mandatory peak hour trip reduction, requirements for staggered work hours, telecommunications, increased development of employment centers where transit usage is highly viable, encouraging ride sharing in the public and private sector, provision for park and ride facilities adjacent to the regional transportation system, preparation of Traffic Management Plans and provision for transit subsidies. The County in its role as a major employer shall commit to the use of trip reduction and vehicle miles traveled reduction strategies identified by Transportation Demand Management and Transportation Systems Management programs.”

Policy example of employer incentives to reduce VMT:

Sutter County, 2011:

“R2-T1 Employment Based Trip and VMT Reduction. Implementation of this measure would require adopting a voluntary trip reduction ordinance that promotes commuter-choice programs, employer transportation management, guaranteed ride home programs

and commuter assistance and outreach type programs intended to reduce commuter vehicle miles traveled.”

Policy example of increasing public transit safety and efficiency:

San Diego County, 2020:

“GOAL M-5 Safe and Efficient Multi-Modal Transportation System. A multi-modal transportation system that provides for the safe, accessible, convenient, and efficient movement of people and goods within the unincorporated County.

Policies M-5.1 Regional Coordination. Coordinate with regional planning agencies, transit agencies, and adjacent jurisdictions to provide a transportation system with the following: ■ Sufficient capacity consistent with the County General Plan Land Use Map ■ Travel choices, including multiple routes and modes of travel to provide the opportunity for reducing vehicle miles traveled ■ Facilities sited and designed to be compatible with the differing scales, intensities, and characteristics of the unincorporated communities while still accommodating regional, community, and neighborhood travel demands ■ Maximized efficiency to enhance connectivity between different modes of travel

Implementation 4.1.1.A Regional Transportation Plan (RTP). Coordinate with SANDAG and adjacent cities during updates to the RTP to identify a transportation network that maximizes efficiency, enhances connectivity between different modes of travel, minimizes impacts when locating new freeways and State highways, and provides regional roads are properly planned, sited, and designed.

Implementation 4.1.1.B RTP Implementation. Coordinate with Caltrans and adjacent jurisdictions during planning and design for improvements to the freeway and State highway network. Caltrans is the design agency to finalize alignment, design, and construct freeways and State highways based on projects and funding priorities identified by the RTP.

Implementation 4.1.1.C Regional Transportation Funding. Coordinate with SANDAG for the County to receive its fair share of TransNet funds for transportation facilities in the unincorporated County.”

Example of policy co-benefits:

Mono County, 2017:

“Objective 3.A. Improve the health of all people by incorporating health considerations into decision-making across sectors and policy areas consistent with the Health in All Policies initiative. Policy 3.A.1. Build relationships, work collaboratively with the community, and implement procedures that make health a priority for the community. Action 3.A.1.a. At all levels of decision making and policy development, raise awareness of the connections between General Plan policies and community health, including, but not limited to, the following: • Conservation/Open Space Element: Protects air quality,

establishes resource efficiency policies to reduce energy use and vehicle miles traveled, and protects open space and agricultural lands.”

Amador County, 2016:

“Goal C-9: Maintain and improve air quality. Policy C-9.1: Encourage development of commercial or industrial businesses which provide jobs for county residents in order to reduce vehicle miles traveled for residents who must drive elsewhere for employment.”

Merced County, 2013:

“Goal ED-1 Support and promote growth and diversification of the County’s economy.

Policy ED-1.5: Infrastructure Investment (MPSP/FB) Direct infrastructure investments to infill areas and other areas with the greatest potential for economic growth in an effort to obtain the greatest pay-off in terms of economic development. This will include taking advantage of existing infrastructure such as Interstate 5, State Route 99, UC Merced, Castle Commerce Center and Airport, as well as planned infrastructure such as the California High-Speed Rail. Encourage the grouping of related and complementary activities and discourage isolated facilities, except when necessary based upon their locational or operational characteristics, in order to minimize vehicle miles traveled (VMT), especially for diesel trucks.”

San Bernardino, 2020:

“Goal NR-1 Air Quality Air quality that promotes health and wellness of residents in San Bernardino County through improvements in locally-generated emissions. Policy NR-1.1 Land use. We promote compact and transit-oriented development countywide and regulate the types and locations of development in unincorporated areas to minimize vehicle miles traveled and greenhouse gas emissions.”

Equity-focused Approaches

Two counties included an equity-focused approach to VMT reductions in the General Plans, Sacramento County and Yolo County. Both policies focused on prioritizing Environmental Justice Communities and tribal groups in the development of infrastructure and land use design necessary to reduce VMT. The Yolo County policy utilizes particularly strong equity language, using terms such as “inclusion,” “fair treatment,” and “equitable outcomes” within their policy. The policies are listed below:

Sacramento County, 2017:

“Objective: Coordinate private development with the provision of adequate public facilities and services. LU-68. Give the highest priority for public funding to projects that facilitate and encourage infill, reuse, redevelopment and rehabilitation, mixed-use development, particularly in Environmental Justice Communities, and that will result in per-person vehicle miles traveled lower than the County average, and the lowest priority

for projects that do not comply with public facilities Master Plan phasing sequences (Sacramento County General Plan, 2017).”

Yolo County, 2009:

“GOAL LU-6 Intra-County Coordination. Ensure inclusion, fair treatment and equitable outcomes for the County in land use planning matters involving other local government entities. Policy LU-6.12 Coordinate with and encourage the Rumsey Band of Wintun Indians to prepare, adopt, and implement a long-range tribal General Plan for tribal trust land and meet or exceed a vehicle miles traveled (VMT) threshold of 44 miles generated per household per weekday.”

Similarly, only four counties (17% of the 23 counties with CAPs) clearly showed an equity focus in their CAP VMT policies. San Mateo and San Francisco gave this significant attention.

Example of equity policy:

San Mateo County 2022:

“T-3.4 PROGRAMS TO FACILITATE TRANSPORTATION EQUITY Facilitate transportation equity through targeted provision of programs and infrastructure that support equity priority communities including but not limited to people of color, low-income households, community members with limited English proficiency to take transit, walk, bike, and use ride- or car-share. “

San Francisco City/County 2021:

“TLU.6-7 Design public space and the transportation system to advance disability justice by codeveloping plans and projects with diverse elements of the disability community and understanding their needs before designs are complete.”

Results

The total score for county general plans ranged from 0-40, with 24 counties scoring a 0. Counties with high scores generally are located in the northern section of the San Joaquin Valley, perhaps indicating policy diffusion from the capital. For General Plans, San Luis Obispo County earned the highest total VMT policy score with a score of 40, followed by Tuolumne County with 26 total points, and Riverside County with 23 points.

Similar to previous sections, CAPs scored higher, demonstrating more focused effort in CAPs to address VMT. Total VMT scores in county-level CAPs ranged from 0-126, with an average score of 36. The three highest scoring county-level CAPs were San Diego (126), Butte (109), and Alameda (89). As with other plan evaluations, there was not a neat alignment between high-scoring General Plans and high-scoring CAPs indicating policy lag or local favoring of alternate planning vehicles depending on the goals.

The top scoring county General Plan for VMT policies was San Luis Obispo, which contained 11 policies covering transportation demand management, land use designations and site amenities,

and transit. Below is an example of the strong policy with a specific implementation strategy from San Luis Obispo 2010:

“Policy AQ 1.2 Reduce vehicle miles traveled: Require projects subject to discretionary review to minimize additional vehicle travel.

Implementation Strategy AQ 1.2.1 VMT reduction strategies: Strategies to reduce new demand for vehicle travel may include, but are not limited to, minimum densities along transit corridors, Transportation Demand Management, and alternative transportation infrastructure as follows:

- a. All new development in the Residential Multifamily (RMF) land use category located within 1/2 mile of a transit node, existing bus route, or park and ride facility with regularly scheduled, daily service should have a minimum density of 15 dwelling units per acre.
- b. New multi-family projects subject to discretionary review should include Transportation Demand Management (TDM) measures, such as reduced parking for affordable, workforce, or senior housing projects, subsidized public transportation passes, car sharing, vanpools, shuttles, or ride-matching programs, based on site-specific review.
- c. New or expanded commercial, industrial, public, or mixed- use projects with 25 employees or more should provide TDM programs such as parking cash-out, subsidized transit passes, ridesharing incentives, vanpools, employee showers, and bicycle parking and storage facilities.
- d. Install adequate and secure bicycle racks and storage facilities at a ratio of 1 per every 10 vehicle spaces in new commercial and public buildings with a corresponding reduction in required automobile parking spaces. Showers and changing facilities should also be encouraged.
- e. Incorporate design features and infrastructure into new projects that enable access by transit, bicycling, and walking.
- f. Establish minimum residential densities on appropriate sites in urban areas where resources are available.
- g. Rezone land to Residential Multi-Family (RMF) in existing urban areas where resources and services are available and expanded.
- h. Reduce parking requirements in areas such as central business districts where a variety of uses and services are planned in close proximity to each other and to transit. Work with communities and developers to fund additional parking where needed, for example, through in-lieu parking fee programs.”

Timeline: 2010; Funding: Department Budget; Personnel: Planning and Building.

The second highest scoring county General Plan for VMT policies was Tuolumne County with six policies covering alternative transportation, traffic impact fees, and transit-oriented development. The following is the policy on traffic impact fees from Tuolumne County 2013:

“2.B.s Traffic Impact Fees to Reduce Offset Vehicle Miles Traveled Where appropriate, consider developing a traffic impact fee program whereby all development would

contribute payment of fees for construction of pedestrian facilities to reduce vehicle miles traveled consistent with Senate Bill 743. (BOSPC)”

Timeline: Ongoing; Funding: General Fund, Road Fund; Personnel: Board of Supervisors, Community Resources Agency.

Riverside was the third highest scoring county General Plan with nine VMT policies covering workplace strategies to reduce VMT, construction equipment and fleets, transit-oriented development, and adoption and implementation of a climate action plan. Below is an example of a policy from Riverside 2015 with specific action items:

“AQ 22.1 The County shall implement programs and requirements to achieve the following objectives related to reducing greenhouse gas emissions associated with transportation (AI 110, 111, 120, 146, 147): a. Reduce vehicle miles traveled by providing or requiring expanded multi-modal facilities and services that provide transportation alternatives, such as transit, bicycle and pedestrian modes. b. Reduce vehicle miles traveled by facilitating an increase in transit options. In particular, coordinate with adjacent municipalities, transit providers and regional transportation planning agencies to develop mutual policies and funding mechanisms to increase the use of alternative transportation.

Action Item 110: Participate in the development and update of the regional air quality management plans required under Federal and State law.

Action Item 111: Develop Air Quality policies for the South Coast, Salton Sea, and Mojave Air Basins. (Coordinate policy efforts with the following agencies; Environmental Protection Agency (EPA), South Coast Air Quality Management District (SCAQMD), Southern California Association of Governments (SCAG), Western Riverside Council of Governments (WRCOG), Coachella Valley Association of Governments (CVAG), and the Mojave Desert Air Quality Management District (MDAQMD).

Action Item 120: Develop stricter control measures for the length of time commercial trucks may be idled, in collaboration with the EPA, SCAQMD and MDAQMD.

Action Item 146: Adopt and implement a Climate Action Plan (CAP) and incorporate the included Implementation Measures (IMs) into the General Plan as an Appendix. The CAP includes a variety of IMs set forth by the Federal and State governments (known as Reduction Measures, A.K.A. “R-measures”) Reduction Measures required by Federal and State law are shown as “R-1” Measures and are already required of all development applications and municipal operations. The CAP expands further on this practice and incorporates local Reduction Measures or R-2 Measures. The list of R2 measures divided into eight major categories, which are transportation, land use, energy use, water and biota use, waste generation, municipal (i.e., County) operations and existing uses not otherwise covered. efficiency the County can incorporate into the new development projects are to achieve an AB 32 compliant reduction target of 15% below existing emissions levels by the year 2020.

Action Item 147: Adopt, implement, and update a set of community protocol implementation and design measures to aid in the reduction of GHG emissions from new development authorized under the Land Use Element of the General Plan. The CAP includes Appendix F (Screening Tables) which incorporates the R-1, R-2, and the voluntary R-3 Reduction Measures from the CAP along with standardized reduction values (or points) that are associated with each set of reduction measures. In order for new development projects to achieve compliance with the County's CAP and therefore with the County's General Plan, each project must achieve a minimum of 100 points for their project or provide an independent GHG emissions reduction analysis with equivalent reductions in GHG emissions."

Timeline: Ongoing; Funding: None; Personnel: Transportation and Land Management Agency-Planning Department.

Policy Strength

Of all the policies examined in CAPs, 52% used strong language such as "shall" or "will." San Francisco and Butte counties had the highest number of strong policies. Six of the 23 counties had more than 75% of their total policies characterized as strong.

Example of strong CAP VMT policy:

San Diego County 2018:

"T-2.4: Shared and Reduced Parking in New Non-Residential Development

MEASURE SUMMARY

Require shared and reduced parking for all new nonresidential development to reduce new commute Vehicle Miles Traveled (VMT) by 10% by 2030"

*includes the following statement in the description: "This measure is a requirement."

Similarly, out of Riverside County's nine VMT policies, six used strong policy language, the most out of all the counties. The following is a policy with specific, strong language with its associated action item:

"AQ 29.1 The County shall implement programs and requirements to achieve the following Objectives related to reducing greenhouse gas emissions from County transportation, such as fleet composition, construction equipment, employee commuting and travel on County business (AI 146): c. Reduce total vehicle miles traveled by County employees, both commuting to work sites and travel for the conduction of County activities.

Action Item 146: Adopt and implement a Climate Action Plan (CAP) and incorporate the included Implementation Measures (IMs) into the General Plan as an Appendix. The CAP includes a variety of IMs set forth by the Federal and State governments (known as Reduction Measures, A.K.A. "R-measures") Reduction Measures required by Federal

and State law are shown as “R-1” Measures and are already required of all development applications and municipal operations. The CAP expands further on this practice and incorporates local Reduction Measures or R-2 Measures. The list of R2 measures divided into eight major categories, which are transportation, land use, energy use, water and biota use, waste generation, municipal (i.e., County) operations and existing uses not otherwise covered. efficiency the County can incorporate into the new development projects are to achieve an AB 32 compliant reduction target of 15% below existing emissions levels by the year 2020.”

Another example of a strong policy with specific directives:

“El Dorado County 2019 - MEASURE LU-Q Promote Infill Development: The program shall be linked to land-use, housing, air quality, transportation and circulation strategies that support development within existing communities, reduce vehicle miles traveled, increase energy efficiency, and encourage the development of affordable housing. The program shall include, but not be limited to:

- a) Adopt criteria to be used within existing communities with developed areas currently capable of being served by public water, recycled water, and public or private sewer;
- b) Provide incentives for residential and commercial infill development including financial incentives for pedestrian-oriented and transit-friendly design features;
- c) Amend the zoning code to include a new Traditional Neighborhood Design zone within Commercial and Multi-Family Land Uses;
- d) Support medium and high density residential or mixed use development along commercial and transportation corridors;
- e) Develop and utilize approved standard plan types (i.e. zero-lot line, duplex with carriage house unit over garage, z-lot, bungalow, etc.) to streamline the approval process for infill projects. Standard plans shall include various housing and commercial types and styles. Standard plan(s) approved as part of a project shall be compatible with neighboring residential or commercial district patterns for which the development is located; and
- f) Develop or update, as considered necessary, applicable community plans, specific plans and design guidelines to incorporate pedestrian-oriented, transit-friendly, and or energy efficient configurations design as primary goals.”

Timeline

Most counties listed “ongoing” for their VMT policies. For example, the San Luis Obispo 2010 General Plan included a timeframe to start but no duration:

“Implementation Strategy AQ 4.4.3 Reduce GHG emissions from community-wide transportation activities: Reduce greenhouse gas emissions resulting from communitywide transportation activities through expanded use of alternative fuel vehicles, increased use of alternative transportation modes, decreased VMT, development of compact, mixed-use, infill projects in established communities and urban areas, and other strategies identified in the Climate Action Plan.” Timeframe to start: Immediately; Funding: Planning and Building Department Budget; Personnel: County Department of Planning and Building, cities, San Luis Obispo Council of Governments.

Yuba County 2011 - Policy timelines include milestones and plans for action:

“Goal CD16. Level of Service: Roadway System. Maintain a roadway system that provides adequate level of service, as funding allows, and that is consistent with the County’s planning, environmental, and economic policies

Policy CD16.5 Where a new development would exceed the County’s Level of Service policies, applicants shall first consider feasible revisions to the proposed development that would increase connectivity, enhance bicycle/pedestrian/transit access, provide additional travel demand management measures, and/or provide other revisions that would help to meet LOS standards by reducing vehicle miles traveled on roads exceeding the target LOS, prior to consideration of adding capacity to roadways and intersections.

Action CD2.1 Revise Standards. Following the General Plan adoption, the County will review and revise zoning, development standards, impact fees for all County facilities (library, parks, jail, roads, etc.), and related plans and standards to ensure consistency with the General Plan. As a part of these amendments, the County will focus on removing constraints and creating incentives for mixed-use, infill development that is consistent with the General Plan. Time Frame: Update Zoning Ordinance and development standards by 2013

Action CD14.1 Impact Fees and Tax/Revenue Agreements Following General Plan adoption, the County will coordinate with the cities and other public service agencies on revenue sharing, redevelopment pass-through funding, development impact fees, and other important fiscal arrangements to implement General Plan policies. Time Frame: Ongoing during General Plan buildout.”

As in previous sections, county-level CAPs offered stronger timeline commitments for action. Of all the policies examined in county CAPs, 63% had a timeline or prioritization for implementation. Butte, Santa Barbara, San Diego, and San Francisco counties state specific years for implementation, while others use the short/medium/long-term convention.

Example of policy with specific timelines, **San Francisco City/County 2021**:

“TLU.1-6 By 2025, implement 50 miles of Muni Forward transit priority improvements, including 30 miles of new transit-only lanes. to increase reliability, frequency and safety for riders.”

Example of implementation with specific years, **Butte County 2021**:

“Time Frame: The year by which a strategy should be effective by fiscal year’s end. The exact status of a strategy will vary based on its actions, and many strategies will be ongoing through and beyond 2030. An effective strategy is one that will be actively on track to achieve its targeted GHG emission reductions, support adaptation to climate change effects, or achieve long-term resilience. For a strategy to be effective, the necessary programs and efforts should be active, and any infrastructure or other capital improvements should be in place. The effective year is not the end year, as many of the strategies are programs that are intended to remain in effect for the foreseeable future,

and so they do not have end dates. Time frames for effectively setting up the strategies are described as follows:

--Immediate

--Near-Term (by 2023)

--Mid-Term (by 2025)

--Long-Term (by 2030)”

Funding

Solano, Tuolumne, and Yuba counties had funding sources listed for all of their VMT policies. Common sources of funding listed among all counties include: general funds, planning department budgets, road funds, and grants. Only one policy specified a grant:

San Luis Obispo 2020:

“Program C Designation of Additional Land for Residential Uses; Description: Consider and, if appropriate, amend the Land Use and Circulation Elements to designate additional land for residential uses in areas described under Policy HE 1.01. While adequate land has been identified in the inventory of sites to accommodate the County’s share of the regional housing needs allocation, as described in “Chapter 7: Sites Analysis”, additional land for residential uses will be necessary to accommodate future population growth beyond 2028. Newly designated additional land for residential uses may contribute to the inventory of sites in future Housing Element cycles. Implementation of this program can assist in reducing housing price escalation, vehicle miles traveled, and resource consumption. Additionally, larger parcels (i.e. five (5) acres or larger) would allow for additional site amenities, such as open space and parks”. Target Start: Spring 2021; Target Completion: Spring 2027; Funding: General Funds, LEAP Grant; Personnel: Department of Planning and Building.

This strong focus on funding in General Plans contrasts with weak funding commitments in CAPs, perhaps demonstrating the differences in plan types where General Plans are often more closely tied to planning general fund expenditures. Of the 23 county CAPs, only three included funding sources for their policies. No counties provide details on funding sources for each CAP policy. Instead, the few that address funding at all provide a list of potential funding sources. For example, the Alameda County CAP (2014) provided an exemplary funding strategy and list of potential funding sources. Similarly, San Francisco City/County developed a funding approach to implement their CAP, as shown below.

Example of funding approach, San Francisco City/County 2021:

“Overall, recommended next steps include:

1. Create an interdepartmental climate finance working group to assess the economic, social, political, and administrative viability of securing new funding sources.
2. Develop a detailed cost estimate for implementing CAP actions (beyond high-level estimates in the CAP).
3. Identify all opportunities to fund CAP strategies from existing funding sources and approved measures.
4. Assess which CAP strategies are not funded or partially funded to identify funding gaps.
5. Investigate a new tax (carbon tax, food tax) and/or increase existing taxes (sales tax, property tax) as a major contributor to reducing funding gaps.
6. Seek out and apply for relevant federal, state, and local grant opportunities which can serve as important seed funding for implementing CAP strategies or other supporting activities such as community engagement or technical analysis.”

Staff and Personnel

Calaveras, Inyo, Los Angeles, Merced, San Mateo, Solano, Stanislaus, Tuolumne, and Yuba counties listed personnel for all of their VMT policies. The top three highest scoring county-level General Plans (San Luis Obispo, Tuolumne, and Riverside) designated personnel for most of their policies (60%). Common internal departments listed across counties were: planning, public works, community development, building, and transportation. Other personnel listed included: air pollution control districts, council of governments, transit agencies, arts commission, board of supervisors, and land management agencies.

CAPs showed similar staff commitments. Just over 57% of county-level CAP policies included an assignment to a specific department or agency for implementation, such as community development or public works. These are usually listed in an implementation table and not discussed in detail. Notably, Alameda County conducted a detailed assessment of staffing needs for implementing their CAP; see the example below.

Example of CAP section discussing staffing, Alameda County 2014:

“STAFF TIME FOR CAP IMPLEMENTATION

The successful implementation of the CAP will, in great part, be achieved through voluntary programs that will be managed and overseen by County staff. The emphasis on voluntary programs was a result of feedback from County staff, community members, and local professionals that the CAP should limit the number of mandates imposed on the community. Consequently, many measures require staff time to develop programs, implement outreach campaigns, and oversee policy development such as ordinances. The cumulative staff requirements for each Action Area were assessed, with the results shown in the table below. Since there are many potential synergies in measure implementation (i.e., energy efficiency and solar programs for residences may have joint implementation

as the target audience of that suite of measures is the same constituency). Furthermore, as the implementation of many measures only requires staff time (with, for instance, no capital cost requirement), the total staff time requirement and associated cost is aggregated at the level of the Action Area. See Appendix C for more details on the costs and savings analysis. It should be noted that these staff requirements do not necessarily represent additional County hires; the staff time requirements to implement the CAP could potentially be included in an existing staff member's job description."

Vehicle Miles Traveled plan evaluation for cities

Policy Approaches

Similar to the county-level plan evaluation, the terms coded for this section include "vehicle miles traveled" and "compact development." Policy approaches to reducing vehicle miles traveled among cities cover compact, transit-oriented, and infill development; alternative transportation; growth management; and transportation demand management.

Example of compact development policy, City of Campbell 2001:

"H-4.3a Achieve Target Densities. Promote compact development by encouraging properties to develop to General Plan densities. Inform developers of policy to strive to achieve at least 75% of General Plan density within specified areas. Review development proposals for residential and mixed-use projects to strive to achieve "planned-for" densities." Timeline: 2015-2023; Funding: General Fund; Personnel: Community Development.

Example of reducing VMT policy, City of Elk Grove 2021:

"Policy MOB-1-1: Achieve State-mandated reductions in VMT by requiring land use and transportation projects to comply with the following metrics and limits. These metrics and limits shall be used as thresholds of significance in evaluating projects subject to CEQA. Projects that do not achieve the daily VMT limits outlined below shall be subject to all feasible mitigation measures necessary to reduce the VMT for, or induced by, the project to the applicable limits. If the VMT for or induced by the project cannot be reduced consistent with the performance metrics outlined below, the City may consider approval of the project, subject to a statement of overriding considerations and mitigation of transportation impacts to the extent feasible, provided some other stated form of public objective including specific economic, legal, social, technological or other considerations is achieved by the project.

(a) New Development – Any new land use plans, amendments to such plans, and other discretionary development proposals (referred to as "development projects") are required to demonstrate a 15 percent reduction in VMT from existing (2015) conditions.

(i) Land Use – Development projects shall demonstrate that the VMT produced by the project at buildout is equal to or less than the VMT limit of the project's

General Plan land use designation, as shown in Table 6-1, which incorporates the 15 percent reduction from 2015 conditions.

(ii) Cumulative for Development Projects in the Existing City-Development projects within the existing (2017) City limits shall demonstrate that cumulative VMT within the City including the project would be equal to or less than the established Citywide cumulative limit of 6,367,833 VMT (total daily VMT).

(iii) Cumulative for Development Projects in Study Areas – Development projects located in Study Areas shall demonstrate that cumulative VMT within the applicable Study Area would be equal to or less than the established limit shown in Table 6-2.

(b) Transportation Projects – Transportation projects likely to lead to a substantial or measurable increase in VMT shall:

(i) Not increase VMT per service population. Projects must demonstrate that the VMT effect of the project does not exceed the project's baseline condition VMT.

(ii) Be consistent with the regional projections and plans. The project shall be specifically referenced or listed in the region's MTP/SCS and accurately represented in the regional travel forecasting model. Qualifying transportation projects that are not consistent with the MTP/SCS shall also demonstrate that the cumulative VMT effect does not increase regional VMT per service population.

Action 1.4 Development Review Requirements and Process Refinements. Update the submittal requirements and review processes for land use applications for consistency with General Plan policies, as follows:

- Require development applications, as appropriate, to include plans for necessary infrastructure improvements (e.g., roads, stormwater drainage and treatment facilities, utilities). (LU-3-29, LU-3-32, MOB-7-1)
- Prepare and regularly update guidelines for the preparation of transportation impact analyses for consistency with vehicle miles traveled (VMT) policies. As part of the guidelines, the City shall:
 - Identify appropriate methodologies for calculating VMT for both land use and transportation projects.
 - Monitor citywide VMT and identify areas of the City that may be exempt from subsequent analysis.
 - Monitor the effectiveness of VMT reduction strategies and update a list of appropriate strategies on an ongoing basis. (MOB-1-1)
- Update City guidelines for the preparation of transportation impact analyses for consistency with Roadway Performance Target policies. (MOB-1-3, MOB-1-4, MOB-1-5, MOB-1-6)

- Update requirements for acoustical analysis to be submitted with applications for development of noise-sensitive land uses for:
 - noise-sensitive land uses proposed in areas exposed to existing or projected exterior noise levels exceeding the levels specified in Table 8-3 or the performance standards of Table 8-4 (N-1-5), and proposed nonresidential land uses likely to produce noise levels exceeding the performance standards of Table 8-4 at existing or planned noise-sensitive uses (N-1-6).
- When applications are received to establish sensitive land uses in proximity to air pollution sources, refer the application to the Sacramento Metropolitan Air Quality Management District for comment. (NR-4-9)”

Time Frame: FY 18/19 - FY 19/20; Funding: None; Personnel: Development Services Planning; Development Services Engineering, Public Works, Strategic Planning.

Example of transportation demand management policy, City of Culver 1995:

“MEASURE 3. CONTINUE TRANSPORTATION DEMAND MANAGEMENT (TDM), While the proposed highway, bus, and rail programs would increase the supply of transportation option, Transportation Demand Management (TDM) Programs promote the demand for alternative transportation by creating incentives to reduce single occupant auto trips and overall trip-making, TDM programs are intended to: Enhance the attractiveness of ridesharing as a alternative to single ‘occupant automobile travel; maximize ridership on the evolving bus and rail systems and carpool lane networks; reduce overall trips and vehicle miles traveled.

A. Participate in MTA's 30 Year Plan Long Term Planning. Coordination between MTA and AQMD has resulted in compatibility between AQMP and CMP requirements. Participation by Culver City in MTA's TDM programs fulfills its obligations under the CMP. City TDM programs included in the Circulation Element and Air Quality Plan will also meet the current requirements for Transportation Control Measures under the AQMP (see the Air Quality Plan).

B. Adopt a Transportation Demand Management Ordinance. Under the Congestion Management Plan, prior to the approval of a specific development project, TDM improvements must be included. The type and amount of TDM would vary with the size of the project but could include items such as providing a bulletin board displaying transportation information such as current maps, routes and schedules for public transit routes serving the site and ridesharing information; providing preferential parking for car and van pools; and providing bicycle facilities. The City should take a proactive approach to TDM and reduction of Vehicle Miles Traveled (VMT), beyond minimum regional requirements. In high density commercial and industrial areas (such as Fox Hills, Downtown, Hayden Tract, studio areas) determine what TDM goals are desirable and attainable, and who should be implementing and monitoring these measures. Provide incentives, such as reduced parking requirements, for developments that encourage

alternate commute modes. These facilities could include showers, lockers, bike racks, and "in-lieu" payments for not driving to work."

Example of growth management policy, City of Norco 2013:

"Program Action 6.1 Sustainable Land Use Planning. The City of Norco recognizes that long term planning efforts should focus on sustainability and the reduction of greenhouse gases. To progress towards these goals the City understands that it must provide an adequate supply of housing that is sufficient for a range of income groups thereby excluding long commutes in search of affordable housing. This requires planning for sufficient housing supply in the right locations - close to jobs, services, and amenities = which will in ur reduce congestion and long commutes. To achieve this, the City will promote infill and compact development patterns, has adopted higher densities in the Housing Development Overlay zone and will conserve habitat and environmentally sensitive areas including residential lots that are appropriate for animal keeping and agricultural uses. Objectives: Identify and advertise development opportunities within the Housing Development Overlay zone at City Hall, on its website to encourage compact development in key growth areas. Promote use of the Multifamily Green Building Guidelines. Investigate opportunities to reduce fees and provide priority processing for residential development to promote development within specific growth opportunity areas." Timeline: Ongoing, 2014-2021; Funding: Departmental Budget; Personnel: City of Norco Planning Division.

Example of VMT comparative approach, City of Long Beach CAP 2022:

"T-9: Integrate SB 743 Planning with the CAAP Process

Evaluate the effectiveness of VMT reductions resulting from SB 743 compliance in achieving the City's GHG reduction target.

T-9.1: Evaluate the effectiveness of new VMT thresholds, metrics, and mitigations as the City's updated Transportation Impact Analysis (TIA) guidelines are implemented.

T-9.2: Monitor what types of mitigation strategies are working in other cities that could apply in the Long Beach context to reduce emissions and meet aligned City objectives.

T-9.3: Consider strategies to fund the implementation of VMT mitigation strategies, such as collecting in lieu fees and participating in a regional mitigation bank program.

T-9.4: Evaluate VMT mitigations and adjust as needed to maximize effectiveness on an ongoing basis."

Results

Total VMT policy scores in city General Plans ranged from 0-18, with 323 cities scoring a zero. The highest scoring cities were: Santa Clara with 18 points, followed by Milpitas and Paso Robles with 15 points each. Total scores ranged from 0-9 for "compact development" with 411 out of 482 cities scoring a zero in their General Plans. The top four cities for "compact

development” were Rancho Cordova with nine points, and Azusa, Tulare, and Windsor with eight points each. High scoring city General Plans (including both terms) were primarily located in the greater San Francisco Bay region and greater Los Angeles region, perhaps indicating an emphasis on population and commuting.

This contrasts with the sample of city-level CAPs. Total VMT plan scores in city-level CAPs ranged from 0-127, with an average score of 29. The three highest scoring cities were San Leandro (127), Long Beach (58), and Hughson (52). Again, CAPs show a stronger climate readiness policy focus than their General Plan counterparts even in the same cities.

Equity-focused Approaches

Equity focused VMT and compact development policies were rare. This is of interest as anti-development (NIMBY) and pro-development (YIMBY) discourses can both run counter to environmental justice efforts to prevent displacement. On the one hand, no-growth scenarios can result in limited housing and rising rental rates which spur displacement. Similarly, pro-growth scenarios can create displacement where new development caters primarily to higher income earners by providing luxury apartment buildings or large-lot development. The lack of focus on equity in VMT policies in both General Plans and CAPs should signal a need for state agencies to more closely align policy guidance between housing, transportation, and EJ.

City of Corona 2004:

“Objective C-11A: Improve air quality and public health and reduce ambient noise by promoting Active Transportation programs. Recommendation C-11.3: Increase pedestrian and bicycle trips, thereby reducing vehicle trips and vehicle miles Traveled.”

Compact Development, City of Folsom 2018:

“LU 1.1.12 Infill Development. Coordinate with the real estate development community to encourage infill development in key parcels north of U.S. Highway 50. Infill development should follow these guidelines: Respect the local context. New development should improve the character and connectivity of the neighborhoods in which it occurs. Physical design should respond to the scale and features of the surrounding community, while improving critical elements such as transparency and permeability. 2. Work with neighbors. Infill development requires neighborhood consultation to understand the concerns, goals, and needs of existing neighborhoods. Ensure the planning and design process provides proper avenues for neighborhood input while fulfilling the community’s larger goals for walkability and compact development.”

City of Greenfield 2014: “Policy 6.7.2 Provide transportation choices and travel efficiency in housing areas. Program 6.7.G Promote infill and compact development to facilitate non-motorized transportation. In the approval of subdivision maps and site plans, facilitate land use patterns and development densities that place services close to residences and promote use of lower-energy means of transportation, including walking, bicycling, and car-pooling to make less costly transportation alternatives available and feasible and reduce costs associated with transportation, especially for low income residents.”

Only two cities clearly showed an equity focus in their VMT policies, Long Beach and San Leandro. The City of Long Beach CAP (2022) includes an equity statement in all of their VMT policies, offering a laudable model.

Example of equity policy, City of Long Beach 2022:

“T-3: Increase Bikeway Infrastructure Citywide

Equity Strategy

Assess existing and planned bikeway infrastructure to ensure equitable distribution based on CalEnviroScreen and other environmental justice indicators. Increase accessibility of active transportation and micro mobility options for low-income individuals by working with providers and by exploring subsidies and specialized programs.”

Policy Strength

All of the VMT and “compact development” policies from the cities of Alhambra, Dixon, Dublin, and Gilroy General Plans used strong language. Gilroy is the best example of this with three VMT policies and two “compact development” policies, all of which were descriptive and specific.

Gilroy 2016:

“Growth Management Goal: A clearly defined, well-managed development process that ensures that (a) the rate of growth does not outpace the City’s and other agencies’ ability to provide necessary infrastructure and services; (b) the demands created by new growth do not exceed resource and system capacity constraints; (c) new growth is directed first to areas where municipal services are available and capacity exists; (d) the incremental public service costs generated by new growth are paid for by new growth; and (e) the resulting pattern of development is compact, efficient, and contiguous.

Policy 2.01 Location of Growth. Maximize existing infrastructure and service investments— and avoid premature investment for facility and service extensions—by directing new growth to vacant and under-utilized lands within the Urban Service Area, consistent with the Urban Growth Boundary ("UGB") adopted by initiative in 2016. As a second-tier priority, direct new development to areas that border on existing urban development or are immediately adjacent to the Urban Service Area, prohibiting costly “leap frog” development and ensuring a compact development pattern, consistent with the UGB.” Timeline: None; Funding: None; Personnel: None.

Rancho Cordova 2006:

“Policy LU.2.8 - Grant density bonuses and other related incentives, consistent with state law and local policy, for the provision of affordable housing.

Action LU.2.8.1 - Amend the Zoning Code to include flexible parking standards and parking reductions to encourage compact development, shared parking, and higher

density projects in specified locations throughout the City. Timeline: 2006-2007, ongoing; Funding: General Fund; Personnel: Planning Department, Public Works.”

In CAPs, of all the policies examined, 44% used strong language such as “shall” or “will.” Long Beach and San Leandro had the highest number of strong policies. Seven of the 21 cities in the sample had more than 75% of their total policies characterized as strong.

Example of strong policy: City of San Leandro CAP 2021:

“AT-1: Transportation Demand Management (TDM). Require local employers above a certain number of employees to develop programs that promote ridesharing, flextime, telecommuting, and other means to reduce commute trips and congestion, and target 10% mode shift.”

Timeline

Most policies did not have a timeline, but of those that did, common timelines were “ongoing.” Without firm benchmarks listed in plans, it is difficult for local communities to hold their planning process accountable. The lack of timelines also hinders a statewide understanding of when and how communities will meet targets.

Example of specific timeline, Ceres 2018:

“Goal 3.A Provide for the long-range planning, development, and maintenance of the city’s roadway system to ensure the safe and efficient movement of people and goods through a variety of travel modes. 3.A.4 Reduce Vehicle Miles Traveled (VMT). Support statewide efforts to reduce vehicle miles of travel (VMT) from existing and new development by encouraging infill and mixed-use development, providing a multi-modal transportation network, and incorporating transportation and parking demand management measures into new development by design.” Timeline: 1-3 years, update every 3-5 years; Funding: None; Personnel: Engineering, City Council, Community Development, Public Works.

CAPs included bolder timelines for implementation. Of all the policies examined in the sample of 21 CAPs, 65% had a timeline or prioritization for implementation. Some cities used a specific year such as Hughson, while other would use the short/medium/long-term convention. It should be noted that this same of city-level CAPs is meant to draw from the strongest policies and may not represent CAPs overall.

Example of CAP VMT policy with detailed timelines, City of Escondido 2021:

“Measure T-3.5: Update Bicycle Master Plan. Update the City’s Bicycle Master Plan and install new or improve existing Class II or better bicycle lanes.

2023 Develop an Active Transportation Plan that includes an update to the City’s Bicycle Master Plan.

2024 Develop and implement a citywide bike rack policy.

2025 Complete construction of the Class I Escondido Creek Bike Path, funded through Prop 68, to facilitate a larger network of active transportation access points and opportunities.

2025 Develop and implement a program to incentivize City employees commuting to work by bike or other modes of alternative transport as a model for other local employers.

2030 Install at least 19 miles of new Class II or better bicycle lanes by 2030.

2035 Install at least 30 miles of new Class II or better bicycle lanes by 2035.”

Funding

Similar to timelines, most policies in General Plans did not list a funding source. Those that had a funding source listed “general fund”, “department budget”, or “grants.” The emphasis on local funding indicates a bottleneck in climate readiness planning and implementation as many cities indicate that they will look for internal funds to support implementation.

specific grants, City of Oxnard 2017:

“Program 4: Urban Village Program The Urban Village Program (UVP) is part of the 2030 General Plan. The UVP is conceptually described in the 2030 General Plan. The UVP initially designated seven villages that are envisioned as mixed-use areas designed to encourage persons to live near their place of employment and/or support services and readily accessible to transit. Urban Villages should occur in the designated areas but may be proposed in others as a General Plan Amendment. The integration of land uses is intended to provide and promote a pedestrian orientation to reduce trips and vehicle miles traveled in order to reduce greenhouse gas emissions. Urban Villages are implemented with a specific plan or a strategic plan similar to the Central Business District Strategic Plan. UVP guidelines may be developed if useful to qualify for Affordable Housing and Sustainable Communities (AHSC) Program funding. A minimum of 15 percent of the UVP housing would be affordable. The UVP would consider the rezoning and reuse of commercial and industrial land for housing, the consolidation of parcels, and mandating a local preference program for affordable housing. The City will also consider renaming this program “Transit-Oriented Development Neighborhood, District, or Corridor.” By 2021, 290 affordable units are anticipated within the Teal Club and East Village UV’s.” Timeline: End of 2021, ongoing; Funding: General Fund, SGC AHSC Grant (Cap & Trade) EDC set-aside for highly qualified census tracts; Personnel: Development Services.

Examples of specific external sources of funding, Point Arena 2019:

“3-1.4 Encourage construction of new houses in or near downtown core area to reduce the need for City utility extension and reduce vehicle miles traveled (VMT) by:

- Encouraging development projects near or adjacent to the urban core to fund off-site pedestrian and bicycle facilities for non-vehicular access to downtown.

- Encouraging development of new clustered or attached housing for efficient land, materials and energy use, and for a more sustainable community.
- Permit solar power and water heating, water conservation devices, and energy-saving construction materials. Promote grid-tie solar system use.
- Encourage development of microgrids. Promote battery backup systems.
- Promote energy efficiency measures in new developments such as building siting, energy efficient windows and doors, and drought tolerant landscaping. Review applications for compliance when such provisions are adopted.”

Timeline: Ongoing; Funding: PG&E, North Coast Energy Services assistance, Housing Trust Fund, Sonoma Clean Power; Personnel: City, PG&E, North Coast Energy Services.

Tustin 2018:

“Air Quality GOAL 2: Improve air quality by influencing transportation choices of mode, time of day, or whether to travel and to establish a jobs/housing balance.

Policy 2.2: Reduce total vehicle miles traveled (VMT) through incentives, regulations and/or Transportation Demand Management.

Implementation 1. Non-Motorized Transportation: Amend the City's TDM ordinance incorporating non-work trip reduction provisions requiring: (1) major retail centers to offer customer mode-shift travel incentives and provide facilities for non-motorized transportation needs; and (2) large capacity special event centers (over 10,000 seating capacity) to include park-n-ride and off-site facility lots, auto free zones, street closure during peak periods, and enhanced transit performance as appropriate (implements measure TCM-01 of 1997 AQMP)

Implementation 2. Rideshare and Transit Incentives: Adopt or amend a TDM ordinance incorporating strategies for employers of over 250 people and those of over 25 people, encouraging the formation of Transportation Management Associations, and encouraging employer van pool programs and use of clean fuel vans (implements TCM-01 of the 1997 AQMP).

Implementation 8. Congestion Management: Participate with the Orange County Transportation Authority in defining and implementing the County's Congestion Management Plan (implements measure TCM-01 of the 1997 AQMP).

Implementation 9. Interagency Communication/Coordination: Participate in available communication networks with key elected officials and staffs involved in air quality planning as the basis for identifying and implementing programs which effectively reduce airborne pollutants. Implementation 10. Development Projects: Continue to require participation in transportation demand management programs for development projects which have been determined to have a potential impact on air quality (implements measure TCM-01 of the 1997 AQMP).”

Timeline: Ongoing; Funding: City General Fund, TDM Fees, Measure M, Proposition III Funds; Personnel: Community Development, Public Works, Administrative Services, All Affected Departments.

Of the 21 city CAPs examined, only six included funding sources for their policies and in most of those cases there was little detail beyond listing a source such as the “general fund” or “grants.” The Dublin CAP was notable in the level of detail included in their funding plan, which included the source of funding and how the funding would be used. Of note, some cities showed policies that required only staff time as low or no funding required.

Example of policy with funding, City of Dublin 2020:

“Measure SM-5: Update the Bicycle and Pedestrian Master Plan

The Metropolitan Transportation Commission collects Transportation Development Act (TDA) funds. Two percent of TDA funds are allocated to TDA Article 3 (TDA 3) funds which are redistributed to each county and must be used for bicycle and pedestrian projects. In Alameda County the TDA 3 funds are distributed to jurisdictions based on population.

Measure B was approved by Alameda County voters in 1986 and renewed in 2000. It provides a one-half-cent sales tax to improve transportation throughout Alameda County.

Voters passed Measure BB in November 2014 and collection of the initial half-cent transportation sales tax by the Board of Equalization began on April 1, 2015 and will extend through March 31, 2022. The full one-cent sales tax authorized by Measure BB will begin April 1, 2022 and will extend through March 31, 2045. Starting in July 2015, Alameda CTC began making monthly local distribution payments to local jurisdictions and transit agencies, per the 2014 Transportation Expenditure Plan, for the following programs: local streets and roads (including county bridges), bicycle and pedestrian, transit and paratransit.”

Staff and Personnel

Most cities did not list specific personnel to implement General Plan VMT policies, but of those that did, the most common were: community development, public works, planning, city manager and city council, and engineering.

Example of General Plan policy with many internal and external personnel listed as responsible for policy implementation, Burlingame 2019:

“Goal M-6: Create an integrated transportation program that reduces peak-period vehicle trips and vehicle miles traveled.” Timeline: 5 years; Funding: General Fund, Grants; Personnel: Community Development, Central County Fire Department, City Attorney, City Manager (Sustainability Coordinator), Parks and Recreation, Public Works.

Unlike General Plans, the sample of 21 city CAPs showed a strong focus on identifying responsible staff to carry out policies. About two-thirds of CAP VMT policies included an

assignment to a specific department or agency for implementation, such as community development or public works. These are usually listed in an implementation table and not discussed in detail.

Example of CAP section discussing staffing, City of Del Mar 2016:

“Implementation of the recommended mitigation measures will require ongoing management, oversight, and staffing. The implementation plan identifies departmental responsibility for overseeing or leading implementation of the individual mitigation measures based on consistency of the mitigation measures with the department’s scope of responsibility. In addition, the City Council-appointed Sustainability Advisory Board will monitor and advise the City Council and staff on implementation of the CAP.”

Unique approaches to decarbonization across cities and counties

Albany 2016:

“GOAL T-2: SUSTAINABLE TRANSPORTATION Reduce the consumption of non-renewable resources and the emission of greenhouse gases and other air pollutants related to transportation.

Action T-2.I: Multi-Modal Levels of Service Establish multi-modal level of service (MMLOS) standards for arterial streets, and apply these standards in the evaluation of future development proposals and planning studies. In support of the City’s efforts to reduce greenhouse gas emissions, service standards should utilize vehicle miles traveled (VMT) as the primary metric, rather than the total number of trips generated or projected motor vehicle delays.” Timeline: None; Funding: None; Personnel: None.

Azusa 2004:

“EC 2 EMPLOYMENT DISTRICT PROGRAM. Employment District Planning. Encourage efficient use of land through compact development, high densities, reduced parking ratios (with effective alternatives), and proper incentives for redeveloping underutilized land. Users that are amenity sensitive, operate at relatively high densities, and are most likely to make use of transit infrastructure should be accommodated in the vicinity of the future Gold Line station and Downtown.” Timeline: 2006; Funding: General Fund; Personnel: Community Development, Economic Development/Redevelopment.

Coachella 2015:

“Goal 3. Water Resources. Protected and readily available water resources for community and environmental use. 3.10 Retention Basins. Encourage storm water retention basins to be underground in future development so as to achieve the most efficient use of land and compact development and promote the urban character goals of the General Plan.” Timeline: None; Funding: None; Personnel: None.

Norco 2013:

“Policy 6.2 Adopt higher densities and promote infill and compact development patterns to ‘encourage housing affordability, maximize existing land resources, reduce pressure to convert agricultural resources, and conserve habitat and environmentally sensitive areas.”
Timeline: None; Funding: None; Personnel: None.

City of Orange 2010:

“GOAL 2.0: Create commercial and mixed-use areas of varying scale and function that are visually distinct and complement the City’s identity.

Policy 2.1: Transform corridors such as Chapman Avenue, Main Street, The City Drive, and Katella Avenue into active, pedestrian-friendly streets that balance auto, transit, and pedestrian mobility. These streets should accommodate compact development that is oriented to the sidewalks to promote active street life.

Program III-1 California Environmental Quality Act. Comply with all provisions of CEQA. In addition to thresholds that may be established or adopted by the City in the future, use the following thresholds and procedures for CEQA analysis of proposed projects, consistent with policies adopted within the General Plan:

Circulation & Mobility

- Level of service (LOS) D (volume-to-capacity [V/C] ratio less than or equal to 0.90) shall be the lowest acceptable level of service for both roadway segments and peak- hour intersection movements.
- Orange County’s Congestion Management Plan (CMP) specifies LOS E (V/C ratio less than or equal to 1.00) as the operating standard for roadways on the CMP highway system. o Projects that increase V/C by .01 or more on affected roadway segments or intersections experiencing LOS E or LOS F conditions without the proposed project are considered to create significant impacts, and mitigation is required.

Parks and Recreation

- The City shall require dedication of parkland at a rate of 3.0 acres per 1,000 anticipated residents or payment of in-lieu fees for new residential projects.

Noise

- The City shall apply the noise standards specified in Tables N-3 and N-4 of the Noise Element to proposed projects analyzed under CEQA.
- In addition to the foregoing, an increase in ambient noise levels is assumed to be a significant noise impact if a proposed project causes ambient noise levels to exceed the following:

- Where the existing ambient noise level is less than 65 dBA, a project related permanent increase in ambient noise levels of 5 dBA CNEL or greater.
- Where the existing ambient noise level is greater than 65 dBA, a project related permanent increase in ambient noise levels of 3 dBA CNEL or greater.

Historic and Cultural Resources

- “Historical resource” for the purposes of CEQA shall mean “historic district” in the case of a contributor to a historic district.
- Historic resources listed in the Historic Register shall have a presumption of significance pursuant to CEQA Section 21084.1 and shall be treated as historical resources under CEQA.
- The historical significance of an archaeological historic resource is evaluated using the criteria of Public Resources Code Section 5024.1 and Section 15064.5 et seq. of the state CEQA Guidelines.

All future development proposals shall be reviewed by the City for potential regional and local air quality impacts per CEQA. If potential impacts are identified, mitigation will be required to reduce the impact to a level less than significant, where technically and economically feasible. Time Frame: Ongoing; Funding: General Fund, development fees; Personnel: Community Development Department, Public Works Department, Community Services Department.

Program IV-6 Transportation Demand and System Management: Participate in regional efforts to implement TDM requirements and support implementation of the employer TDM provisions of the South Coast Air Quality Management District’s Air Quality Management Plan by working with the SCAQMD to identify employers within Orange most suitable for participation in the TDM programs to achieve major reduction of VMT. Complete intersection capacity improvements and coordinate traffic signals as necessary to improve traffic flow. Time Frame: Ongoing; Funding: General Fund; Personnel: Community Development Department, Public Works Department.

Program V-3 Adjacent Jurisdictions and Special-Purpose Agencies and Organizations: Continue to coordinate with adjacent jurisdictions and special-purpose agencies and organizations for the following purposes:

- Land use planning efforts;
- Growth and facility planning, management, and maintenance;
- Planning and developing major east/west and north/south arterials and rapid transit;
- Ensuring that Orange benefits from the planned Anaheim Regional Transportation Intermodal Center (ARTIC);

- Connecting City trails to trails in adjacent jurisdictions and regional trails networks, including Santiago Creek, the Santa Ana River, and the proposed Tustin Branch Trail;
- Completing vision plans for Santiago Creek and the Santa Ana River;
- Maintaining an appropriate level of transportation impact fees and other public service fees;
- Continuing and adopting mutual-aid agreements;
- Maintaining flood control facilities and implementing a capacity analysis;
- Developing trails along service roads for flood control channels;
- Aircraft corridor planning, minimizing aircraft overflights in the City, and coordinating approval of heliport/helistop operations;
- Disaster preparedness and emergency response for earthquakes and wildland fires;
- Participating in interjurisdictional planning forums through the established Growth Management Areas (GMAs) adopted by the Regional Advisory Planning Council as well as the City's Joint Powers Agreements with adjacent cities to address cumulative traffic impacts and to coordinate improvements in transportation facilities; and
- Monitoring and compiling information on faults within the planning area.

Time Frame: Ongoing; Funding: General Fund, development fees, gas tax funds; Personnel: Community Development Department, Public Works Department, Fire Department, Policy Department.

Program V-5 Orange County Transportation Authority: Work closely with the OCTA to achieve the following objectives:

- Maintain consistency with the County Master Plan of Arterial Highways, including the reclassification of roadways described in the Circulation & Mobility Element, such as La Veta Avenue.
- Implement provisions of Renewed Measure M.
- Implement the OCTA Congestion Management Plan (CMP).
- Expand and improve the efficiency of bus service within the City.
- Encourage the expansion of alternative local transportation options such as a community circulator bus service between transit centers and major commercial, employment, and residential areas.
- Improve paratransit or other public transportation systems that enhance the mobility of Orange's senior and youth populations, and the disabled.
- Encourage provision of attractive and appropriate transit amenities.
- Support and implement the OCTA Commuter Bikeways Strategic Plan and participate in future updates and revisions to the Plan.
- Reduce noise impacts of OCTA operations and facilities.

Time Frame: Ongoing; Funding: General Fund, State Transit Assistance funds;
Personnel: Public Works Department, Community Development Department.

Program V-6 California Department of Transportation and Transportation Corridor
Agency:

Work closely and coordinate with the California Department of Transportation (Caltrans) and the Transportation Corridor Agency (TCA) on all plans, activities, and projects that may affect state roadway facilities or transportation corridors passing through Orange. Additionally, work with these agencies to achieve the following objectives:

- Provide appropriate screening to control the visual impacts of transportation facilities.
- Provide landscaping within transportation facilities.
- Study the potential for a future interchange at State Route 55 and Meats Avenue.
- Determine the feasibility of conversion or joint use of surplus or otherwise underutilized lands under Caltrans or TCA control for open space.
- Plan for noise abatement along freeways and highways.
- Install, maintain, and update freeway and highway right-of-way buffers and soundwalls.
- Provide adequate visual buffers such as berms or landscaping between freeways and railways and adjacent land uses.”

Time Frame: Ongoing; Funding: General Fund, gas tax funds; Personnel: Public Works Department, Community Development Department.

Yountville 2015:

“Policy C 1.3 The Town’s current operating standards call to maintain all street intersections at a level of service “C” or better. Consider replacement of vehicle Level of Service standards for traffic conditions in Yountville with Vehicle Miles Traveled (VMT) or other recommended metrics once Senate Bill 743 is implemented.” Timeline: None; Funding: None; Personnel: None.

ZEV Implementation Evaluation

This section research reviews 1) where CAPs have been created in relation to socioeconomic and geography to understand community characteristics in creating CAPs, 2) where CAPs and general plans address ZEV readiness.

Methods

Socioeconomic data were collected from the 2020 Census and aggregated with data from the 2014-2019 American Community Survey. Census tracts were aggregated to the city level. To address whether or not jurisdictional socioeconomic status and geography influence the adoption of a CAP, we used multivariate logistic regression to assess associations between CAPs, total population, median household income, and percent white population.

To understand plan mentions, policy strength and implementation, we combined city-level plan scores and term mentions with the prevalence of EV charging stations from the federal EV charging station database, which includes 15,688 station locations and 45,891 Electric vehicle supply equipment (EVSE) charging ports for California. Data were downloaded on Nov 13, 2023. We did not use the California Energy Commission data on 87,707 public and private EVSE because this data is only available at the county-level and not the city-level. An EVSE port provides power to charge one vehicle at a time. Based on federal data, there are 14,200 charging stations within California cities, and 1,964 charging stations outside of city jurisdictions on county land.

We used ordinary least squares (OLS) multivariate regression models. To understand the influence that jurisdictions have on neighboring jurisdictions' likelihood of having a CAP and on the number of EVSE charging ports, we used the spectral normalization weighting matrix. Because California cities are spatially clustered around two main areas (the Bay Area and the Los Angeles region), we employed Moran's I to assess if the errors were spatially correlated as a post-estimation test for each of our adjusted regression models. Where spatial autocorrelation was present, we fit generalized spatial two-stage least-squares autoregressive (GS2SLS) models with spatial lags on the dependent variables. Our data analyses were conducted using the logistic, regress, estat moran, spatbinary, spregress, and estat impact commands in STATA/BE version 18 (SataCorp, 2023).

Limitations

More recent plans are more likely to have ZEV-related policies. Further, a county may have strong ZEV policies that benefit a city without such policies, leading to temporal and spatial mismatch.

Cities with a CAP and ZEV implementation

We found no association between a city having a CAP and the city's population size (Figure 2). Whether or not a city has a CAP was not significantly associated with total population, median household income, or the percent of the population identifying as white. This finding aligns with a similar study conducted by Bery et al., 2022, which found that “only two factors—(a) city staff dedicated to environmental/energy policy and (b) the presence of an institution of higher education—had statistically significant effects on the level of ambition of a city's climate action plan.”

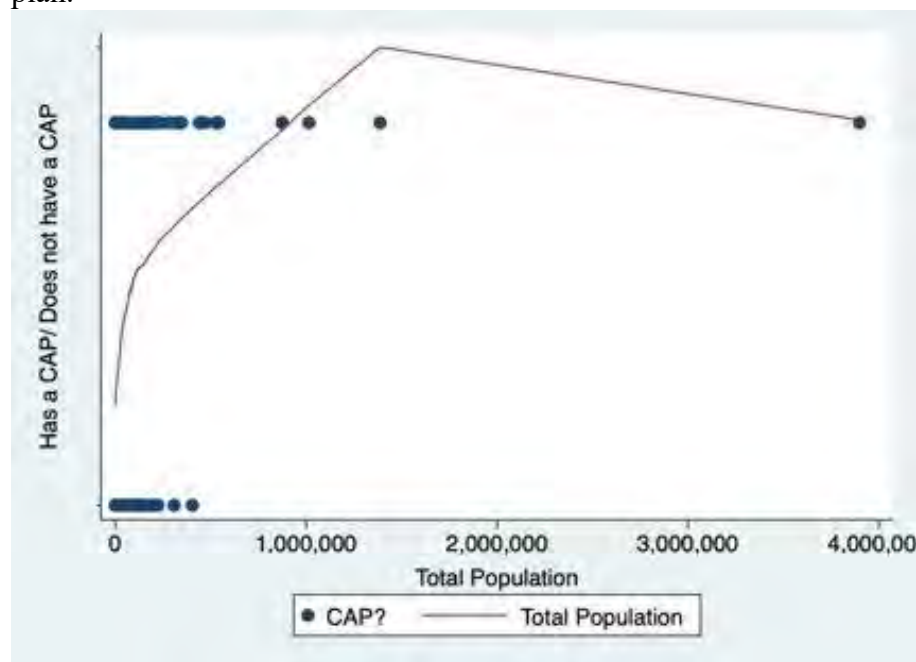


Figure 2. A scatter plot graph of a logistic regression displaying data points plotted on a scatter graph depicting the relationship between a city adopting a CAP and a city's total population size.

Planning and siting EV charging ports

We find that ESVE charging ports are not randomly distributed across cities in California. The number of ESVE charging ports was significantly associated with whether or not a city had a CAP ($B = 30.05$; 95% CI = 9.87, 50.23; $p = .004$) when controlling for percent white population and median household income. For every city with a CAP, we can expect an increase of 30 ESVE ports compared to cities without a CAP.

Moran's I revealed significant evidence of spatial autocorrelation ($p < .001$), indicating the the need for a spatial regression model. Spatial regression results were similar to the linear regression results in showing a positive, statistically significant relationship between having a CAP and implementing more ESVE charging posts ($B = 19.5$; 95% CI = .60, 38.48; $p = .04$). There was also a significant positive correlation between the number of ESVE charging ports in

one city and the number of ESVE charging ports in a neighboring city ($B = .07$; 95% CI = .02, .12; $p = .01$).

We also find a significant positive association between ESVE charging ports and EV mentions in CAPs ($B = .68$; 95% CI = .05, 1.31; $p = .04$). Thus, the more a plan addresses the topic of ZEV readiness, the greater the likelihood of implementation outside of the plan. For every mention of “electric vehicle” in a CAP, we can expect an increase of nearly 1 charging port. Again, Moran’s I revealed significant evidence of spatial autocorrelation ($p < .001$). As with the linear regression model, spatial regression results were similar and significant ($B = .61$; 95% CI = .02, 1.20; $p = .04$). Further, there was a significant positive correlation between ESVE charging port numbers in one city and ESVE charging port numbers in neighboring cities.

As a point-in-time measurement, these results do not indicate whether jurisdictions with more ESVE ports are more likely to create a CAP or whether the CAP resulted in more ESVE charging ports being sited. Causality aside, the results do underscore the correlation between creating a CAP, addressing ZEV readiness, and siting ESVE charging stations.

Summary comparison with municipal reach codes

To understand if plans and policies correlated with actions in municipal codes, the research team explored a subset of terms in plans, overall policy scores, and the presence of municipal reach codes.

Table 4. This table compares term mentions related to ZEV adoption across city-level CAP and General Plans. Note: 56 cities (11%) adopted reach codes for “Electric Vehicle Ordinances” in 2019 and 2022 according to the Statewide Reach Codes Program

	Alternative Fuel	Electric Vehicle	Zero-Emission Vehicle (ZEV)	Plug-In Electric Vehicle (PEV)	Battery-Electric Vehicle (BEV)	Plug-In Electric Hybrid Vehicle (PHEV)
CAP (of 231)	76%	92%	50%	26%	18%	0%
General plan (of 482)	35%	26%	1%	0%	0%	0%

Table 5. This table compares term mentions for decarbonization across city-level CAP and General Plans. For reference, 73 cities (15%) adopted reach codes for “energy efficiency” + “all electric” during the 2019 and 2022 cycles according to the Statewide Reach Codes Program

	Decarbonization	Heat pump	Solar	Reach code	Energy	Energy storage	Energy efficiency	Microgrid	Carbon neutral	Green building
CAP (of 231)	20%	32%	99%	25%	100%	36%	98%	19%	40%	96%
General plan (of 482)	0%	2%	91%	1%	100%	2%	91%	1%	2%	78%

Table 6. This table compares term mentions for VMT reduction across city-level CAP and General Plans. There are no commiserate VMT-related reach codes for municipal code comparison.

	Vehicle miles traveled	Compact development
CAP (of 231)	95%	21%
General Plan (of 482)	49%	37%

To understand how planning for one policy objective is related to planning for others, we use correlation of term mentions and plan scores. Correlation indicates the relationship of two variables whenever one variable changes. If an increase in one variable results in an increase in the other variable, both variables are said to have a positive correlation. A perfect positive correlation is equal to “1”, while no correlation is equal to “0” and a perfect negative correlation is equal to “-1”.

We find that the number of mentions of “electric vehicle” in county General Plans did not correlate with policy score strength (Pearsson product correlation: -0.01). Thus, the number of times a plan mentions EV does not neatly correlate to the strength of EV policies within the county plan. Similarly, the number of mentions of “electric vehicle” in city General Plans did not

correlate with policy strength in city plans (Pearsson product correlation: 0.08) nor the presence of a municipal reach code for electric vehicle ordinances (Pearsson product correlation: 0.07).

Similarly, we find no correlations between the number of mentions of the term “energy” and the strength of policies that support decarbonization. The number of mentions of “energy” in county General Plans weakly correlated with policy score strength for decarbonization (Pearsson product correlation: 0.048). At the city level, the number of mentions of “energy” did not correlate with the presence of reach codes for Energy Efficiency of “All Electric ordinances” according to the 2019 & 2022) (Pearson product correlation: -0.01).

In planning for VMT, we also found little correlation between the number of times a term was mentioned and the strength of policies within the plans. The number of mentions of “vehicle miles traveled” in county General Plans weakly correlated with policy score strength for VMT (Pearsson product correlation: 0.42), but no relationship was found at the city-level which includes a larger sample size (Pearsson product correlation: 0.34)

Nor did term mention or scores correlate across terms. In other words, a jurisdiction may mention a term often, but that does not correlate with strong policies that would score highly. Further, a jurisdiction may mention or craft strong policies in one domain (such as ZEV), but that does not correlate with similar attention in other domains (such as reducing VMT).

Climate readiness workshop feedback

CBOs conducted 13 workshops on climate readiness planning from October 2023 through April 2024. Across the 13 workshops, there was a combined attendance of 367 attendees representing over 155 organizations.

Please see below for a list of selected attendee organizations in alphabetical order:

Aequor Solutions - American Federation of Teachers - Bay Conservation and Development Commission - Belle Haven Community Development Fund - Belle Haven Empowered - Breakthrough Communities Institute - Black & Veatch - BlueSphere Partners - Building Decarbonization Coalition - Burbank Water & Power - CA State Assembly - CAC - Cal Poly - Cal Trans - California Coastal Commission - CARB - Catalyst SD - CCL - Center for Energy Efficiency - Center for Policy Initiatives - City Heights CDC - City of Alhambra - City of Beaumont - City of Chico - City of Encinitas - City of Gardena - City of Irvine - City of La Mesa - City of Long Beach Department of Health and Human Services - City of Los Angeles - City of Los Angeles, Department of City Planning - City of Los Angeles, Department of Transportation - City of Los Angeles, General Services Department - City of Los Angeles, LA Sanitation & Environment - City of Malibu - City of Oceanside - City of Pico Rivera - City of Pomona - City of Redlands - City of San Francisco - City of San Leandro - City of Santa Monica - City of San Rafael - City of West Hollywood - Clean Power Alliance - Climate Action Campaign - Climate Reality Project - Climate Resolve - Climate Resilient Communities - Coalition for Earth Justice - Coastal Hazards Adaptation Resiliency Group - Community Action for a Sustainable Alameda - Community Agency for Resources and Services (CARAS) - CORE Response - Council for Watershed Health - County of San Mateo - County of Santa Clara - County of San Diego - County of Santa Barbara - CPUC - Cumming Group - County of Marin - East Bay Municipal Utilities District (EBMUD) - Encino Conservancy - Energy Coalition - ESA - evolveEA - Fehr

& Peers - FFF OC - Fridays for Future OC - Friends of Ballona Wetlands - Great Basin Bakery - Green New Deal Alliance - In Good Company - Interfaith - Karuk Tribe - LA Cleantech Incubator - LA County - LA Metro - LACP - LADOT - LADPH - LADWP - Los Angeles County - Los Angeles Regional Collaborative for Climate Action and Sustainability - Marin City Climate Resilience - Metropolitan Transportation Commission - Move LA - MPNA - Mt. Shasta Mountain - Mycelium Youth Network - National Oceanic and Atmospheric Administration (NOAA) - Nevada County - Ninth Root - NRDC - Nuestra Casa - Pathways Climate Institute - Placer County - Policy Studio - Raimi + Associates - RAND - Redwood Energy - Reform and Sustain - Retired from Los Angeles County Sheriff's Department - Renewable Technologies - Rhie Planning LLC - Rincon - San Diego Regional Climate Collaborative - San Diego State University Center for Environmental Justice and Sustainability - San Diego Urban Sustainability Collaborative - San Francisco Bay Area Planning and Urban Research Association (SPUR) - San Francisco Estuary Institute - San Francisco International Airport - Save the Bay - SCAG - SCEDD - Scripps Institution of Oceanography - SD350 - Sierra Club - Siskiyou County - Siskiyou Outdoor Alliance - SoCal Edison - Solano County - Sonoma County Regional Climate Protection Authority - Student Conservation Association - Sustainable Solano - Sunrise Movement OC - Surfrider - Sustainable Ramona - The Catalyst Group - The Climate Registry - The Collective Identity Mentoring - The Educator Collective for Environmental Justice - The Energy Coalition - The Sohagi Law Group, PLC - The Tenacious Group - Three Valleys Municipal Water District - Thrive Alliance - Town of Corte Madera - Town of Truckee - Trinity County - TRPA - UC Davis Center for Regional Change - UCLA - UCLA Luskin Center for Innovation - UCLA Sustainability - UN Association OC - Urban Collaborative Project - USC Sea Grant - USGBC-LA - Valley Transportation Authority - Veterans for Peace - Wellbeing Economy Alliance – Willdan

Table 7. CBO climate readiness workshop attendees by organizational representation

Organization type	Percentage
Government	42%
Nonprofits	44%
Industry	13%
Tribes	1%

CBOs expertly managed attendee lists for the workshops. For example, to create a collaborative learning and sharing environment, a nonprofit might attend one workshop while the utility company would be invited to a separate workshop. Workshops were primarily attended by local nonprofits and local government staff. CBOs reported a focus on building long-term relationships with career staff in local jurisdictions to promote institutionalized change that would extend beyond those holding elected office. Workshops also included tribal representation and were attended by industry representatives (13%), including planning firms. Overall, CBOs reported that virtual meetings have proven effective, drawing participants from various counties across the state. Further, CARB's role as an invited and attentive listener in select workshops was reported as valued and advantageous. Local communities reported feeling acknowledged when the agency actively participates, and they requested future opportunities for CARB to attend and listen, noting that it was a *“good look for CARB”* and local communities feel heard when *“CARB comes to us.”*

Additionally, CBOs expertly juggled messaging strategies. While CARB’s motivational framing, particularly GHG reduction, resonates with some communities, it fails to strike a chord with others. Notably, the 280-page 2022 Scoping Plan, references "rural" nine times without offering specific actions for these areas, such as low population exemptions for SB 1232 food waste collection. Motivations for climate action vary significantly across communities, including considerations of financial benefits, clean air and water, and local power and ownership, as seen with Community Choice Aggregation (CCA) programs. However, concepts like VMT are unfamiliar or carry negative connotations due to concerns around mileage taxes, or dependence on gas tax funding, in certain regions. To address these disparities, it is recommended to continue collaborating with CBOs to align state goals with locally valued approaches. As one CBO noted, *“there are other needs of greater importance in many communities right now (health care access, poverty, wildfire threat), and understanding rural needs will be crucial in having the state's climate goals adopted.”* Thus, not only will CARB’s desired policies need to be reframed in local values for adoption and implementation, but those priorities will also need to be aligned with local priorities to even be considered in policy making circles.

Barriers to success

CBO Quote, *“A significant barrier is access to funding and grant opportunities - either due to a lack of capacity or knowledge about these opportunities.”*

While workshops offered opportunities to showcase new funding and tools, they also hosted conversations about the various approaches that local public and private agencies were taking toward climate readiness. Funding was consistently reported as a general barrier to climate action implementation across local governments. In part, some of the funding limitations related to technical assistance. For example, CBOs frequently face inquiries that fall within the state's purview, such as equitable access to funding and transparency in allocation. Similarly, CBOs request the state create and support a standardized GHG inventory methodology and as well as analysis for each jurisdiction. It is worth noting that a bill that would have provided funding for this (SB 511) was not ultimately adopted by the legislature last year.

CBOs also highlighted the importance of recognizing that rural areas, while they may not always meet criteria for Disadvantaged Community (DAC) status or diversity requirements, present distinct challenges that warrant consideration. Despite not fitting traditional metrics, rural regions often have significant populations of BIPOC individuals, lower median household incomes, and face high costs of living. Further, rural regions often advocated for geographic equity over population-based metrics to rectify historical injustices. This approach would celebrate city- and county-level advances instead of weighting results by population. Such approaches may require different funding efforts that are more focused on landscape-level treatments, such as carbon sequestration credits for forest management. Staggered compliance requirement timelines were also mentioned as a way to support policy transfer from early adopted jurisdictions that have piloted new technologies or policies to success.

Further, attendees expressed a desire for state agencies to provide assistance with grant writing and to reduce the burdensome requirements for grant acceptance. For example, CBOs suggested

that when a community-generated plan promised a strong focus on ZEV-readiness, the state could award such policies with non-competitive, automated ZEV funding. These non-competitive funding opportunities could help reduce the amount of effort needed to search and apply for grants. In addition, reading and rewarding promising plans and policies would close the loop on local-to-state policy coordination. As one CBO also reported, there are “*constricted grant funding timelines for implementation [that are] not aligning with time needed to build local relationships and capacity.*” If already existing local relationships and capacity is what is ultimately rewarded, then the state could use planning documents like CAPs and the General Plan to award partnerships and planned programs toward faster implementation.

Moreover, attendees also highlighted an important consideration: certain communities face deficiencies in funding for planning, while others encounter challenges in securing funding for implementation. CBOs stressed the importance of funding for community-driven design to result in plans and policies with wide public buy-in. Oversubscribed grant programs do not provide CBOs with enough capacity to engage in these important processes. When querying their partners, a CBO contracted through this project reported, “*funding was by far the most common answer*” to barriers to implementation. Despite excitement about new funding opportunities, partners expressed concern over the posed challenges of grantees' requirements in applying for funding, particularly funding restrictions based on the source of funds.

Recommendations

CBOs recommend several strategies for state agencies to improve funding access and support for local governments and organizations. First, they suggest establishing a state agency liaison to facilitate direct communication and engagement with counties and cities. It is also essential for state representatives to meet local entities in their communities, reducing the need for them to travel to the state capitol. Simplifying language and minimizing technical jargon can enhance accessibility and engagement, ensuring that barriers are not created from the outset.

Collaboration among state and regional agencies is crucial to streamline requests and avoid overwhelming local governments and CBOs with individual requests. Moreover, providing comprehensive support such as training, materials, equipment assistance, and letters of support can bolster their capacity. Strategies aimed at reducing bureaucratic hurdles in funding acquisition are essential, alongside facilitating connections to relevant resources, funding opportunities, and continuing with capacity-building initiatives. Further, collaborating with individual communities to pinpoint their specific needs and offering customized assistance will lead to optimal solutions for overcoming these barriers. As a CBO noted when asked about what would be most helpful for spurring climate readiness planning and implementation: “*lead regional collaboration and conversations in this space so we can be better coordinated in our approach and go after funding.*” A recommendation emerged to sustain and nurture relationships beyond the current contract.

Recommendations from CBOs also focus on methods. Regarding methods, there is a call to account for ecosystem services in the next update of the scoping plan, allowing for the crediting of natural and working land management practices toward local mitigation mandates. For instance, there is an ongoing pilot approach with tribes, demonstrating the potential effectiveness

of this strategy. Outreach and engagement efforts should continue to ensure that marginalized communities have decision-making power while offering support both financial and technical. To this end, CBOs noted that state agencies can bolster CBO actions by encouraging local governments to actively involve CBOs in the development of CAPs and General Plans, facilitating accessibility to documents for public input. This access and input has the added advantage of helping to validate climate data analysis with lived experiences to inform social vulnerability mitigations and resource allocation. One CBO called attention to the California Strategic Growth Council Regional Climate Collaborative (CA SGC RCC): *“The CA SGC RCC grant program would be a place the state could increase investment in, as for two years programs have organized structures to propose to this program that achieve goal, but the grant program is oversubscribed with only 6 awards last year and a similar number anticipated for this year.”* When communicating with the public, rather than inundating them with hard data, it is beneficial to guide them through the rationale of how these measures impact their daily lives. As one CBO reported: *“oftentimes communities don't know about the options available to them - it is the responsibility of the state/local government to provide these options, make technical info more accessible, and take the communities input and interpret it into policy actions.”* Another CBO concluded: *“By taking proactive steps and engaging with stakeholders, regional agencies can help address these challenges and create a more sustainable and equitable energy future for all.”*

In addition, CBOs advocate for various climate readiness approaches, distinguishing between CAPs and General Plans. General plans are commonly utilized in rural areas, while CAPs are high-visibility documents. Safety and hazard mitigation plans are typically revised for Federal Emergency Management Agency (FEMA) compliance, also making them optimal avenues for engagement.

CBOs also seek various forms of support. They desire research assistance, including both quantitative and qualitative analysis of General Plans and CAPs. They note a scarcity of California Environmental Quality Act (CEQA) certified CAPs and lack of standardized formats for both CAPs and General Plans. Additionally, there is a need for cover pages outlining zero emissions timelines, such as by 2040 or 2050.

CBOs also emphasized the need for free, automated, standardized GHG inventories, as well as planning templates and Environmental Justice (EJ) element templates. Some CBOs already work with local jurisdictions to provide GHG inventories. CBOs noted that inventories would need to be tailored to each jurisdiction, and that help from CARB would entail CBOs assisting local jurisdictions with data gathering and review of a standardized output from a state agency. To provide such GHG inventories free of cost to all local governments, a legislative appropriation or philanthropy would need to support CBO and state involvement. Notably, a Senate Bill proposed in 2023 (SB 511) would have appropriated funding to CARB to assist with preparing GHG inventories. This bill was not ultimately adopted by the legislature.

CBOs also advocate for more opportunities to provide feedback to CARB and to facilitate small, local gatherings to foster community relationships. To meet these needs, one CBO recommended that state agencies, *“hire full-time staff dedicated to integrating and communicating with coalition networks across communities.”*

The feedback from CBOs encompasses both community aspirations and the challenges encountered by local governments in implementing decarbonization, reducing VMT, and promoting ZEVs. Reflections underscore the importance of addressing barriers to effective climate action at the local level. Moreover, the feedback outlines possible next steps for achieving community goals, emphasizing the need for coordinated support from state agencies. By identifying ways to overcome obstacles and providing tailored assistance, state agencies can play a pivotal role in empowering local governments and CBOs to drive meaningful progress in equitably addressing climate change within their communities.

Discussion

Communities spend many years assembling plans. Many years can also pass where plans are under review before being adopted. The resulting, varied, and slow-moving timelines mean that community-level goal-setting dialogues may run in tandem with policy action and well before a plan is adopted and in place. To improve upon this process, this contract created climate readiness tools and presentations for community groups across California in relation to three CARB climate readiness priorities: Zero Emission Vehicle (ZEV) uptake, reducing Vehicle Miles Traveled (VMT), and decarbonization. These deliverables were designed to help communities learn from each other about the many approaches to improving climate readiness while reducing the level of effort needed for future plan updates.

Given limited time and resources, our findings could help guide local jurisdictions and the state in considering policy avenues. Our finding that the population size of the city does not correlate with creating a CAP runs counter to many policy discussions that consider CAPs the product of large, well-funded cities. For example, An et al., (2022) asserted that larger cities are more likely to adopt CAPs than smaller cities. An et al. (2022) found that 49 cities among 190 cities within the five county Southern California Region adopted climate action plans (CAPs) from 2000 to 2018. This data compares to that in our CAP database in that we show 98 city-level CAPs, with 66 adopted in the same region between the same time period of 2000 to 2018. In working with a more comprehensive dataset, we are better positioned to provide more accurate results. In explanation, An et al. (2022) drew data from a state-level CAP-Map portal that is out of date and labels some jurisdictions as having a CAP though the reference policies are actually found in municipal code or the general plan. Such discrepancies in findings highlight the need for high fidelity, public-facing, accurate planning data. Easy access to plans and policy can improve uptake of promising approaches.

This is precisely the data infrastructure built through this contract. With PlanSearch and the CAP portal, the public can also more easily research planning approaches—learning from the advances of their neighbors. One drawback to such tools is the steep learning curve for public involvement. For example, many people will not know what a heat pump or a microgrid is. Nor will the public know which plans or municipal codes are appropriate for addressing various

topics. By way of example, we note that, in general, energy planning is under-represented in General Plans and CAPs. Only three counties mention “heat pump” in their General Plans. The public might not recognize heat pump programs as decarbonization or energy policy. Further, CBOs explain the lack of plan emphasis on decarbonization by calling attention to the role of Municipal Building and Reach Codes that are more commonly used to regulate individual buildings. Thus, while CAPs and General Plans contain many policies, they may not present an accurate reflection of *all* policies. Our review of municipal reach codes in relation to terminology in General Plans and CAPs helps highlight where various local policy documents crosstalk, and where there will be gaps in assessing local action.

In part, some gaps in policy coverage are the result of a lack of coordination. For example, CBOs note that the state regulatory framework in California does not financially encourage local responsibility for clean energy distribution, an important topic for decarbonization. To help open additional opportunities for local decarbonization planning, state agencies may reconsider the financial implications of enabling local clean energy production, storage, and distribution as well as the rate at which utilities would reimburse neighborhoods and cities for low-carbon electricity contributed to the grid. Such conversations will take coordination, and CBOs are well positioned as trusted conveners.

Summary and Conclusion

We find that communities are choosing to address climate policies in different planning vehicles, perhaps due to timing of policy windows and perhaps due to planning capacity. We also find that the language used in state goal-setting documents is often discordant with both research and local policy action. For example, the term “decarbonization” occurs in only one city-level and one-county level general plan though this term is well-represented in research and state policy. In part, varied language choice is a byproduct of the rapidly evolving landscape of climate readiness. As previous data infrastructure products, like CapMAP have demonstrated, pre-coding of policies is both labor-intensive and will not generate an accurate reflection of planned actions. Similarly, one-size-fits-all state-level recommendations often fail to resonate across the geographically, politically, and socially varied state. Instead, CBOs emphasize the need for peer-to-peer, regionally specific collaboration to advance climate readiness planning at the local level.

To foster immediate, real-time planning advances for equitable climate readiness, there is a great need for public, transparent data. Local jurisdictions often operate with few staff and limited time for information-seeking. We recommend that the state better support local planning with greater access to aggregated public data. For example, state level EV charging station data is only available at the county-level. Offering more fine-grained analysis at the city-level for the public, local staff, or CBOs would allow local municipalities to better mark progress and urge action. Similarly, though plans are required to be publicly available, they are often sequestered on individual jurisdictional websites, difficult to find, and difficult to understand. Creating more

standardized language in more accessible plans would facilitate finding examples for local planning boards to consider.

The lack of Findable, Accessible, Interoperable, and Reusable data guidelines for land-use plans, incomplete compliance with existing mandates and guidance, and variation in structure and formatting of General Plans and CAPs creates particular challenges to designing data infrastructure. This contract has overcome some of these obstacles, with the notable benefit of the PlanSearch tool winning the 2023 California American Planning Association Award for Excellence. To maintain and expand these early efforts, we recommend the state provide guidance or regulation on the accessibility of plans (standardized formatting available in machine readable PDFs available at local government websites). This guidance could come from LCI in the next General Plan Guideline update and be reiterated by additional state agencies.

Encouraging that plans be published in machine-readable formats (such as computer-generated or OCR-readable PDFs) and that images be described with machine-readable tags would help to support text extraction and search while also bringing plans into compliance with ADA. With better formatting and data storage protocols, updates to a plan database could be automated, for example with an API that notifies database coordinators when a new plan is submitted for state agency review. CBOs involved with climate readiness planning also note a desire for a standardized GHG inventory methodology to galvanize action and simplify the planning process.

Practically, new data tools open opportunities for greater plan coordination. Additional roles need to be supported with new enabling legislature and funding. For example, we encourage the consideration of new legislation that requires local jurisdictions to report when individual elements and General Plans are updated and submit adopted documents to a central agency. The agency could scan such documents to ensure that mandates were achieved. These concerns will be of interest to multiple state agencies and could reduce staff time elsewhere spent searching for documents. For example, in reporting on meeting EJ mandates, the Attorney General could note how disadvantaged communities were defined, identified, and mapped, as well as cross-reference which goals and policies are EJ-related.

By making planning more transparent, it will be important not to lose sight of the rationale for mandates or the value of local efforts that feed into the planning process and implementation. “Plug and play” cover forms that are easy to fill out or prefilled will simplify plan updates and strengthen community involvement by facilitating the use of common language aligned with desirable state policies. Such forms would enable better indexing of plans and comparison of policies, thereby helping local communities to explore promising policies that community members support. At the same time, it is also important to allow plans to use a format that is flexible enough to incorporate unique and valuable insights that will be useful to local communities.

References

- Bery, S., & Haddad, M. A. (2023). Walking the Talk: Why Cities Adopt Ambitious Climate Action Plans. *Urban Affairs Review*, 59(5), 1385-1407.
<https://doi.org/10.1177/10780874221098951>
- Mui, Y., Khojasteh, M., Judelsohn, A., Sirwatka, A., Kelly, S., Gooch, P., & Raja, S. (2021). Planning for regional food equity. *Journal of the American Planning Association*, 87(3), 354-369.
- Grafakos, S., Viero, G., Reckien, D., Trigg, K., Viguie, V., Sudmant, A., ... & Dawson, R. (2020). Integration of mitigation and adaptation in urban climate change action plans in Europe: A systematic assessment. *Renewable and Sustainable Energy Reviews*, 121, 109623.
- Reckien, D., Flacke, J., Dawson, R. J., Heidrich, O., Olazabal, M., Foley, A., ... & Pietrapertosa, F. (2014). Climate change response in Europe: what's the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries. *Climatic change*, 122(1), 331-340.
- Campagna, M., & Craglia, M. (2012). The socioeconomic impact of the spatial data infrastructure of Lombardy. *Environment and Planning B: Planning and Design*, 39(6), 1069-1083.
- Berke, Philip, and David Godschalk. 2009. "Searching for the Good Plan: A Meta-Analysis of Plan Quality Studies." *Journal of Planning Literature* 23 (3): 227-40.
<https://doi.org/10.1177/0885412208327014>.
- Braunschweig, Katrin, Julian Eberius, Maik Thiele, and Wolfgang Lehner. 2012. "The State of Open Data Limits of Current Open Data Platforms."
- Bronin, Sara C. 2021a. "Zoning by a Thousand Cuts: The Prevalence and Nature of Incremental Regulatory Constraints on Housing." *SSRN Electronic Journal*, February. Elsevier BV.
doi:10.2139/SSRN.3792544.
- Bronin, Sara. 2021b. "Testimony on SB 1024."
[https://www.cga.ct.gov/2021/pddata/tmy/2021SB-01024-R000315-Bronin, Sara, Lead Organizer-DeSegregate CT-1024 Support-TMY.PDF](https://www.cga.ct.gov/2021/pddata/tmy/2021SB-01024-R000315-Bronin,%20Sara,%20Lead%20Organizer-DeSegregate%20CT-1024%20Support-TMY.PDF).
- Campbell, Tim. 2009. "Learning Cities: Knowledge, Capacity and Competitiveness." *Habitat International* 33 (2). Pergamon: 195-201. doi:10.1016/J.HABITATINT.2008.10.012.
- Campbell, Tim. 2012. *Beyond Smart Cities: How Cities Network, Learn and Innovate*. 1st edition. Abingdon, Oxon ; New York, NY: Routledge.
- CARB. 2005. "Air Quality and Land Use Handbook: A Community Health Perspective." California Environmental Protection Agency California Air Resources Board. www.aqmd.gov.

CEJA. 2021. "SB 1000 Toolkit: Planning for Healthy Communities" California Environmental Justice Alliance. Accessed September 9. <https://caleja.org/2017/09/sb-1000-toolkit-release/>.

Chen, Y., Sabri, S., Rajabifard, A., Agunbiade, M. E., Kalantari, M., & Amirebrahimi, S. (2020). The design and practice of a semantic-enabled urban analytics data infrastructure. *Computers, Environment and Urban Systems*, 81, 101484.

Coleman, Miles. 2008. "Banning the Flames: Constitutionality, Preemption, and Local Smoking Ordinances." *South Carolina Law Review* 59 (3). <https://scholarcommons.sc.edu/sclr/vol59/iss3/4>.

Colpaert, Pieter and Joye, Sarah and Mechant, Peter and Mannens, Erik and Van de Walle, Rik. 2013. "The 5 Stars of Open Data Portals." In *7th International Conference on Methodologies, Technologies and Tools Enabling e-Government, Proceedings*, edited by Álvarez Sabucedo, Luis and Anido Rifón, Luis, 61–67. Universida de Vigo.

Corburn, Jason. 2009. "Toward the Healthy City : People, Places, and the Politics of Urban Planning." MIT Press, 282.

Corburn, Jason, Shasa Curl, Gabino Arredondo, and Jonathan Malagon. 2014. "Health in All Urban Policy: City Services through the Prism of Health." *Journal of Urban Health : Bulletin of the New York Academy of Medicine* 91 (4). Springer: 623. doi:10.1007/S11524-014-9886-3.

Cumbers, Andrew, and Danny McKinnon. 2009. *Clusters in Urban and Regional Development*. Routledge.

Duane, Daniel. 2020. "San Francisco Was Uniquely Prepared for Covid-19 | WIRED." August 11, 2020. <https://www.wired.com/story/san-francisco-uniquely-prepared-covid-19/>.

Elkins, Z., & Ginsburg, T. (2005). Comparative constitutions project. <https://comparativeconstitutionsproject.org/> accessed Dec 31, 2021

Elkins, Zachary; Ginsburg, Tom; Melton, James. 2018. "Constitute: Constitutional text for scholars and drafters". Qualitative Data Repository. <https://doi.org/10.5064/F6TD9V7G>. QDR Main Collection. V1

European Commission. n.d. Smart Cities—Smart Living. Available from: <https://ec.europa.eu/digital-single-market/en/smart-cities> [Accessed 20 April 2020].

Fulton, William B., and Paul. Shigley. 2012. "Guide to California Planning." Solano Press Books, 505.

Hall, Peter. 1982. "Great Planning Disasters." University of California Press, 308.

Haupt, Wolfgang, Lorenzo Chelleri, Sebastiaan van Herk, and Chris Zevenbergen. 2020. "City-to-City Learning within Climate City Networks: Definition, Significance, and Challenges from a Global Perspective." *International Journal of Urban Sustainable Development* 12 (2): 143–59. <https://doi.org/10.1080/19463138.2019.1691007>.

- HCD. 2021a. “HCD Building Blocks.” California Department of Housing and Community Development. Accessed September 9. <https://www.hcd.ca.gov/community-development/building-blocks/index.shtml>.
- HCD. 2021b. “Housing Elements.” Accessed September 9. <https://www.hcd.ca.gov/community-development/housing-element/>.
- Healey, Patsy. 2013. “Circuits of Knowledge and Techniques: The Transnational Flow of Planning Ideas and Practices.” *International Journal of Urban and Regional Research* 37 (5).
- Hensel, Anna. 2016. “How the World’s Most Cutting-Edge Cities Balance Growth and Innovation.” *Inc.Com*. April 26, 2016. <https://www.inc.com/anna-hensel/lessons-from-most-innovative-cities.html>.
- Hoyt, Lorraine. 2006. “Importing Ideas: The Transnational Transfer of Urban Revitalization Policy.” *International Journal of Public Administration* 29 (1–3): 221–43. <https://doi.org/10.1080/01900690500409096>.
- Kim, H. M., Sabri, S., & Kent, A. (2021). Smart cities as a platform for technological and social innovation in productivity, sustainability, and livability: A conceptual framework. In *Smart Cities for Technological and Social Innovation* (pp. 9-28). Academic Press.
- Kitchin R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*. 79:1–14.
- Kontokosta, Constantine E. 2018. “Urban Informatics in the Science and Practice of Planning.” *Journal of Planning Education and Research*. SAGE Publications Inc. doi:10.1177/0739456X18793716.
- McFarlane, Colin. 2011. *Learning the City*. 1st edition. Malden, MA: Wiley-Blackwell.
- Moser, Caroline, James Pickett, and Pamela Sparr. 2007. “Cutting-Edge Development Issues for INGOs: Applications of an Asset Accumulation Approach.” *Asset Debate Paper*. Brookings Global Economy of Development. https://www.brookings.edu/wp-content/uploads/2016/06/200707INGO_moser.pdf. accessed Dec 31, 2021
- MitigateNY, 2021 (<https://mitigateny.availabs.org/>) accessed Dec 31, 2021
- Municode. 2021. “Municode Home Page.” Municode - Powered by CivicPlus. 2021. <https://www.municode.com/home>.
- Open Knowledge Foundation. 2005. “The Open Definition—Defining Open in Open Data, Open Content and Open Knowledge.” <https://opendefinition.org/>. accessed Dec 31, 2021
- LCI. 2020. “2020 Annual Planning Survey Report.” Governor’s Office of Planning and Research. www.opr.ca.gov.
- LCI. 2021a. “Annual Planning Survey.” Governor’s Office of Planning and Research. <https://opr.ca.gov/publications.html>.

LCI. 2021b. “General Plan Guidelines and Technical Advisories.” Governor’s Office of Planning and Research. Accessed September 9, 2021. <https://opr.ca.gov/planning/general-plan/guidelines.html>.

Palm, Matthew, and Deb Niemeier. 2017. “Achieving Regional Housing Planning Objectives: Directing Affordable Housing to Jobs-Rich Neighborhoods in the San Francisco Bay Area.” *Journal of the American Planning Association* 83 (4): 377–88. <https://doi.org/10.1080/01944363.2017.1368410>.

Raye, Reginald. 2014. “Fifteen Cutting Edge Strategies for Sustainable Urban Development.” January 21, 2014. <https://www.triplepundit.com/story/2014/fifteen-cutting-edge-strategies-sustainable-urban-development/46586>.

Reckien, D., Salvia, M., Heidrich, O., Church, J. M., Pietrapertosa, F., de Gregorio-Hurtado, S., ... & Dawson, R. (2018). How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of cleaner production*, 191, 207-219.

Reis, Juan Ribeiro, José Viterbo, and Flavia Bernardini. 2018. “A Rationale for Data Governance as an Approach to Tackle Recurrent Drawbacks in Open Data Portals.” In *Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age*, 1–9. Dg.o ’18. New York, NY, USA: Association for Computing Machinery. <https://doi.org/10.1145/3209281.3209354>.

Rockmore, D. N., Fang, C., Foti, N. J., Ginsburg, T., & Krakauer, D. C. (2018). The cultural evolution of national constitutions. *Journal of the Association for Information Science and Technology*, 69(3), 483-494.

Roggema, Rob. 2021. “Bypassing the Obvious: Implementing Cutting Edge Ideas for Futuring Urban Landscapes.” *Urban and Regional Planning* 6 (1): 1. <https://doi.org/10.11648/j.urp.20210601.11>.

“Southern California Area Government GIS Open Data Portal.” n.d. <https://gisdata-scag.opendata.arcgis.com/>.

Wilkinson, Mark D., Michel Dumontier, IJsbrand Jan Aalbersberg, Gabrielle Appleton, Myles Axton, Arie Baak, Niklas Blomberg, et al. 2016. “The FAIR Guiding Principles for Scientific Data Management and Stewardship.” *Scientific Data* 3 (1): 160018. <https://doi.org/10.1038/sdata.2016.18>.

Wilson, Bev, and Cong Cong. 2021. “Beyond the Supply Side: Use and Impact of Municipal Open Data in the U.S.” *Telematics and Informatics* 58 (May): 101526. <https://doi.org/10.1016/j.tele.2020.101526>.

Appendices

Appendix 1. Literature Review

The overall goal of the below literature reviews is to assess the barriers to creating local climate policies with an emphasis on climate justice. We identify relevant policies in relation to the three priority areas: reducing VMT, ZEV readiness, and building decarbonization. Material from the literature reviews was used to shape informational handouts for use in Capacity Building Workshops.

Zero Emissions Vehicles

- California Code Terms
 - Near-zero-emission vehicles
 - Clean Vehicles
 - Clean transportation
 - Battery
 - Fuel cell
 - Clean burning vehicles
 - Emission controls

- Scientific Scholarly Terms
 - Charging infrastructure
 - Battery
 - Low-carbon transportation
 - ZEV mandates
 - GHG targets
 - ZEV uptake
 - Non-compliance penalties
 - ZEV credits
 - High occupancy vehicle (HOV) lanes
 - Plug-in electric vehicles (PEV)
 - special electricity rates for PEV owners
 - Electrifying public transportation fleets
 - Municipally-owned charging station networks
 - EV car sharing service
 - Parking privileges
 - Fuel cell vehicles
 - ZEV sales target
 - Technology adoption model

Building Decarbonization

- California Code Terms
 - Energy efficiency
 - Green Buildings
 - Low emissions development
 - Near-zero-emission building technologies
 - All-electric buildings
 - Energy storage systems
 - Incentives greenhouse gas emissions reductions
 - Heat pumps
 - Solar thermal systems
 - Advanced energy efficiency systems
 - Solar photovoltaic system
 - Energy storage system
- Scientific Scholarly Terms
 - Insulation
 - Energy-efficient end-use appliances
 - Building thermal properties
 - Less carbon-intensive fuels
 - Hourly service demand
 - Building optimization
 - Decarbonization of electricity supply
 - Building efficiency
 - Building energy codes
 - Retrofitting
 - Energy efficiency gap
 - Embodied energy (energy used to produce materials for a building)
 - Net-zero energy buildings
 - On-site carbon-free renewable energy
 - Off-site carbon-free renewable energy
 - Carbon offsets
 - Electric heat pumps
 - Peak electricity demands
 - Low-carbon heating
 - Dual source systems
 - Alternative fuels
 - Building refurbishment
 - Weatherization
 - Air infiltration/ sealing
 - Energy efficiency standards
 - Water efficient appliances
 - Landscape irrigation
 - Passive solar heating systems
 - Indoor air quality
 - Energy burden

- o Ventilation

Reducing Vehicle Miles Traveled

- California Code Terms
 - o Emissions per-passenger-mile traveled
 - o Average vehicle ridership
 - o Reduce vehicle trips
 - o Transportation control requirements
 - o Vehicle emissions
 - o Vehicle maintenance practices
 - o Clean burning vehicles
 - o Transit system ridership
 - o Transformative capital improvement
- Scientific Scholarly Terms
 - o Work related VMT
 - o Home related VMT
 - o High density development
 - o Micro mobility
 - o Vehicle efficiency standards
 - o Transit investment
 - o Employment density
 - o Pricing policies for driving and parking
 - o Road use fees
 - o Gas tax
 - o Carbon offsets
 - o GHG mitigation
 - o Transportation land use
 - o Ridesharing
 - o Multimodal transportation networks
 - o Traffic congestion
 - o VMT co-benefits
 - o Travel behavior
 - o Average trip length
 - o Pedestrian-friendly design
 - o Non-motorized transportation modes
 - o Smart growth
 - o Transit-oriented development
 - o First mile/ last mile
 - o Private vehicle use
 - o Behavioral mode choice
 - o Coordinated transportation systems

Appendix 1A. Zero Emission Vehicle (ZEV) Readiness

The role of ZEVs in California Climate Policy

ZEV Challenges

With this review on Zero Emission Vehicle (ZEV) readiness, we focus on the state of research and California policy to identify opportunities and barriers for local jurisdictions in California. ZEV readiness includes actions described by the California Air Resource Board's (CARB) ZEV Readiness guidelines,^[1] such as:

- Siting adequate and appropriate refueling infrastructure to meet the jurisdiction's transportation needs for all vehicle classes, including emerging electric mobility.
- Accessible clean mobility transit options, including zero-emission, reliable and safe multi-modal transportation and new and used ZEVs available for purchase or lease.
- Supportive policies and programs for ZEV uptake, including permit streamlining, incentives, and public outreach to develop a ZEV-informed population; and
- Training a skilled workforce with access to high road jobs that support ZEVs, ZEV infrastructure, and the ZEV industry.

In particular, this review is focused on ZEV readiness for California's vulnerable populations who often serve at the frontline of new industries, commute long distances for work, and bear a great percentage of the cost-burden for job-housing mismatches that necessitate commuting. To achieve broad and equitable ZEV adoption, ZEV readiness policies must support historically Disadvantaged Communities (DACs) and low-income families.

The main findings of this review are:

1. The first major barrier to ZEV adoption is that battery electric vehicles (BEVs) cost up to one quarter more than manufacturing internal combustion engines (ICEs) (Slowik et. al, 2019). The slow production of BEV batteries is another key bottleneck for both market price and uptake (Rietmann et. al, 2020). However, recent price analysis studies show costs dropping below the price of conventional vehicles by 2027, with the lowest range of ZEVs reaching price parity in 2024 (Shaheen et. al, 2020). This is an especially important factor to consider as higher household income is significantly correlated with greater ZEV adoption (Javid and Nejat, 2017). **This barrier can be overcome in the near term with increased rebates, cost offsets, and education about the package of financial incentives that exist, particularly for low-income families.**
2. A second major barrier is insufficient charging infrastructure: consumers are reluctant to purchase ZEVs without wide availability of dense refueling infrastructure. Yet, fuel suppliers are hesitant to build public infrastructure until enough alternative fuel vehicles are on the road to make it profitable (Gnann and Plötz, 2015, Melaina et al., 2017). There is also a lack of charging infrastructure in multi-unit dwellings where much of Californians reside (Horesh et al., 2023).

Charging at home is the most convenient and economical means to charge one's vehicle. The lack of dense charging station infrastructure increases range anxiety, which diminishes interest in plug-in vehicles (Carley et al., 2013). **To overcome this barrier, local jurisdictions can engage the community in siting ZEV charging stations, streamline permitting processes, offer incentives to reduce the cost of charging infrastructure, adopt voluntary CALGreen ZEV charging building codes, establish ZEV-friendly zoning codes and ordinances, and offer parking incentives. All of these policies should explicitly include and support DACs and low-income families. Further, regional and state infrastructure plans can offer options for corridor charging that enable long-range driving.¹²¹**

3. The third area of concern is the carbon intensity of the electricity generation mix that ZEVs rely on. Currently, about 33.6% of California's electricity comes from renewable sources (the largest shares are solar and wind), 37.9% from natural gas, and only 3% from coal, most of which is generated outside the state (California Energy Commission, 2021). **To overcome this barrier, local jurisdictions, in coordination with utilities, will need to plan energy infrastructure: siting new renewable facilities, safeguarding transmission, balancing local grids and energy storage. This includes siting and support for microgrids and automatic adjustment of charging coordinated with grid load.** Historically, energy infrastructure has been sited in low-income communities resulting in Locally Unwanted Land-Uses (LULUs) that depress housing values and impact health. As new energy infrastructure is sited, attention to equitable siting and clean technologies will be especially needed to demonstrate that the energy transition will not result in legacy LULUs and create or compound DACs.
4. Concern over the uncertainty of future ZEV incentives increases hesitation over private and public transitions to ZEV (Cano et al., 2018). Trencher (2020) recommends that **a combination of legislative mandates with incentives can build long term confidence in ZEV-related investments.**

How ZEV Impacts Greenhouse Gas Emissions

Below, we review the state of the research on ZEV policy recommendations and California government codes. We then discuss models for reaching GHG emissions reductions goals through ZEVs while comparing these models to the policies currently in place. Last, we identify gaps between how California codes and current research are framing the problems and solutions.

In California, the transportation sector is responsible for 40% of greenhouse gas (GHG) emissions, making it the largest contributing sector of state emissions (CARB, 2022). Light-duty vehicles produce the majority of transportation sector emissions. Because of this, reducing carbon emissions from the transportation sector has emerged as a priority action by the state to

combat climate change. ZEV technologies have been presented by policy makers as one solution for this decarbonization task in the form of battery electric vehicles (BEVs), plug-in electric hybrid (PHEVs), and fuel cell electric vehicles (FCEVs). ZEVs offer a path not only for larger GHG emissions reduction goals due to operating solely on electricity (depending on the source of electricity used for charging), but will also gradually improve regional air quality by reducing exhaust (Rietmann et al., 2020).

Energy science and policy experts credit California as a leader in statewide ZEV adoption due to the recent Advanced Clean Cars II regulation, adopted by CARB in 2022 (CARB, 2022). To ensure a gradual phase-out of new sales of internal combustion engine vehicles, this mandate sets annual sales requirements for ZEV and plug-in hybrid vehicles from model years 2026 to 2035 and stricter exhaust and evaporative emission standards. Through the ZEV mandate and Executive Order N-79-20 (Governor Newsom, 2021), the state aims to achieve 100% light-duty ZEV sales by 2035 and 100% medium- and heavy-duty ZEV sales in California by 2045. Executive Order B-48-18 (Governor Brown, 2018) targets five million ZEVs in California by 2030 and the installation of 200 hydrogen fueling stations and 250,000 ZEV chargers statewide by 2025. .

Because of these mandates and regulations in California, and the rapidly expanding uptake of these programs in other states, ZEVs are a growing segment of the automotive market and reached 25.4% market share in California (CEC, Quarter 4 of 2023).

ZEV Background on Terms: State of the Research

This section reviews federal, state and local policies pertaining to ZEV adoption.

Vehicle Emissions Standards (VES) specify the maximum GHG emissions (in grams of CO₂-equivalent/ km) from newly sold light-duty vehicles, and can be used for both GHG reduction and ZEV sales goals. In an attempt to raise VES, **ZEV mandates** have been used to force a proportion of major automaker's sales to come from ZEV. As an incentive, automakers receive **ZEV credits**, which are earned when manufacturers sell ZEV vehicles in ZEV states (such as California). One sale does not equal one credit, rather they are awarded based on the type and range of the vehicle sold. A full ZEV is worth more than a hybrid ZEV, and long-range vehicles are worth more than short range vehicles. The ZEV credit policy ultimately encourages automakers to build long range electric vehicles over other options. Automakers can also sell their surplus ZEV Credits to other automakers who have not met their quota for the year, thereby increasing profits for companies that sell the most ZEVs. ZEVs include plug-in hybrid electric vehicles (PHEVs) that use batteries to power an electric motor and another fuel, such as gasoline, to power an internal combustion engine (ICE). PHEV batteries can be charged using a wall outlet or charging equipment, by the ICE, or through regenerative braking. The vehicle typically runs on electric power until the battery is nearly depleted, and then the car automatically switches

over to use the ICE. A fuel cell electric vehicle (FCEV) generates electricity using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat. Battery-electric vehicles (BEVs) run solely on electricity stored in a battery pack that energizes one or more electric motors and produces zero tailpipe emissions. Their driving ranges on a full charge vary widely from about 80 to more than 300 miles.

In an effort to increase ZEV adoption, there are various mandates and regulations offering several incentives to ZEV owners. A common incentive is the **Clean Vehicle Rebate Project (CVRP)** offered by CARB. This initiative provides rebates to California residents who meet certain eligibility for the purchase of PHEV, BEV, or FCEV's (CARB, 2023). The DMV also offers reduced registration fees. State and federal governments offer tax credits.^[3] Other incentives are special ZEV electricity charging rates to residential charging stations, or time of use (TOU) rates. All of these incentives result in driver savings that are accrued from lower operating costs. Other incentives come in the form of convenience privileges, like being able to use High Occupancy Vehicle (HOV) lanes, or free or reserved parking for ZEV owners.

Other ways that ZEV adoption has been promoted is through making municipally owned charging station networks publicly available, electrifying public transportation fleets, and ZEV carsharing and ridesharing services. A community can support further ZEV adoption by taking ZEV readiness actions as described by the California Air Resource Board's ZEV Readiness guidelines.^[4] Much of the literature discussed in following sections analyzes which of the incentives in combination are the most successful at promoting ZEV adoption.

California Codes

According to California legislative code, "electric vehicle" means a vehicle that uses a plug-in battery to provide all or part of the motive power of the vehicle, including battery electric, plug-in hybrid electric, or plug-in fuel cell vehicle. Codes also used terms like clean transportation and clean burning transportation as other identifiers of ZEV. Various efforts to promote ZEVs occur through emission control and rebate programs, covered in the previous section. State codes also specify electricity price privileges for EV owners, and time of use (TOU) rates. These are seen as part of an **electric vehicle grid integration strategy**, which is defined as any method of altering the time, charging level, or location at which grid-connected electric vehicles charge, in a manner that optimizes plug-in electric vehicle interaction with the electrical grid and provides net benefits to ratepayers. There are special ZEV **parking privileges** outlined in these codes, where ZEV spaces can count as more than one parking space depending on the compliance with applicable minimum parking space requirements established by a local jurisdiction. Most of the codes address **electric vehicle charging station infrastructure** for residential, commercial, industrial, and agricultural zones, and laws that would make that installment process easier.

Research on ZEVs: ZEV Program in California

This section discusses the history and impact of the ZEV program in California.

California implemented a ZEV program in 1990. A policy brief by McConnell and Leard (2021) examined the motivation for the ZEV program in California, and how it has achieved outcomes such as innovation in electrification, rising rates of vehicle sales, and reductions in costs. The results showed evidence of electrification innovation by auto manufacturers through the number of patents related to ZEVs which jumped from none in 1990 to more than 70 per year by the late 1990s. The results also showed a decline in battery costs over time, which have translated into slight declines in vehicle purchase prices and greater ZEV range. While ZEVs still have not achieved cost and convenience parity with gasoline vehicles, most forecasts predict such parity sometime between 2022 and 2030, depending on vehicle size and type (Lutsey and Nicholas, 2019). Overall research consensus is that the California ZEV mandate can be effectively combined with price-based policies like a carbon tax to encourage greater ZEV uptake.

Additional California legislative codes broadly address the goals of ZEV adoption across the state. For example, under SB 350 (Deleon, 2015), the California Public Utilities Commission (CPUC) prioritizes energy procurement decisions that effectively reduce GHG emissions. The bill sets a target of achieving a 40 percent reduction in emissions below 1990 levels by 2030 and 80 percent GHG reductions below 1990 levels by 2050. To reach this goal, the California Public Utilities Commission (CPUC) must prioritize procuring a minimum of 50 percent renewable energy, doubling energy efficiency, and promoting transportation electrification. Additionally, this legislation emphasizes the importance of improving air quality and economic conditions in disadvantaged communities. This approach aims to drive significant progress in reducing emissions and advancing sustainable energy practices while ensuring that the benefits of clean energy and pollution reduction extend to all Californians. Achieving these goals requires better grid management and integration from renewable energy resources. AB 2127 (Ting, 2018) continues to support the goals of the ZEV adoption by requiring that the State Air Resources Board and the Public Utilities Commission prepare a statewide assessment of the electric vehicle charging infrastructure needed to support the levels of electric vehicle adoption required for the state to meet its goals of putting at least five million zero-emission vehicles on California roads by 2030, and of reducing emissions of greenhouse gasses to 40 percent below 1990 levels by 2030.

The California Energy Commission's Second Electric Vehicle Charging Infrastructure Assessment: Assessing Charging Needs to Support Zero-Emission Vehicles in 2030 and 2035 was completed in 2024 and looks at existing infrastructure and future infrastructure needs throughout California, including in low-income communities. According to the analysis outlined in this report, it is estimated that California will require 1.01 million chargers (including 39,000 direct current fast chargers) to accommodate 7.1 million light-duty plug-in electric vehicles by 2030. Further, it is projected that by 2035, California will require 2.11 million chargers

(including 83,000 direct current fast chargers) to adequately sustain a fleet of 15.2 million light-duty plug-in electric vehicles. California will also require about 109,000 depot chargers and 5,500 public chargers for 155,000 vehicles in 2030 and 256,000 depot chargers and 8,500 public chargers for 377,000 vehicles by 2035 to support medium and heavy-duty plug-in electric vehicles.

A third code that addresses statewide ZEV goals is the Charge Ahead California Initiative, or AB 1275 (De Leon, 2014). The goal of AB 1275 is to place in service at least 1 million zero-emission and near-zero-emission vehicles by 2023. This is part of an effort to establish a self-sustaining California market for ZEVs in which they are a viable mainstream option for vehicle purchasers, businesses, and public fleets. AB 1275 identifies the need to increase access for disadvantaged, low-income, and moderate-income communities in order to enhance air quality, lower greenhouse gasses, and promote overall benefits for those communities and consumers.

The Advanced Clean Cars II rule (Executive Order N-79-20) establishes a year-by-year roadmap so that by 2035 100% of new cars and light trucks sold in California will be ZEVs, including plug-in hybrid electric vehicles (CARB, 2022). To meet federal air quality standards, the regulation is expected to deliver a 25% reduction in smog-causing pollution from light-duty vehicles by 2037. From 2026 through 2040 the regulation is estimated to result in cumulative avoided health impacts worth nearly \$13 billion including 1,290 fewer cardiopulmonary deaths, 460 fewer hospital admissions for cardiovascular or respiratory illness, and 650 fewer emergency room visits for asthma (CARB, 2022). The regulation also includes provisions that enhance equity in the transition to zero-emission vehicles and provides consumers certainty about the long-term emission benefits, quality, and durability of batteries for clean cars and trucks.

In focusing on public fleets, the California Air Resources Board (CARB) passed the Innovative Clean Transit Regulation in 2019, requiring all public transit agencies to transition to zero emission technologies by 2040 (CARB, 2019). Beginning in 2029, 100% of new purchases by transit agencies must be zero-emission buses (ZEBs), with a goal for full transition by 2040. A ZEB Rollout Plan is required from each transit agency, and must be approved by its Board, to show how it is planning to achieve a full transition to zero-emission technologies by 2040 (CARB, 2019). Large transit agencies must submit their Rollout Plan by July 1, 2020, and small transit agencies by July 1, 2023. The regulation also encourages transit agencies to provide innovative first and last-mile connectivity and improved mobility for transit riders.

Interface between Statewide, Municipal, and Regional ZEV Programs

Many municipalities, along with their parent counties and regional governments, offer a variety of incentives to owners and operators of ZEVs to make adoption more convenient and affordable. A study by Clark-Sutton et. al (2016) presents an index that ranks the “readiness” of

36 major U.S. cities to deploy electric vehicles. They define readiness as the degree to which adoption of electric vehicles is supported, as reflected in policy instruments, infrastructure development, and municipal investments in PEV technology. They also compared cities within states that participate in a ZEV program with those that do not. The results from a weighted scoring system showed that the highest-scoring cities all offer substantial purchase incentives for ZEVs and charging equipment, and they offer time of use electricity rates. The results also showed no statistically significant difference between ZEV and non-ZEV states, indicating the importance of local policies; some cities in ZEV states rank quite highly (e.g., Portland, Oregon, and Los Angeles, California), some cities in non-ZEV states (e.g., Washington, DC, Denver, and Atlanta) also rank highly. This study identified factors that local jurisdictions may control (e.g., city parking access for ZEV owners, city-subsidized charging stations, and streamlined permitting procedures for home charging station installation) and how they interplay with state policies (e.g., HOV-lane access, state-level cash rebates or tax credits for ZEV owners, the state's gasoline tax rate, and the structure of electricity pricing). Considering the complex interactions that state and city level policies exert upon each other, this study concludes that in order to increase ZEV adoption, policies at both scales need to complement each other. For California, these findings demonstrate the need to celebrate and support local jurisdictions that demonstrate strong ZEV adoption and provide capacity building for jurisdictions that have not yet adopted ZEV-supporting policies (see plan evaluations for more information).

Two California-focused studies, Javid and Nejat (2017) and Searle et. al (2016) review the degree to which counties and cities have adopted ZEV policies as well as the policies' effectiveness at making ZEV more convenient and accessible. Javid and Nejat use a multiple logistic regression analysis of the 2012 California Household Travel Survey dataset, to understand the influence of demographics and travel-related characteristics, socioeconomic variables, and infrastructural and regional specifications. The results show that the average level of ZEV penetration across the state appears to be associated with infrastructural factors such as greater availability of public charging stations per capita and higher retail gas prices. These findings suggest that local efforts should target siting charging stations for public and private fleets. Searle et al. (2016) use a multivariate regression analysis to show that ZEV model availability, public electric vehicle charging network, local promotion activities for ZEVs (e.g., outreach events, informational websites, electric car sharing services, and government and fleet programs) and high median income in California cities are all positively correlated with new electric vehicle sales share. These findings note that higher income households are more likely to adopt ZEV use, indicating the care needed to craft equity-focused policies that support lower income households that often rely more on their vehicles for long commutes to and from work. Both studies note that policy support in California is bolstering the electric vehicle market. Major metropolitan areas in California had 3 to 13 times the average U.S. electric vehicle uptake in 2015 (Searle et. al, 2016). Furthermore, the 30 cities in California with the highest electric vehicle uptake—with 8 to 25 times the U.S. electric vehicle uptake—are also those with the

most implementation of abundant, wide-ranging electric vehicle promotion programs (Searle et. al, 2016).

Approved in 2015, AB 1236 focuses on local ordinances related to ZEV charging stations. The bill requires local governments to adopt an ordinance that establishes an expedited and streamlined permitting process for ZEV charging stations. Sharing a common objective with AB 1236, AB 970 (McCarty, 2022) describes how existing law requires a city, county, or city and county to administratively approve an application to install a ZEV charging station through the issuance of a building permit subject to a limited review by the building official of that city, county, or city and county. Existing law requires every city and county to create an expedited and streamlined permitting process for ZEV charging stations. State law also requires local jurisdictions to create an application checklist to expedite review of ZEV infrastructure proposals. This bill clarifies that these provisions apply to all cities, including charter cities. Monitoring to ensure compliance with AB 1236/970 can occur through climate action capacity building coalitions—particularly where municipal code and plans are readily available for comparative policy analysis and community-to-community learning.

ZEV Uptake in Disadvantaged Communities

This section discusses ZEV uptake in disadvantaged communities, the challenges that exist, and legislative codes addressing these concerns.

While the previous studies investigate socioeconomic and demographic characteristics, they did not delve specifically into equity and environmental justice (EJ). Disadvantaged Communities, or DACs, as defined by the California Environmental Protection Agency in Health and Safety Code (Cal. Gov. Code § 39711), are defined as “areas disproportionately affected by environmental pollution and other hazards that can lead to negative public health effects, exposure, or environmental degradation” and “areas with concentrations of people that are of low-income, high unemployment, low levels of home ownership, high rent burden, sensitive populations, or low levels of educational attainment” (California Gov. Health and Safety Code - HSC § 39711). Guidelines for incorporating EJ from the Governor’s Office of Land Use and Climate Initiatives (LCI) require both distributional and procedural EJ focus through the identification of disadvantaged communities within the planning area and creation of objectives and policies to (1) “reduce the unique or compounded health risks in disadvantaged communities by means that include, but are not limited to, the reduction of pollution exposure, including the improvement of air quality, and the promotion of public facilities, food access, safe and sanitary homes, and physical activity,” (2) “promote civil engagement in the public decision-making process,” and (3) “prioritize improvements and programs that address the needs of disadvantaged communities” (Gov. Code Sec. 65302(h)). Ultimately, adoption of a new element, usually the housing element, triggers the mandatory revision of several other components of the general

plan, including identifying “disadvantaged communities” (Gov. Code § 39711) and the state mandate to address Environmental Justice (Gov. Code § 65302(h)).

A study by Canepa et. al (2019) reviews PEV adoption in DACs, considering PEV market share, socioeconomic characteristics of PEV owners, and PEV charging infrastructure, including questionnaire survey data, department of motor vehicle (DMV) registration data, and infrastructure data. They find that adoption of both new and used PEVs in DACs occurs at comparatively low rates of 5.7% and 8.7% of all PEV sales (Canepa et. al, 2019). Owners of new or used PEVs in DACs have slightly lower incomes (\$135,102) than PEV owners in non-disadvantaged communities (\$153,175). However, as a group, PEV owners in DACs have higher incomes, are more educated, and fewer are home-renters than the DAC average, indicating that PEV-owners in DACs are not representative of the communities in which they live. Canepa et. al also map the charging infrastructure present in DAC census tracts (0.93 level 2 chargers per 1000 households, and 0.61 DC fast chargers per 1000 households), suggesting that further PEV adoption could be supported with greater siting of charging infrastructure. Additionally, there are higher proportions of used PEVs in DACs than new PEVs, which indicates reliance on used PEV markets to reach DAC households. Key barriers to ZEV adoption in DACs are the prohibitive price of the technology, lack of knowledge about or ease of accessing PEV incentives, and lack of access to public or private charging infrastructure located near multi-unit housing. These barriers require a combination of state and local efforts with intentional focus on engaging DAC households.

Some current California legislative codes respond to ZEV barriers for low-income households. One example of this is the California Clean Vehicle Rebate Project (2023), which allocates additional funds to low income consumers. The incentive program offers up to a \$7500 rebate to buyers of BEVs and \$6500 to buyers of PHEVs. This applies to households with an income cap of \$135,000 for single filers, \$175,000 for head-of-household filers, or \$200,000 for joint filers (CARB, 2023). However, these incentives are currently only applicable to new PEV purchases or leases. Similarly, the AB 193 Zero-Emission Assurance Project (2018) allocates rebates for battery and fuel cell replacements on used ZEV vehicles. Furthermore, pursuant to SB 1000, which mandates the California Energy Commission assess ZEV infrastructure deployment in California (Lara, 2018), the CEC found that public Level 2 and direct current fast chargers are unevenly distributed among air districts and counties (CEC, 2020). Findings also indicated that low income communities in California have fewer public Level 2 chargers deployed per capita. Limited availability of Level 2 chargers in low income communities can act as a barrier to ZEV adoption. Thus, the results from this report and the ongoing assessment will help inform program investments to ensure equitable access to charging infrastructure.

Some of the California legislative codes have tried to make ZEV information more accessible through other initiatives. For example, SB 68 (2022) supports building owners in decarbonizing

buildings and adding energy storage or electric vehicle charging capacity to buildings. The Public Utilities Commission, the Department of Housing and Community Development, the California Building Standards Commission, and other relevant state agencies, are required to develop and publish on the commission's internet website guidance and best practices to help building owners, the construction industry, and local governments overcome barriers to electrification of buildings and installation of electric vehicle charging equipment. Similarly, in an effort to make information on PHEVs and PEVs more widely accessible, SB 1455 (2011), says that the State Energy Resources Conservation and Development commission, in consultation with the Public Utilities Commission, shall develop and maintain a website containing specific links to electrical corporation and local publicly owned electric utility web sites that contain information specific to plug-in hybrid or fully electric vehicles. This resource information is intended to direct a consumer on how to find out if their residence will require a utility service upgrade, basic charging circuit requirements, and utility rate options. Both of these codes, however, do not offer information on rebates to ZEV owners.

Effectiveness of ZEV Consumer Financial Incentives and Rebates

This section discusses the effectiveness of financial incentives and rebates to encourage consumers to choose ZEV.

One priority area for equitable ZEV adoption by low-income households is the development and funding of price supports and rebates. Hardman et al. (2017) aim to understand the effectiveness of purchase incentives in increasing ZEV sales and find through a systematic literature review that ZEV rebates play a significant role in the increase of ZEV adoption. Narassimhan and Johnson (2018) quantify the influence of key incentives on PEV adoption, and through a regression of vehicle purchase data from 2008–2016, find that rebates are usually more effective in driving ownership decisions than tax credits. Another study by Wu and Kontou (2022) looks at a planning horizon of the next 30 years using the 2021 National Household Travel Survey trip data to calculate average daily vehicle miles traveled (VMT) in the US. They also use historical ZEV registration data from the year 2011 (when electric vehicles entered the market) to the year 2020. Their analysis indicates that rebates should be provided earlier than chargers due to neighborhood effects of ZEV adoption and the minimization of expenditure. They conclude that rebates are more effective for modest drivers while charging stations should be prioritized for frequent drivers. In sum, rebates are successful in spurring adoption and can be further aimed at supporting ZEV purchases by low-income households. After a critical mass of ZEV purchases, incentivizing ZEV charging stations in DACs would sustain ZEV adoption further.

Challenges for Increasing ZEV Charging Infrastructure

This section discusses the challenges for increasing ZEV charging stations and their role in promoting consumer confidence.

While the previous section identifies rebates as the primary motivator to purchase a ZEV, many studies quantify the value of charging infrastructure in ZEV uptake. One such study by Greene et. al (2020) analyzes the value of public charging infrastructure to owners of PEVs through a willingness-to-pay (WTP) survey that was derived from simulation modeling and econometric estimates of the value of enabled miles of vehicle travel powered by electricity. Through their case study on California's public charging network in 2017, they find that for a ZEV owner, public charging infrastructure is worth between \$1500-\$6500 a year. Charging at home, work, or public locations also significantly increases consumers' willingness to purchase ZEVs. Similarly, Kontou et al. (2019) analyze GPS travel survey data from three metropolitan areas and find that the most frequently used and most important piece of infrastructure in convincing consumers to purchase a PEV is home charging. Without access to charging at or near home, consumers are unlikely to purchase a PEV. Their results show that the next most important charger location for consumers is the workplace. Finally, like Greene et al. (2020), they conclude that charging infrastructure in public locations and on travel corridors is instrumental in encouraging consumers to purchase PEVs, however they find that these are utilized less often than home or work location chargers. These findings suggest that for equitable ZEV adoption, local jurisdictions should consider fast-track, low-cost permitting for charging stations in DACs. Public financing for siting charging infrastructure in DACs will also benefit equitable ZEV uptake.

With this framing, it is unsurprising that charging infrastructure is the most commonly cited aspect of ZEV uptake in California legislative code. For example, SB 1340 (Added by Stats, 2011), recognizes that the upfront cost of installing electric vehicle charging infrastructure for residential, commercial, industrial, and agricultural zones, prevents many property owners from making those improvements. In response, SB 1340 proposes that public agencies finance the installation of ZEV charging infrastructure. Another code, AB 1092 (Levine, 2014), specifies mandatory building standards for the installation of future ZEV charging infrastructure for parking spaces in multifamily dwellings and nonresidential development. SB 676 (2020), specifies time-of-use rates for customers with ZEVs to incentivize charging at periods of low demand and low grid congestion. SB 626 (2010), outlined how the Energy Commission, State Air Resources Board, electrical corporations, and the motor vehicle industry, promises to further evaluate policies to develop infrastructure sufficient to overcome any barriers to the widespread deployment and use of ZEVs. Topics of concern addressed in this code are:

- The impacts upon electrical infrastructure, including infrastructure upgrades necessary for widespread use of plug-in hybrid and electric vehicles and the role and development of public charging infrastructure.
- The role the state should take to ensure that technologies employed in plug-in hybrid and electric vehicles work in a harmonious manner and across service territories.

- The impact of ZEVs on grid stability and the integration of renewable energy resources.
- The technological advances that are needed to ensure the widespread use of plug-in hybrid and electric vehicles and what role the state should take to support the development of this technology.
- The existing code and permit requirements that will impact the widespread use of plug-in hybrid and electric vehicles, and any recommended changes to existing legal impediments.

ZEV in Other Sectors

Ride sharing is another opportunity for ZEV adoption. Shaheen et. al (2020) review the impact of car sharing services in ZEV uptake through a nationwide survey of car2go, DriveNow, eGo, CarShare, and Zipcar members. Results show that users who shared PHEVs or BEVs more frequently were more likely to support ZEV policies. The results also suggest that exposure to PHEVs or BEVs through carsharing increased a user's reported likelihood to purchase a ZEV in the future. Collectively, the results note that temporary exposure to ZEVs through car sharing improves perceptions that may lead to an expanded ZEV market share. Findings hold promising implications for ZEV ridesharing and ZEV municipal fleets.

Supporting ZEV rideshare policies at the state level can further bolster ZEV adoption. For example, in 2021, CARB adopted the Clean Miles Standard to reduce emissions from transportation network companies (TNCs) like Uber and Lyft.^[5] The standard sets goals for ZEV fleet adoption in TNCs and offers optional credits for trips that connect to transit. To focus on heavy-duty vehicles, the California Clean Truck, Bus, and Off-Road Vehicle, and Equipment Technology Program was created by AB 992 (Cooley, 2022). The program funds development, demonstration, and early commercial deployment of ZEV trucks, buses, off-road vehicles, and equipment technologies. According to the 2007 State Alternative Fuels Plan analysis by the Energy Commission and the State Air Resources Board, light-, medium-, and heavy-duty vehicle electrification will result in approximately 70 percent fewer greenhouse gasses emitted (AB 1007, Pavley). AB 992 also outlines how priority shall be given to projects benefiting DACs. CARB's Moving California Heavy-duty Project in Action^[6] specifically addresses the environmental challenges that heavy-duty vehicles pose, aiming to facilitate the transition to cleaner transportation for both on- and off-road fleets in disadvantaged communities. Similarly, the Light-duty Projects in Action focuses on increasing access to long-term clean transportation for income-qualified residents and residents of disadvantaged and tribal communities. These initiatives address transportation equity to ensure that all residents have access to cleaner transportation options while seeking to improve neighborhoods that host commercial heavy-duty traffic.

Conclusion: Feasibility of Reaching GHG Emissions Reductions Goals through ZEV

B-48-18 states that California ZEV goals include placing in service at least 1 million ZEVs by 2023, with 1.5 million ZEVs on the road by 2025. B-48-18 and SB 589 both discuss how ZEV will be part of the strategy to reduce emissions of greenhouse gasses to 40 percent below 1990 levels by 2030, and to 80 percent below 1990 levels by 2050. For all of the ZEV owners who are a part of that electrified transportation transition, they can expect benefits like fuel savings, maintenance savings, reduced vehicle prices (after parity), and greenhouse gas emission reductions. Excluding the benefits from reduced greenhouse gas externalities, the 2020–2050 cumulative benefits outweigh the cost of ICE by a factor of about 7 in the United States (Slowik et. al, 2019).

While this literature review has laid out feasibility and incentives to increase ZEV adoption, the benefits are expected to accrue not only to ZEV owners but the state as air pollution is reduced. Yet, the rate of change may not be quick enough to reach GHG emissions reductions goals. Studies suggest that while reductions in CO₂ emissions can be achieved with the predicted ZEV growth, given the current energy mixes, CO₂ emissions will continue to rise until 2035 (Rietmann et. al, 2020). Of the twelve California legislative codes that were found to address ZEV adoption, eight went into effect in the last three years. This suggests that supportive ZEV codes are increasing as reaching GHG emissions reductions goals grow more dire. Clearly, more ZEV regulations and mandates at the state and local scale are needed to achieve emissions reduction goals.

Table 1. California’s Electric Vehicle Legislation

AB 1092	2014	Specifies mandatory building standards for installing future electric vehicle charging infrastructure for parking spaces in multifamily dwellings and nonresidential development.
AB 1275	2014	Place at least 1 million zero-emission and near-zero-emission vehicles in service by 2023 while increasing access for disadvantaged, low-income, and moderate-income communities to enhance air quality, lower greenhouse gasses, and promote overall benefits for those communities and consumers.
AB 1236	2015	Focuses on local ordinances related to electric vehicle charging stations. The bill requires local governments to adopt an ordinance establishing an expedited and streamlined permitting process for ZEV charging stations.

AB 193	2018	Allocates rebates for battery and fuel cell replacements on used ZEV vehicles.
AB 2127	2018	Requires CARB and the Public Utilities Commission to prepare a statewide assessment of the electric vehicle charging infrastructure needed to support the levels of electric vehicle adoption required for the state to meet its goals of putting at least five million zero-emission vehicles on California roads by 2030, and of reducing emissions of greenhouse gasses to 40 percent below 1990 levels by 2030.
AB 970	2022	Requires every city, county, and county to create an expedited, streamlined permitting process for electric vehicle charging stations and to adopt a checklist under which an application that satisfies the information requirements in that checklist shall be deemed complete and, therefore eligible for expedited review. This bill clarifies that these provisions apply to all cities, including charter cities.
AB 992	2022	Specifies funding for The California Clean Truck, Bus, and Off-Road Vehicle and Equipment Technology Program initiative. It also outlines how priority shall be given to projects benefiting disadvantaged communities.
B-48-18	2018	The state aims to deploy five million ZEVs by 2030 in the public sector and achieve 50% ZEV auto sales by 2035. Executive Order B-48-18 also targets installing 200 hydrogen fueling stations and 250,000 EV chargers statewide by 2025
N-79-20	2022	Establishes a year-by-year roadmap so that by 2035, 100% of new cars and light trucks sold in California will be ZEVs, including plug-in hybrid electric vehicles
SB 626	2010	the Energy Commission, State Air Resources Board, electrical corporations, and the motor vehicle industry shall evaluate policies to develop infrastructure sufficient to overcome barriers to the widespread deployment and use of ZEVs.
SB 1340	2011	Proposes public agencies finance electric vehicle charging infrastructure installation on these types of properties.
SB 1455	2011	The State Energy Resources Conservation and Development Commission, in consultation with the Public Utilities Commission, shall develop and maintain a website containing specific links to electrical corporations and local publicly owned electric utility websites that have information specific to plug-in hybrid or fully electric vehicles.

SB 350	2015	The bill targets achieving a 40 percent reduction in emissions by 2030. To reach this goal, the CPUC must prioritize procuring at least 50 percent renewable energy, doubling energy efficiency, and promoting transportation electrification. Additionally, this legislation emphasizes the importance of improving air quality and economic conditions in disadvantaged communities.
SB 1000	2018	Mandates the California Energy Commission to assess ZEV infrastructure deployment in California.
SB 589	2021	ZEV will be part of the strategy to reduce emissions of greenhouse gasses to 40 percent below 1990 levels by 2030 and to 80 percent below 1990 levels by 2050
SB 68	2022	Supports building owners in decarbonizing buildings and adding energy storage or electric vehicle charging capacity.

Key Words

BEV	Battery Electric Vehicle run solely on electricity stored in a battery pack that energizes one or more electric motors
CARB	California Air Resources Board
DAC	Disadvantaged Communities, census tracts in California that suffer from a combination of economic barriers and environmental burdens
EV	Electric Vehicle, a vehicle that uses a plug-in battery to provide all or part of the motive power of the vehicle, including battery electric, plug-in hybrid electric, or plug-in fuel cell vehicle
FCEV	Fuel-cell electric vehicle, generates electricity using oxygen from the air and compressed hydrogen
GHG	Greenhouse Gas
HOV	High Occupancy Vehicle
ICE	Internal Combustion Engine

PEV	Plug-in Electric Vehicle, draws electricity from a battery and does not have the ability to be propelled by gasoline
PHEV	Plug-in Electric Hybrid Vehicle, use batteries to power an electric motor and another fuel, such as gasoline, to power an internal combustion engine
Ridesharing/ Ridesourcing	Form of shared vehicles, bikes, and scooters, enabling users to gain short-term access to transportation modes on an “as-needed” basis.
TOU	Time of use rate for electric charging
VES	Vehicle Efficiency Standards; how much Co2 per mile can be emitted by a vehicle, and the fuel efficiency of vehicles miles per gallon.
ZEB	Zero Emissions Bus
ZEV	Zero Emission Vehicles, use a plug-in battery to provide all or part of the motive power of the vehicle, including battery electric, plug-in hybrid electric, or plug-in fuel cell vehicle
ZEV credits	Earned when manufacturers sell ZEV vehicles in ZEV states. Awarded based on the type and range of the vehicle sold
ZEV mandates	Require a proportion of major automaker's sales to come from ZEV

References

Air pollution: alternative vehicles and vehicle infrastructure. Senate Bill 589 (Hueso) in 2022 (Ca. Public Resources Code, § 44272.2)

Building electrification and electric vehicle charging. Senate Bill 68 (Becker) in 2021 (Ca. Public Resources Code, § 25711.5) <https://ww2.arb.ca.gov/2021-senate-bill-68-becker-josh-building-electrification-and-electric-vehicle-charging-chaptered>

Building standards: electric vehicle charging infrastructure. Assembly Bill 1092 (Levine) in 2014 (Ca. Health and Safety code, § 18941.10)

California Air Resources Board. (2022, August). California moves to accelerate to 100% new zero-emission vehicle sales by 2035. <https://ww2.arb.ca.gov/news/california-moves-accelerate-100-new-zero-emission-vehicle-sales-2035>

California Air Resources Board. (2019). Innovative Clean Transit Program.
<https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/about>

California Air Resources Board. (2022). Current California GHG Emission Inventory Data.
<https://ww2.arb.ca.gov/ghg-inventory-data>

California Air Resources Board. (2023). Clean Vehicle Rebate Project.
<https://ww2.arb.ca.gov/our-work/programs/clean-vehicle-rebate-project-cvrp>

California Clean Truck, Bus, and Off-Road Vehicle and Equipment Technology Program. Senate Bill 992 (Cooley) in 2021 (Ca. Health and Safety Code, § 39719.2)

California Clean Vehicle Rebate Project <https://cleanvehiclerebate.org/en>

California Energy Commission. 2021 Total System Electric Generation.
<https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2021-total-system-electric-generation>

California Energy Commission (2023). New ZEV Sales in California.
<https://www.energy.ca.gov/zevstats>.

California Energy Commission (2020). California Electric Vehicle Infrastructure Deployment Assessment: Senate Bill 1000 Report: Increasing Access to Electric Vehicle Infrastructure for All
<https://www.energy.ca.gov/publications/2020/california-electric-vehicle-infrastructure-deployment-assessment-senate-bill>

California Public Utilities Commission. (2015). Clean Energy and Pollution Reduction Act of 2015 (SB 350).
<https://www.cpuc.ca.gov/sb350/>

Canepa, Kathryn, Scott Hardman, and Gil Tal. (2019) An Early Look at Plug-in Electric Vehicle Adoption in Disadvantaged Communities in California. *Transport Policy* 78: 19–30.
<https://doi.org/10.1016/j.tranpol.2019.03.009>.

Cano, Zachary P., Dustin Banham, Siyu Ye, Andreas Hintennach, Jun Lu, Michael Fowler, and Zhongwei Chen. (2018). Batteries and Fuel Cells for Emerging Electric Vehicle Markets. *Nature Energy* 3, no. 4: 279–89. <https://doi.org/10.1038/s41560-018-0108-1>.

Carley, Sanya & Krause, Rachel & Lane, Bradley & Graham, John. (2013). Intent to Purchase a Plug-In Electric Vehicle: A Survey of Early Impressions in Large US Cities. *Transportation Research Part D Transport and Environment*. 18. 10.1016/j.trd.2012.09.007.

Charge Ahead California Initiative. Assembly Bill 1275 (De Leon) in 2014 (Ca. Health and Safety Code § 44258)

Clark-Sutton, K., Siddiki, S., Carley, S., Wanner, C., Rupp, J., & Graham, J. D. (2016). Plug-in electric vehicle readiness: Rating cities in the United States. *The Electricity Journal*, 29(1), 30–40. <https://doi.org/10.1016/j.tej.2015.12.006>

Clean Energy and Pollution Act. Senator Bill 350 (Deleon) in 2015 (Ca. Health and Safety Code § 44258.5)

- Creation of Contractual Assessment Program. Senate Bill 1340 (Added by Stats) in 2011 (Ca. Streets and Highways code, § 5899.3)
- Gnann, Till, Patrick Plötz, André Kühn, and Martin Wietschel. (2015). Modelling Market Diffusion of Electric Vehicles with Real World Driving Data – German Market and Policy Options. *Transportation Research Part A: Policy and Practice* 77, no. C: 95–112.
- Executive Order B-48-18, Zero-Emission Vehicle Executive Order (2018). Governor Brown.
- Electric Vehicle Infrastructure Training Program and Energy Efficiency Programs. Assembly Bill 841 (Ting) in 2021 (Ca. Public Utilities Code, § 740.12)
- Electric vehicle charging infrastructure: assessment. Assembly Bill 2127 (Ting) in 2018 (Ca. Public Resources Code § 25229)
- Greene, David L., Eleftheria Kontou, Brennan Borlaug, Aaron Brooker, and Matteo Muratori. (2020). Public Charging Infrastructure for Plug-in Electric Vehicles: What Is It Worth? *Transportation Research Part D: Transport and Environment* 78: 102182.
<https://doi.org/10.1016/j.trd.2019.11.011>.
- Hardman, Scott, Amrit Chandan, Gil Tal, and Tom Turrentine. (2017). The Effectiveness of Financial Purchase Incentives for Battery Electric Vehicles – A Review of the Evidence. *Renewable and Sustainable Energy Reviews* 80: 1100–1111.
<https://doi.org/10.1016/j.rser.2017.05.255>.
- Horesh N, Zhou Y, Quinn J. Home charging for all: Techno-economic and life cycle assessment of multi-unit dwelling electric vehicle charging hubs. *Journal of Cleaner Production*. 2023 Jan 10;383:135551.
<https://doi.org/10.1016/j.jclepro.2022.135551>
- Javid, Roxana J., and Ali Nejat. (2017). A Comprehensive Model of Regional Electric Vehicle Adoption and Penetration.” *Transport Policy* 54: 30–42.
<https://doi.org/10.1016/j.tranpol.2016.11.003>.
- Klippenstein, M. (2017). Electric Vehicle Sales in the United States: 2017 Half-Year Update. Fleet Carma (2017) retrieved August 1, 2022, from <https://www.fleetcarma.com/electric-vehicle-sales-united-states>
- Kontou, Eleftheria, Changzheng Liu, Fei Xie, Xing Wu, and Zhenhong Lin. (2019). Understanding the Linkage between Electric Vehicle Charging Network Coverage and Charging Opportunity Using GPS Travel Data.” *Transportation Research Part C: Emerging Technologies* 98: 1–13. <https://doi.org/10.1016/j.trc.2018.11.008>.
- Local ordinances: electric vehicle charging stations. Assembly Bill 1236 (Chiu) in 2015 (Ca. Gov. code § 65850.7)
- Low Emission Vehicle regulation (1990) <https://ww2.arb.ca.gov/our-work/programs/low-emission-vehicle-program/about#:~:text=and%20Compliance%20Division-.About,1994%20through%202003%20model%20year>
- Lutsey, N., & Nicholas, M. (2019). Update on electric vehicle costs in the United States through 2030. *Int. Counc. Clean Transp*, 12.

- McConnell, V., & Leard, B. (2021). Pushing New Technology into the Market: California's Zero Emissions Vehicle Mandate. *Review of Environmental Economics and Policy*, 15(1), 169–179. <https://doi.org/10.1086/713055>
- Melaina, Marc, Matteo Muratori, Joyce McLaren, and Paul Schwabe. (2017). Investing in Alternative Fuel Infrastructure: Insights for California from Stakeholder Interviews: Preprint. National Renewable Energy Lab. (NREL), Golden, CO (United States). <https://www.osti.gov/biblio/1347196>.
- Narassimhan, Easwaran, and Caley Johnson. (2018). The Role of Demand-Side Incentives and Charging Infrastructure on Plug-in Electric Vehicle Adoption: Analysis of US States. *Environmental Research Letters* 13, no. 7: 074032. <https://doi.org/10.1088/1748-9326/aad0f8>.
- Planning and zoning: electric vehicle charging stations. Assembly Bill 970 (McCarty) in 2021 (Ca. Gov. code § 65850.71)
- Rietmann, Nele, Beatrice Hügler, and Theo Lieven. (2020). Forecasting the Trajectory of Electric Vehicle Sales and the Consequences for Worldwide CO2 Emissions. *Journal of Cleaner Production* 261: 121038. <https://doi.org/10.1016/j.jclepro.2020.121038>.
- Rodier, Caroline. (2009). Review of International Modeling Literature: Transit, Land Use, and Auto Pricing Strategies to Reduce Vehicle Miles Traveled and Greenhouse Gas Emissions. *Transportation Research Record* 2132, no. 1: 1–12. <https://doi.org/10.3141/2132-01>.
- Searle, Stephanie, Nikita Pavlenko, Nic Lutsey. (2016). Leading Edge of Electric Vehicle Market Development in the United States: An Analysis Of California Cities. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/ICCT_EV_Calif_Cities_201609.pdf
- Senate Bill 1455 (Caballero) in 2011 (Ca. Public Resources code, § 25227)
- Shaheen, Susan, Elliot Martin, and Hannah Totte. (2020). Zero-Emission Vehicle Exposure within U.S. Carsharing Fleets and Impacts on Sentiment toward Electric-Drive Vehicles. *Transport Policy* 85: A23–32. <https://doi.org/10.1016/j.tranpol.2019.09.008>.
- Slowik, Peter & Hall, Dale & Lutsey, Nicholas & Nicholas, Michael & Wappelhorst, Sandra. (2019). Funding the transition to all zero-emission vehicles. 10.13140/RG.2.2.32513.81760.
- State Alternative Fuels Plan. Assembly Bill 1007 (Pavley) in 2007 (Ca. Health and Safety Code § 43866)
- Transportation electrification: electric vehicles: grid integration. Senate Bill 676 (Bradford) in 2020 (Ca. Public Utilities code, § 740.16)
- Transportation electrification: electric vehicle charging infrastructure. Senate Bill 1000 (Lara) in 2018 (Ca. Gov. code § 65850.9)
- Trencher, Gregory. (2020). Strategies to Accelerate the Production and Diffusion of Fuel Cell Electric Vehicles: Experiences from California.” *Energy Reports* 6: 2503–19. <https://doi.org/10.1016/j.egyr.2020.09.008>.

Wu, Yen-Chu, and Eleftheria Kontou. (2022). Designing Electric Vehicle Incentives to Meet Emission Reduction Targets. *Transportation Research Part D: Transport and Environment* 107: 103320. <https://doi.org/10.1016/j.trd.2022.103320>.

Zero-Emission Assurance Project. Assembly Bill 193 (Cervantes) in 2018 (Ca. Health and Safety Code § 44274.9)

We review the state of research on building decarbonization adoption to identify opportunities and barriers for local jurisdictions in California. Building decarbonization refers to the umbrella of strategies to reduce residential and commercial building emissions, which include maximizing energy efficiency, use of low- and zero-carbon electricity, demand flexibility, eliminating fuel combustion by electrifying appliances and equipment, and reducing the embodied carbon of building materials, among other actions. To center the needs of the most vulnerable Californians, this review focuses on equity.

Building Decarbonization Challenges

While energy efficiency technology has the potential to reduce emissions from the building sector by half (IEA, 2020), the main challenge to adoption is 1) inconsistent policy frameworks and 2) public knowledge. For example, building decarbonization includes state and local plans for transitioning away from legacy energy infrastructure to lower emission energy supply, as well as updates to individual buildings. One obstacle to success during these simultaneous transitions is the misalignment between local, state, and federal agency goals, metrics, and utility incentives. In part this misalignment is the result of policy flux. While the state and federal governments set goals and building codes, cities and local jurisdictions are innovating new reach building codes and alternate approaches. In turn, the state is observing and recommending successful local building codes and policies, resulting in a ground-up approach with some time lag between the creation of local policy and support for such policies (e.g., retrofit requirements at point-of-sale ordinances, reach codes that require carbon neutrality for new buildings and renovations). Further, research reports insufficient coordination among supportive organizations (e.g., policymakers, local governments, and research institutions) with similarly focused initiatives such as the building weatherization support programs, the California Solar Initiative, and electric vehicle adoption (Building Decarbonization Coalition, 2019). Concurrently, the state plan for transitioning away from legacy infrastructure responsibly and cost-effectively is unclear. In response, local jurisdictions grapple with legacy energy infrastructure, which is often sited in low-income communities resulting in Locally Unwanted Land-Uses (LULUs) that depress housing values and impact health. As new energy infrastructure is sited, DACs and environmental justice communities are wary that siting will not be equitably distributed, and that design and clean technology considerations will not be enough to prevent new energy infrastructure from becoming a LULU.

Solutions include state legislation and regulations that align program and agency metrics to areas of local progress (e.g., utility and community choice aggregation programs). For example, not all utility service territories offer bill savings programs (Pacific Consulting Group, 2023). State policies could encourage or require equity-focused programs. In addition to the mismatched

policies between levels of government, geographic disparities and patchwork implementation create inequities for consumers. To promote equity between jurisdictions and within, the state will need to provide guidance and transparency around where new energy infrastructure is needed to balance the grid.

There is also the need for coalition building to further economic and political support for decarbonization, altering energy consumption incentives, and harnessing market forces (Bernstein and Hoffmann, 2018; Stokes and Warshaw, 2017; Tozer, 2020). Coalition building will also help raise awareness of low-cost policy pathways such as the adoption of heat pumps. Amongst the public, there is a broad, critical lack of awareness and interest in decarbonized technology (e.g., heat pumps, district energy) for residential and commercial buildings. For example, consumers are often confused and misinformed about the benefits of replacing gas with electric appliances (Pacific Consulting Group, 2023). This is due to insufficient customer education on the health and economic benefits of electrification. This challenge can be addressed by raising awareness and educating customers, policymakers, product distributors, and the building trades on the technology's availability and its financial, health, safety, and comfort benefits. In addition to building informed consumer demand, outreach is needed to address the split incentives of decarbonization as landlords invest in improvements, but tenants reap the benefits of lower utility bills and better health. Here, tenant protection and local rental policies are needed to bridge the transition.

In addition to these challenges, there are insufficient financing solutions^[7] to incentivize customer adoption or help manage up-front costs. Financing concerns are particularly relevant for low-income customers or people who live in rental housing. This could be remedied through state-level rebate programs, special use rates for low-carbon appliances,^[8] and support programs for low-income customers^[9], which include the “one-stop shop”^[10] of a vetted contractor network, energy savings guarantees, strong incentives, and integrated project design support by program staff (Less et al., 2022).

Last, building decarbonization has an undeveloped business-friendly environment. There are few paths to market for electric load shift, a lack of markets to monetize grid and climate values, and a lack of coordination at a national level necessary to increase manufacturing. Solutions require removing regulatory and market barriers that are hindering market development (Atwa et al., 2009; Starke et al., 2016). Research suggest that these solutions can be accomplished through production incentive programs, limitations on fuel-switching programs, and rate design. For example, solar producers can be better incentivized to sell energy back to the grid during peak demand. Such market transitions can accelerate product research, development, and deployment programs as they boost demand and open opportunities for micro clean energy businesses. Technical capacity is another barrier due to inadequate electrical paneling at many homes and

businesses and a lack of experts who can install new systems (Sovacool, 2009). To overcome this requires investing in training to expand the clean energy workforce.

How Building Decarbonization Impacts Greenhouse Gas Emissions

In addition to the state, many local governments, organizations, institutions, and businesses have committed to net zero greenhouse gas emissions, a goal and process known as deep decarbonization. Achieving this goal requires a state-level, economy-wide transformation in energy production across five sectors: electricity, transportation, industry, land-based carbon sinks, and buildings. Below, we provide a background on building decarbonization as a priority area for reducing GHG emissions, followed by a review of the state of the research on building decarbonization policy recommendations and California government codes. We then discuss models for reaching GHG emissions reductions goals through building decarbonization, comparing these models to the policies currently in place.

In California, energy use from buildings is responsible for 26% of statewide greenhouse gas emissions, making it the second largest contributor to emissions after transportation (California Energy Commission, 2018). Further, countries that have successfully reduced overall GHG emissions per capita have had more success decarbonizing the built environment than reducing per capita emissions in the transportation sector (Brinkley, 2014), revealing the promise of transitioning the built environment. As a result, many feasibility models for reaching decarbonization rely on significant changes to energy infrastructure and building codes across the residential, commercial, and industrial sectors (review: Hsu et al., 2021). Decarbonizing buildings has thus emerged as a central priority area for meeting CARB's 2022 Scoping plan, which aims to reduce California's GHG emissions 48% below 1990 levels by 2030 and achieve net zero emissions by 2045.^{[11],[12]}

Building decarbonization encompasses several methods, including:

- Building codes and inspection enforcement that prioritize decarbonization
- Weatherization and renovation of existing buildings
- Decarbonizing electricity by growing the low-carbon share of the generation portfolio (such as natural gas, and wind and solar power)
- Growing localized renewable energy production through rooftop solar photovoltaic (PV) and onsite battery storage
- Expanding the use of energy efficiency technology, like district energy and heat pumps
- Increasing the efficiency standards of appliances
- Providing incentives to consumers to shift their electricity use in response to the timing of energy costs, GHG emissions intensity, or electricity grid emergencies.

These strategies address both the direct and indirect sources of emissions from buildings, with direct emissions released by on-site combustion of fossil fuels and biomass (8%), as well as from

indirect emissions attributed to electricity consumption in buildings and district heating (15%) (Levesque et al., 2019). Improving the energy efficiency of buildings is, fortunately, one of the most effective and affordable ways to reduce GHG emissions on a large scale, with the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report projecting that cost-effective energy-efficiency measures in buildings would save the equivalent warming potential of 5.3–6.7 billion metric tons of CO₂ globally per year (Gt CO₂eq/year) by 2030 (Metz et al., 2007). Through the combined efforts of energy efficiency upgrades, reducing the carbon content of energy resources and appliances, and shifting energy usage with available technology, decarbonizing buildings can achieve multiple policy objectives, like reaching state climate goals, saving consumers money through reduced energy bills, supporting grid resiliency and reliability, improving indoor and outdoor air quality, and reducing health risks from buildings (California Energy Commission, 2018).

Regulatory Framework

The primary tool used by the state to regulate building decarbonization is Title 24, or building efficiency energy codes (California Energy Commission, 2022). These codes are written by the California Energy Commission (CEC) and outline a broad set of requirements for structural, mechanical, electrical, and plumbing systems that prioritize energy conservation, green design, fire safety and health, and accessibility. These codes are updated every three years and primarily focus on new construction. The latest version of Title 24 was adopted in 2021 and contained significant strides toward zero-carbon emissions buildings. The code sets energy requirements such as minimum efficiency of walls, windows, and heating and cooling equipment for both new and existing buildings; expanded the requirements for rooftop photovoltaic solar panels and storage for most new single-family and multifamily homes; and a shift to electric heat pump space and water heating. They estimate that an efficient heat pump will save at least 75% of greenhouse gas emissions over its life (California Energy Commission, 2019). These building efficiency energy codes discourage continued use of higher energy and emissions of fossil-fueled heating and hot water, but they are not mandates requiring homes to be solar-powered and all-electric. These codes can better be described as technology-neutral, performance-based incentive programs that strongly encourage lower energy cost solutions and carbon emissions (Delforge, 2021). They provide incentives to builders through compliance credits and penalties. For example, if builders choose high-efficiency electric water or space heating instead of gas furnaces and water heaters, they do not have to make any other energy efficiency upgrades to the rest of the building. However, if they use gas for both space and water heating, they must offset the higher energy use and carbon emissions of gas appliances by including other energy efficiency measures such as more insulation or better windows. This incentive approach gives builders strong financial encouragement to transition off fossil fuels while leaving implementation flexibility for their internal processes, such as training their workforce and evolving their marketing practices. Such considerations are needed as many California

communities depend, in part, on fossil fuels like propane, for heating. With grid instability, winter storms, and sparse rural electrification, fuel flexibility is needed.

Beyond such building codes, more than 50 local jurisdictions in California, including Sacramento, Los Angeles, Santa Barbara, San Jose, and San Francisco, have adopted electric-friendly “reach codes” (Velez and Borgeson, 2022).^[13] In addition to model local and state codes, local jurisdictions may also follow the CALGreen building codes.^[14] The California Green Building Standards Code has the authority to propose CALGreen standards for nonresidential structures that include new buildings or portions of new buildings, additions and alterations, and all occupancies where no other state agency has the authority to adopt green building standards. As a result of local success, the 2022 Energy Code follows the lead of early adopter California Cities and Counties that have implemented more robust local building energy codes.

Several agencies are providing support and incentives for state and local building code adoption. For example, the Bay Area Regional Energy Network (BayREN) offers a suite of electrification programs for businesses and single- and multi-family homes. Multifamily properties that undergo energy and water efficiency upgrades can earn cash-back rebates of up to \$750 per unit; single-family upgrades can earn up to \$2000 cash-back for heat pump water and space heater installations, \$300 for induction cooktops, and \$800 for duct sealing or replacement; and small and medium businesses can earn on HVAC, refrigeration, and lighting upgrades. BayREN's online Home Learning Center also provides multilingual educational and planning resources to help customers transition to electric appliances (Velez and Borgeson, 2022). A second pilot program is the San Joaquin Valley Pilot.^[15] This program is a \$56 million initiative to replace wood and propane appliances in nearly 2,000 homes in the San Joaquin Valley with electric appliances. The pilot will retrofit homes in disadvantaged communities at no cost to the participating household, with the aim of reducing participants’ total energy costs. The goal is to demonstrate the feasibility and benefits of efficient electrification to residents so it can be scaled to all San Joaquin Valley residents currently burdened by high energy costs (Velez and Borgeson, 2022). These local efforts demonstrate how nonprofit, city, and county leadership is essential for equitable local climate action (Faddoul, 2021).

Several additional building decarbonization efforts are led by the state through assessments, incentives, and regulations. For example, AB 3232 (Friedman, 2018) requires the CEC to prepare a Building Decarbonization Assessment, working in consultation with the California Public Utilities Commission (CPUC) and other state agencies, to explore the potential for California to reduce GHGs from buildings by 40 percent below 1990 levels by 2030. The assessment illustrates the state’s pathway to decarbonizing single-family, multifamily, and commercial buildings; identify challenges and opportunities from decarbonizing; estimate the impact of decarbonization activities on the electricity grid; and illustrate topics and data gaps needing additional analysis.^[16] While AB 3232 explores the potential building decarbonization

landscape across the state, Senate Bill (SB) 1477 (Stern, 2018) calls on the CPUC to develop, in consultation with the CEC, two programs (BUILD and TECH) aimed at reducing greenhouse gas emissions associated with buildings. The Building Initiative for Low-emissions, or BUILD Program, offers up to \$20 million per year for four years to promote the construction of new residential housing that utilizes near-zero-emission building technologies and provides additional incentives for all-electric new residential construction. Technology for Clean Heating, or the TECH initiative, will help develop the market for low-emission space and water heating technologies for new and existing residential buildings through consumer education, contractor training, vendor training, and the provision of upstream and midstream appliance incentives. TECH also offers up to \$30 million annually for four years to promote purchases of low-emission space and water heating equipment (CPUC, 2019). AB 209 (2022) authorizes the Equitable Building Decarbonization Program,^[17] which CEC is developing to reduce GHG emissions in homes and advance energy equity through a direct install program that provides retrofits to low- and moderate-income households. The program strives to encourage resilience to extreme heat, improve indoor air quality, improve energy affordability, provide electric grid support, and increase payment of prevailing wage to the implementing workforce. Further, SB 49 (Skinner, 2019) requires CEC to adopt standards for appliances to facilitate the deployment of flexible demand technologies. CEC is currently undergoing a rulemaking to establish these standards and labeling requirements to expand on efforts to facilitate and deploy flexible demand technologies for appliances. Finally, AB 2446 (Holden, 2022) tasks CARB with developing a framework for measuring and reducing the average carbon intensity of the materials used in the construction of new buildings.

State codes also regulate how local jurisdictions can create, procure, and distribute energy. For example, Section 218 of the California Public Utilities Code requires that any entity wishing to sell energy to more than two contiguous parcels become a regulated electrical corporation. These requirements help ensure that the utility is meeting public customer service expectations, public safety standards, and just and reasonable terms and conditions of utility service (Public Utilities Code §§ 451, 454 and 728). Such regulations make small-scale neighborhood microgrids costly to start-up. Similarly, rules developed by the state's investor-owned utilities (PG&E Electric Rule 18, SCE Electric Rule 18, and SDG&E Electric Rule 19; collectively known as Rule 18/19) also govern the supply of electricity to separate premises and often prohibit one premise from supplying electricity to a different premise. In 2021, CPUC issued Decision 21-01-018, directing Southern California Edison Company (SCE) and Pacific Gas and Electric Company (PG&E) to revise their Rule 18, and San Diego Gas & Electric Company (SDG&E) to revise its Rule 19. The Decision allows for microgrids owned by public agencies or by a third party serving public agencies to supply electricity to critical facilities owned or operated by a public agency on adjacent premises without becoming a regulated, electrical corporation. The Decision also directs IOUs to develop a Microgrid Incentive Program to fund clean community microgrids that support the critical needs of vulnerable populations most likely to be impacted by grid outages.

These developments will likely encourage local planning and development of distributed energy approaches.

Zero-emission standards for appliances and equipment are another strategy for achieving building decarbonization. As a part of the 2022 State Strategy for the State Implementation Plan adopted in 2022,^[18] CARB has committed to develop a regulation to require zero-emission GHG space and water heaters to reduce emissions from new residential and commercial heaters sold in California. The Bay Area Air Quality Management District has adopted rules to require the sale of zero-emission NOx space and water heaters sold in the air district.^[19] The South Coast Air Quality Management District has proposed similar rules.^[20]

Aside from legislative bills and building codes, two other well-known voluntary efficiency programs exist: Energy Star and LEED. The Environmental Protection Agency administers the Energy Star program, which assigns the Energy Star label to appliances that meet its efficiency standards. This provides consumers with an easily interpretable signal that these products are energy-efficient. Empirical research has found that consumers are willing to pay ^[21] more for Energy Star appliances—meaning that such appliances are often out of the price range for lower income households, resulting in inequities in adoption (Environmental and Energy Study Institute, 2011). Consumers using Energy Star products prevented more than 300 million metric tons of greenhouse gas emissions in 2014 alone, and saved homes and businesses \$34 billion in utility costs (Environmental and Energy Study Institute, 2011)—underscoring the compounding inequality as such technology primarily benefits higher income households. In comparison with communities that did not implement Energy Star, total disclosure of both energy use and Energy Star together can be credited with a 6% reduction in building energy use intensity (EUI) three years later and a 14% reduction in EUI four years later (Meng et al., 2017). Disclosure of Energy Star scores decreased building EUI by 9% three years later and 13% four years later in New York (Meng et al., 2017). Similarly, the LEED program is a building energy performance and environmental criteria rating system overseen by the U.S. Green Building Council. LEED buildings generally use less energy per unit floor area than non-LEED counterparts and can command higher sales and rental prices (Fuerst and McAllister, 2011; Leibowicz et al., 2022)—thereby catering to higher income families. In sum, these price signals send a message that higher income households care more and will invest more in decarbonization, when in fact, lower income households are simply priced out of joining many decarbonization programs. To counter such signals, outreach programs paired with rebates for low income households can help bring parity to the decarbonization produced and housing markets.

History, Impact, and Feasibility of CA Building Decarbonization

This section discusses the history and impact of the building decarbonization programs in California with attention to feasibility of equitable policy adoption at the local level.

Building Codes for Electrification

Research has shown that reducing GHG emissions in the building sector by electrifying buildings is the most cost-effective near-term decarbonization opportunity. According to a study by Zhu et al. (2022), using renewable energy in the electricity sector can account for roughly 72% of generation in 2050 in high-alignment scenarios (Zhu et al., 2022). Further, Victor et al. (2018) find that achieving 80% GHG emissions reduction below the 2005 levels by 2050 is technically feasible by deploying existing or near-commercially available technologies. GHG reductions are primarily achieved through high levels of electricity sector decarbonization, electrification of end uses, and exchange of the remaining end-uses to lower carbon fuels such as natural gas (Victor et al., 2018). Through preliminary analysis that examines the potential impacts of widespread electrification on the U.S. energy sector, Steinberg et al. (2017) find that electrification, in the absence of any additional power sector carbon policy, can result in 41% reductions (below the 2005 level) in economy-wide fossil fuel combustion emissions. The level of electrification and the degree of decarbonization explored in these scenarios are not, in isolation, sufficient to achieve reductions in economy-wide GHG emissions of 80% below the 2005 level. Yet, despite the need to involve additional strategies for reduction, these cost-feasibility studies demonstrate that electrification will play a significant and vital role in achieving a low-carbon future (Steinberg et al., 2017).

While cost-effective overall, such studies often do not address the household-level economies of building decarbonization. Indeed, the above studies note that to implement changes, the construction phase presents the best opportunity to make buildings more efficient, as many energy and cost-saving options are lost if they are not built into the original design (Brown and Southworth, 2008). Here, Building Energy Codes (BECs) have the potential to reduce these lost opportunities by requiring existing buildings to achieve at least a minimum level of energy efficiency. However, codes vary considerably by region and often lack consistent enforcement and support programs. Uncoordinated efforts result in an overall shortfall in energy performance (Brown and Southworth, 2008). Lower-income households often rent and can achieve cost savings by renting older building stock. According to the 2020 census, renter-occupied households made up 52.9% of households in the lowest income quintile and 42.4% of households in the second lowest income quintile. Not only will local decarbonization-focused building codes need to target landlords without passing the cost burden on to renters, but stronger Zero Emissions Building Codes and enforcement at the state and local level are also needed to help overcome these obstacles (Ürge-Vorsatz et al., 2007). For example, one study that evaluated the BECs of European countries found that a policy mix with multiple equity-focused strategies is the most effective approach to not only achieving decarbonization goals, but preventing the cost burden from being shouldered by already vulnerable populations of renters and low-income people (Kern et al., 2017; Rogge and Reichardt, 2016).

Not only do BECs encourage technology uptake in the construction phase, but the US

Department of Energy projects that the energy cost savings from building efficiency codes will result in \$125 billion by 2040 (Athalye et al., 2016). Some of these cost savings are passed on to renters with direct equity benefits. Koirala et al. (2014) estimate the net implicit price of energy-efficient building codes for American households using sample data from the American Community Survey 2007. They find that BECs provide families a compensating differential of about a 6.47% reduction (about \$7.71) in monthly energy expenditure. Results indicate that the mean household net implicit price for BECs is about \$140.87 monthly in 2006 dollars (\$163.19 in 2013 dollars) (Koirala et al., 2014). However, this estimated price varies significantly by region, energy type, and the rent gradient. With cost savings and reduced emissions, BECs are politically feasible and popular policy instruments (Gillingham and Palmer, 2014). They are especially suitable when dealing with a target group that is unwilling to act or difficult to address (e.g., landlord-tenant energy upgrade spilt incentives) or when aiming at removing the worst products or services from the market with regard to energy consumption (Harmelink et al., 2008). Consequently, implementing effective, coordinated BECs has been proposed as a key issue for building decarbonization in the research (Evans et al., 2018). To help balance these considerations, local jurisdictions should consider estimates of cost savings for households to adopt decarbonization policies. These estimates can be included in the local energy bill and outreach to inform consumers.

As landlords come into compliance with BECs, rent control policies may also need to be put in place. For example, a study on ten US cities and 159,000 rental properties found that as energy efficiency standards and compliance occurred, the implementation of energy efficient features increased the units' rent, overall from 6% to 14% (Im et al., 2017).

Weatherization and Renovation of Existing Building Stock

Weatherization and retrofit policies are also needed to address the energy efficiency of pre-existing buildings. Existing buildings represent a significant component of the building decarbonization arena, as 80% of the existing buildings in 2050 have already been built (Lucon et al., 2014). Since retrofit and weatherization technologies, policies, and costs often differ from those associated with new buildings, they require their own implementation pathways (Coffey et al., 2009).

These strategies are a critical policy arena for low-income areas and disadvantaged communities living in the least energy-efficient buildings in the housing stock. One report from the PEW research center described how low-income households in the US spend, on average, 14% of their income on energy needs, compared with the 3.5% of income spent by other households, based on the authors building sector policy analysis (Brown, 2005; Brown and Southworth, 2008). The federal government has long recognized the importance of renovation and weatherization of low-income homes, dating back to the U.S. DOE's creation of the Weatherization Assistance Program (WAP) in 1976. The purpose and scope of the program are to increase the energy efficiency of

homes owned or occupied by low-income persons, reduce their total residential energy expenditures, and improve their health and safety, especially for low-income persons who are particularly vulnerable, such as older adults, persons with disabilities, families with children, high residential energy users, and households with high energy burden.

To achieve these goals, DOE provides grants to states, territories, and tribes. In 2022, the U.S. Department of Energy (DOE) announced \$32 million to fund following generation building retrofit projects to develop fast, cheap, low-carbon building renovation and construction techniques. These techniques focus on prefabricated walls, air sealing, insulation (e.g., wall, attic, windows), ventilation, and drop-in replacements for high-efficiency heating, cooling, and hot water systems. Together, these measures could cut thermal energy use in buildings by 75% (DOE, 2022). In support, Leibowicz et al. (2022) develop an optimization model to determine the least-cost decarbonization pathways based on the residential buildings sector of Austin, Texas, and find that improving the thermal efficiency of residential buildings through renovation and weatherization generates substantial cost savings and significantly lowers the cost of climate policy. For instance, upgrading building thermal efficiency to a LEED Gold standard reduces annual utility costs. The shift to more efficient energy-use homes reduces costs for peak generation capacity, battery electricity storage, space cooling and heating appliance capacity, and energy consumption (Leibowicz et al., 2022). Such upgrades also present non-energy benefits for the household through income, household expenditures, reduced utility costs, environmental benefits, and improved health and safety, as one study found after conducting a national occupant survey of random samples of weatherized households (Tonn et al., 2014). Descriptive statistics generated from these surveys suggested that post-weatherization, homes are more livable; the physical condition of homes is improved; residents experience fewer ‘bad’ physical and mental health days; household members suffer fewer persistent colds and headaches; households are better able to pay energy and medical bills; and households are better able to pay for food (Tonn et al., 2014). Unfortunately, progress on weatherization, renovation implementation, and enforcement has been slow, hindered by challenging project economics and landlord-tenant split incentives where landlords bear the cost of upgrades, and tenants reap the benefits of lowered utility bills. Local governments can educate and create awareness about federal funding, health benefits, and state laws. Again, rent protections for compliance may help reduce instances where costs of weatherization are passed on to lower-income renters.

Efficiency Standards for Appliances

Within the building, most electricity and energy use goes to residential and commercial end uses from appliances. For example, more than 76% of all U.S. electricity use and more than 40% of all U.S. energy use and associated greenhouse gas (GHG) emissions are used to provide comfortable, well-lit residential and commercial buildings—and to provide space conditioning and lighting for industrial buildings (DOE, 2015). Electricity and energy powers appliances and

equipment, like lighting, refrigerators, water heaters, gas-powered stoves, clothes dryers, central air conditioners and heat pumps, ceiling fans, and dishwashers. Efficiency standards are the most commonly cited tool to reduce appliance GHG emissions. These appliance efficiency standards are developed and proposed as federal regulations, with input from manufacturers, energy experts, consumer advocates, and other stakeholders. Together, they establish technical feasibility and cost-effectiveness parameters and use federal efficiency standards to compel product designers and manufacturers to reduce the amount of energy and water necessary to operate appliances and other building equipment properly. Efficiency standards ensure that minimum efficiencies are met by all regulated products sold while prohibiting the least efficient products from appearing on the market. Appliances and building equipment typically need to be replaced every 15 years, providing a regular opportunity to improve a building's energy efficiency (Delforge, 2021). Studies confirm the significant and widespread benefits of efficiency standards, with the DOE estimating that these standards reduced our national energy bill by about \$80 billion in 2015, the equivalent of the electricity needs of nearly one in three American households (DOE, 2022). An earlier study by Meyers et al. (2003) echoed these cost-effective findings by analyzing initial standards and updates for nine different products from 1988 to 2000. Their study showed that appliance standards cut US electricity use by 2.5% annually, primary energy consumption by 1.3%, and US carbon emissions from fossil fuel use by 1.7%, jumping to 8–9% by 2020. The cumulative net benefit to consumers and businesses is nearly US \$80 billion by 2015 and will grow to US \$130 billion by 2030 (Meyers et al., 2003).

Some appliances and equipment are more important for targeting efficiency standards than others. For residential buildings, 63% of cumulative efficiency savings come from lighting, refrigeration, and central air-conditioning. For commercial buildings, these three uses contribute 81% of the savings (Brown et al., 2005). For example, in reducing cooling emissions, the whole house fan works by producing a wind chill effect, which flushes the house with high volumes of outside air, thereby preventing temperatures from building inside. It also reduces the temperature of attics by about 10 degrees F on a warm summer day, this cooling effect significantly reduces the mean radiant temperature (MRT) of the ceiling (which has a high impact on our comfort level). There are additional benefits in that a whole house fan can quickly remove pollutants such as smoke, cooking odors, and harmful chemicals. A properly selected, installed, and operated fan can reduce overall cooling costs by as much as 50% (Cook, 1992) while costing about as much as a good ceiling fan (\$150-300). Savings usually pay for the fan in less than three years.

Further, emissions from lightbulbs have decreased by more than half due to increased efficiency from LED bulbs, and reducing the use of incandescent bulbs (Leung, 2018). An LED (light-emitting diodes) bulb can last up to 25 times longer than an ordinary incandescent bulb, uses 75 percent less energy to produce the same amount of light, and saves consumers \$119 in operational costs for each bulb throughout its lifetime (Leung, 2018). LEDs are the product of the DOE's partnerships with lighting manufacturers to research, develop, and test solid-state lighting technologies. This technology can be paired with sensors for use in infrequently visited

areas (like restrooms) to further reduce energy use. Local governments can create education programs about these technologies as well as incentive programs for adopting these technologies.

While these cooling, lighting, and refrigeration innovations have allowed a decrease in GHG emission, almost a third of the energy consumed by residential buildings is for space heating, followed by water heating and lighting (both 12%) and air conditioning (11%) (EIA, 2004b). The remaining third of the energy consumed in homes is used for the rest of the appliances, electronics, and other purposes (EIA, 2004b). These energy uses suggest that the most obvious opportunities to reduce GHG emissions beyond the initial focus on lighting, refrigeration, and cooling are through improvements to space and water heating (especially in the residential sector) (Brown and Southworth, 2008). For these reasons, local jurisdictions should focus on demonstrating energy efficient products in public buildings to raise awareness about rebate programs, opportunities to recycle and upgrade appliances for low-income households, and standards for rental codes.

Expanding the use of energy efficiency technology

Public education and outreach is especially important in California where nearly 90 percent of homes use gas for heat or hot water or both, with burning gas for furnaces and water heaters contributing more than half of the emissions from the building sector (Hopkins et al., 2018). Transitioning to clean electric heat is critical to reducing carbon emissions, especially as the electric grid becomes more stable, buildings become more efficient, and utilities align their pricing with carbon-cutting goals (Hopkins et al., 2018).

Heat pumps offer a highly efficient, cost-effective electric alternative that could further cut California's buildings emissions by 7 million metric tons per year by 2030 if a third of California's buildings switched to clean electric heating technology (Hopkins et al., 2018). Electric heat pumps transfer heat from the air into water stored in a tank using compression technology, such as those found on all household refrigerators, instead of burning fuel to create heat. More than emissions reductions alone, heat pumps increase electrical efficiency by replacing electric resistance water heaters and provide utility bill savings for ratepayers due to technology efficiencies and the ability to shift electric consumption to parts of the day when renewable energy resources are abundant, and electricity prices are lowest. In addition to heating homes and water heaters, heat pump technology can be used to power induction cooktops as alternatives to gas cookstoves, dryers, and even HVAC cooling systems. A study by Waite and Modi (2020) synthesizes several disparate publicly available datasets (e.g., monthly state-level energy usage, local hourly temperatures, census tract-level heating fuel, and building floor area) to model the impact of building space heating electrification across the United States and find that currently available electric heat pumps can reduce fossil fuels to 43% of total heating energy supply (currently 70%). Future advances in heat pump technology could reduce this further to 23% (Waite and Modi, 2020). Walker et al. (2022) conduct a state-by-state analysis of space

heating electrification in the US and find that weighted average carbon savings of 35% (and a 1% energy cost increase) were possible nationally using currently available high-performance heat pumps compared with high-performance gas furnaces at 95% efficiency (Walker et al., 2022). Unfortunately, these technologies represent a small share of California's market due to regulatory barriers and high upfront installation costs in older homes. Contractors are unaware and not trained in installation. These market barriers need to be addressed to meet GHG emissions reductions goals by 2030, as explored by Mahone et al. (2018), who develop long-term energy scenarios through 2050 using the California PATHWAYS model, an economy wide, technology-specific scenario tool developed by Energy and Environmental Economics (E3) from 2009 through the present. Their results show that 50% of new HVAC and water heating equipment sales must use heat pump technology by 2030 (Mahone et al., 2018). Heat pumps also benefit from policy support to jump start sales, reduce consumer costs, and make them more broadly available (examples: BUILD, TECH, Self-Generation Incentive Program, the Equitable Building Decarbonization Program). At the federal level, the 2023 federal tax credit for heat pumps is 30% of the purchase and installation cost, up to \$2,000. One review of home heating electrification programs in the US, published by ACEEE, noted the significance of rebates as an incentive for heat pump uptake, ranging from \$165– \$1,600 per ton, and water heating and cooking incentives were commonly \$91- \$800 per unit (Cohn and Efram, 2022). Additional financial incentives include electric rates with a significant difference in peak and off-peak pricing opportunities for customers to set their heat pumps to operate when electricity is cheapest and cleanest (Hopkins et al., 2018). To ensure equitable adoption, local jurisdictions can raise the profile of these cost-saving technologies by encouraging adoption and demonstrating use.

District Energy

Beyond the home, at the scale of neighborhoods and campuses, District Energy (DE) further offers a highly efficient solution to heat and cool multiple buildings simultaneously, reducing operating costs and keeping more energy dollars local. Instead of every home and office operating an individual boiler, heat is produced centrally by water heated in a boiler and distributed through underground insulated pipes to heat exchangers at the point of use for hot water, ambient heat, and cooling (Bouffaron and Koch, 2014; Brinkley 2018). This network of underground pipes is a highly efficient way to heat and cool many buildings in a given locale from a central plant, such as a downtown district, college or hospital campus, airport, or military base. Fuel for the central boiler is highly versatile and can be coupled with various large and small-scale heat sources, such as geothermal and heat produced as a byproduct of industry (Lund et al., 2014). Providing heating and cooling from a central plant requires less fuel and displaces the need to install separate space heating, cooling, and hot water systems in each building. Further, district energy systems also allow for low-cost heat storage during overproduction from more volatile renewable energy sources, such as wind and solar (Lund, 2005; Connelly et al., 2014).

The United Nations estimates that transitioning to DE systems, combined with energy efficiency measures, could result in a 30–50% reduction in primary energy consumption, thereby reducing CO₂ emissions by 58% in the energy sector by 2050 and allowing global temperature rises to stay within 2–3 °C (UNEP, 2018). Sweden presents one case example of implementing district energy on a large scale, as GHG emissions were reduced by 60% from the 1970s, and the energy supply turned from importing 75% of the energy in the form of fossil fuel to greater reliance on locally produced energy, particularly biofuels from forest and agriculture byproducts (Summerton, 1992; Palm, 2006). In Sweden, as elsewhere, thermal planning started at the neighborhood scale and grew with support of national policies (Lund, 2005; Connolly et al, 2014; Han et al.; 2021). DE also offers a transition path for balancing the grid during volatile renewable energy production as energy can be stored as heat (Connolly et al., 2014).

In California, DE is a primary decarbonization pathway for campuses, like schools and hospitals. For example, to align with the state target, the University of California's climate policy, adopted in 2023, expects to eliminate emissions by 2045 largely through upgrading to DE on all 10 campuses. Demonstrating success, since UC began tracking its climate impact in 2009, it has cut carbon emissions by a quarter despite significantly increasing its enrollment, and saved \$400 million in energy costs by improving efficiency. At UC Davis, upgrades to the DE will reduce fossil fuel use on campus by 80%.^[22] Similarly, updates to Stanford University's DE system in 2014 cut campus GHG emissions by 68% and fossil fuel use by 65% (Lapin and Chelsey 2015). These campuses offer demonstrations and there is potential to connect neighborhoods and buildings off-campus to DE systems (Han et al., 2021). Local jurisdictions can explore DE extensions from these established DE systems, building out and plugging in, just as other jurisdictions have joined DE networks. Such effort will take concerted energy planning.

DE benefits communities by reducing their operating costs due to a decreased need to import fuel for heating and cooling. Environmental impacts from heating and cooling are significantly reduced because of these systems' greatly improved efficiency. Developing district energy and Combined Heat and Power (CHP) systems can help ease the power sector's transition as older, polluting coal plants are shut down and removed from the grid. District cooling can cut peak electrical demand that typically occurs in the late afternoon – reducing strain on the grid and avoiding expensive peak power costs (Environmental and Energy Study Institute, 2011). The district nature helps ensure heating and cooling equity as multiple buildings and campuses are joined into a heat and/or cooling grid. In addition to the added resilience of the neighborhood network, DE opens opportunities for microbusinesses to sell heat back to the grid. For example, a bakery can sell excess heat back to the DE grid when there is demand (Werner, 2017).

Importantly, low-cost deployment of DE systems relies on higher density development to ensure that the cost of new pipes carrying heated or chilled water is cost and energy effective. To achieve a lower cost DE system, local jurisdictions will need to review their zoning and land-use planning to encourage high density development. Further, a transition to DE requires

infrastructure investment. Even though the studies above show the significant long term energy savings and environmental benefits – and the fact that projects generate many good paying jobs – the upfront costs of constructing DE systems can discourage developers. Connecting CHP systems to the power grid can also present challenges. Here, the federal government can play an essential role in encouraging investment in DE/CHP systems through various financing and regulatory mechanisms (Environmental and Energy Study Institute, 2011) while local jurisdictions should be mindful to not make new energy infrastructure into LULUs, but desired architectural features—just as many European cities have done with their newly sited DE systems (Brinkley, 2018).

Siting Renewable Infrastructure

Broadly, renewable energy infrastructure is needed to meet the growing demand for clean electricity generation, including bioenergy, wind turbines, solar power, transmission lines, and nuclear power. In the near term, local governments can support renewable energy generation by permitting and siting new renewable energy infrastructure to guarantee adequate clean electricity generation, satisfy rapidly growing demand from end-use electrification, and transition away from fossil fuel sources (Zhu et al., 2022). A study by Waite and Modi (2020) quantifies the relative capacities of fossil fuels and electricity delivery infrastructure and estimated heat pump (HP) penetration possible with current electricity delivery capacity in the US. They estimate that an “all-electric” approach could require a 70% increase in nationwide electricity system capacity—and thus the development of new, local energy infrastructure (Waite and Modi, 2020).

Each renewable energy source presents its own list of challenges and possibilities, with impacts varying by region. For example, the Central Valley (which encompasses 15% of CA by area) has great potential for photovoltaic (PV) solar energy development. Hoffacker et al. (2017) report that the Central Valley comprises a capacity-based energy potential of at least 17,348 TWh year⁻¹ for PV solar power. Accounting for technology efficiencies, this exceeds California’s 2025 projected electricity demands by up to 13 times (Hoffacker et al., 2017). Similarly, biomass and waste incineration have been broadly adopted in European and Asian countries. This renewable resource is in demand in California’s colder, northern counties. Yet, combustion and the placement of affiliated smokestacks are often contentious. Similarly, wind turbines and transmission lines are often criticized for disturbing viewsheds. Brinkley and Leach (2019) reviewed 54 studies spanning over forty years of statistical multivariate housing price assessments about energy supply infrastructure and provided a comparative meta-analysis of both the negative and positive local impacts of siting energy infrastructure locally. They concluded that of all energy infrastructure, only rooftop solar consistently positively impacts home value (Brinkley and Leach, 2019)—leaving local planning to grapple with design decisions to not create LULUs when siting and building new energy production infrastructure.

Indeed, public demand for low-cost and renewable energy often does not match a community’s

willingness to host energy supply infrastructure. The decision to site energy facilities occurs largely at the local level, requiring community support for permitting and construction. As communities consider energy production, they often weigh such benefits against concerns for how facilities may impinge on the local quality of life (Brinkley and Leach, 2019). Zhao et al. (2019) compare decarbonization pathways in California that focus on electrification and those that require siting clean, renewable energy infrastructure. Zhao et al. (2019) estimate that, compared with business-as-usual, a decarbonization pathway that combines electrification and clean renewable energy will reduce concentrations of fine particulate matter (PM_{2.5}) by 18–37% in major metropolitan areas of California and subsequently avoid about 12 100 (9600–14 600) premature deaths. In contrast, only a quarter of the avoided deaths could be achieved through a pathway focusing more on combustible renewable fuels, like biomass boilers. These co-benefits of decreasing GHG emissions while improving local air and water quality are often not considered when citing renewable infrastructure. To help local jurisdictions weigh cost, local environmental impacts, and potential benefits, state and regional governments can create data dashboards and provide tools to help with CEQA review. Where possible, Health Impact Assessments (NRC, 2011) can also be used to quantify human health impacts in addition to expected environmental impacts reviewed under CEQA.

Producing energy locally has also emerged as a priority area for communities and policymakers as it can protect regional economies from volatile import-driven energy markets, reduce the environmental impact of energy production and distribution, and diversify the energy supply (Carbajal, 2016). Andrews (2008) recommends that localization of energy supply requires new conceptual models for thinking about how to right-size demand to distributed supply in an ever-changing landscape. DeRolph et al. (2019) illustrate how creating annual city energy shed snapshots using GIS and grid data provides a visual representation of a respective area's energy portfolio, the extent of the grid required to meet energy demands, and the resulting environmental impacts. Computational models integrating the built environment components with supply side considerations can also help optimize efficiency and loss from the energy shed (Schuler and Cajot, 2019). Kammen et al. (2006) report that transitioning to a renewable energy portfolio can also grow local economies and create jobs; a 20% national renewable energy portfolio by 2020 consisting of 85% biomass, 14% wind energy, 1% solar PV is expected to create 163,669 new jobs for the United States. In addition, community energy aggregation and storage solutions give neighborhoods and homeowners options for uninterrupted renewable electricity during periods of shifting renewable generation and peak load (Atwa et al., 2009; Starke et al., 2016). Here, local jurisdictions can use the energy planning process to help scope out these potential benefits that fall outside of strict cost-feasibility project assessments.

Communities' increased appetite to meet local energy needs through renewables often includes considerations for decentralized microgrids and familiarization with DE generation, representing relatively new approach in local planning (APA, 2004). For example, East Bay Community Energy (EBCE), a community choice aggregator in the San Francisco Bay Area, launched 30

microgrids in San Leandro, Berkeley, Hayward and Fremont, California, with 3.1 MW of solar panels and 6.2 MWh of battery storage. The decision to site such energy facilities occurs mainly at the local level, requiring community support for permitting and construction. Many such demonstration projects face considerable hurdles as a result of Section 218 of the California Public Utilities Code (CPUC) which requires any entity that sells energy to more than two contiguous parcels or across the street to become an electrical corporation regulated by the CPUC. While difficult to quantify, the design of new energy projects can significantly impact reception and spillover impacts on surrounding land and housing values as evidenced by mega projects, like Copenhagen, Denmark's state-of-design Ammager Bakke biomass plant, which is driving new development as an attraction for nearby neighborhoods (Hulgaard and MSc, 2018).

The transition to renewable energy supply also presents a need to store the excess energy—with a role for local governments in siting new energy storage facilities (Hampton et al., 2017). In 2020, the U.S. accounted for 40% of the world's currently operational energy storage projects, and the National Renewable Energy Laboratory expects the U.S. to more than quintuple its storage capacity in the next 30 years (Hicks, 2020). California leads the country with 4.5 gigawatts (GW) of operational pumped hydro storage capacity, about 1.5 GW from batteries operating by Spring 2021 (California Energy Commission, 2015). Governments, utilities, and energy companies are increasingly looking for additional energy storage technologies to extend the availability of variable renewable power sources such as solar and wind. Turley et al. (2022), map and analyze landscapes of renewable energy storage emerging across the Western United States, focusing on the rollout of several interrelated leading technologies: utility-scale lithium-ion batteries and proposals for new pumped storage hydropower. They find that many of the projected transformations and impacts of storage rollout will occur in rural California, presenting just energy transition issues as rural communities bear the burden of hosting energy infrastructure that urbanites refuse. Turley et al. (2022) argue that a full accounting of renewable energies' environmental and social impacts should not be diminished despite the urgency of climate change and the need for climate solutions. Instead, it should be acknowledged that, like any technical solution, energy storage technologies and techniques will have spatial consequences and justice dilemmas (Williams et al., 2019).

Energy storage solutions are also included in California building codes. Building codes from 2019 specify rooftop solar requirements from new single-family and low-rise residential apartments to solar and storage in new multifamily and non-residential buildings. The solar and storage requirements are modest but very cost-effective for the building occupant, saving far more over their lifetime than they cost upfront. They will result in buildings that are more resilient to power outages and can reduce their use of grid electricity at peak times when electricity is scarce, expensive, and dirty. Together, these changes will save Californians \$1.5 billion in costs and 10 million metric tons of greenhouse gas emissions over the 30-year life of the buildings, per CEC estimates (Delforge, 2021).

Energy and Decarbonization Planning

While siting energy facilities remains a contentious planning issue largely under local jurisdictional control, a lack of comparative studies on the local impacts of energy infrastructure makes scenario building difficult for many communities. Land-use planning is an under-represented discipline in energy scholarship, as Sovacool (2014) noted in an analysis of 4,444 research articles covering the past 15 years. Only 1.1 percent of energy articles consist of studies on the role of infrastructure scale and spatial considerations (Sovacool, 2014). In general, land and housing values are influenced by different energy infrastructures *and* their design (Brinkley and Leach, 2019). In addition, planning's role in energy infrastructure has changed. Pitt et al. (2013) noted the shift to a collaborative planning approach focusing initially on municipal facilities, followed by incentives for businesses and residents. DeRolph et al. (2019) and Pitt et al. (2013) assert that the first step toward cities transitioning to renewables is municipal commitment to such a transition that entails coalition building and value setting.

Local governments are well-equipped to work with communities in visioning strategies that match public preferences in energy sourcing with public preferences in local siting. Furthermore, long-range planning can ensure that current policies and pathways are consistent with long-term goals. Building on these approaches, numerous cities and the state of California have adopted Climate Action Plans (Wheeler, 2008; Bassett and Shandas, 2010), many of which include a broad approach in assessing total energy use and seeking simultaneously to reduce use and relocalize energy sources to low-risk, low-impact infrastructure.

Relocalization is increasingly taking the form of Community Choice energy Aggregation (CCA). In 1997, Massachusetts became the first state to allow CCAs, enabling cities and counties to aggregate the electric loads of residents, businesses, and public facilities to facilitate the purchase and sale of electricity. The Cape Light Compact in Massachusetts bought power on behalf of 197,000 customers who saved between 11 and 22% on the generation portion of their bill (Whitcomb, 2002), demonstrating the power of local control over energy efficiency and cost. Ohio was the second state. There, the Northeast Ohio Public Energy Council served 455,000 customers in 112 communities through an agreement with Green Mountain Energy to provide two percent of generation from renewable sources (Brown, 2002). Customer-specific savings ranged from 1 percent to 15 percent, with total cost savings over the life of the five-year contract estimated to be \$10 million (Brown, 2002). California communities have increasingly adopted CCAs—such that 60% of consumers are covered since 2020 (Kennedy and Rosen, 2021)—with the majority being those in wealthier, more urban communities. As some communities can choose cleaner energy, the transition has created tensions with larger-scale utility companies that maintain equipment and have mandates to serve lower income and rural populations.

As communities begin to form value statements around their energy supply, there is room for local planners to engage in conversations about how to match the demand for low-cost, low-

emission energy with housing infrastructure and ensure the transitional costs are met equitably. Tax rebates, such as solar power credits, often privilege the already wealthy (Zycher, 2016). Current regressive energy pricing prompted the federal Low Income Home Energy Assistance Program (LIHEAP) in 1981, which helps low-income families with electricity and heating bills (Kaiser and Pulsipher, 2003). Updating and transitioning energy supplies equitably will require similar progressive measures to not continue overburdening low-income families within local jurisdictions or regionally.

Co-Benefits and Equity

Building decarbonization offers many co-benefits while exposing equity issues rampant within the built environment and resource consumption. Due to structural racism in housing and economic systems in the US, communities of color are disproportionately exposed to pollution, energy costs, and poor housing quality. Many of these communities are also highly vulnerable to extreme weather from climate change, lacking access to cooling and resilient infrastructure (Tan and Jung, 2021).

Low-income families pay a higher percentage of their finances toward energy (Fankhauser and Tepic, 2007; Walker and Day, 2012; Kontokosta et al., 2020) and experience ‘fuel poverty.’ Among lower income households, households of color experience higher energy cost burdens (Kontokosta et al., 2020). Families cannot afford to cool their homes during heat waves or heat their homes during the winter, with fatal outcomes. The negative effect of extreme heat on people in low resourced neighborhoods was apparent during the 1995 heat wave in Chicago. Multiple studies have concluded that heat-related mortality was highest in less affluent neighborhoods and limited access to community-based resources (Browning et al., 2006; Klinenberg, 1999). In addition, low-income families are more likely to rent older housing stock, which is less energy efficient (Nevin, 2010). Renters usually pay the utility bills but face the split incentive of not being able to make energy efficiency upgrades to insulation, boilers, or renewable energy. Low-cost energy improvements could save low income households about \$1,500 annually (Kontokosta et al., 2020). On the other hand, property owners are not directly incentivized to pay for upgrades that benefit their tenants. Thus, equitable policies should include a focus on renter protections.

Numerous reviews of the scientific evidence have concluded that housing interventions that support home warmth, reductions in fuel poverty, and energy upgrades can potentially improve health, particularly for sensitive populations (Ortiz et al., 2019; York et al., 2022). The International Energy Agency (IEA) published a report on the multiple benefits of energy efficiency (2014) describing how positive health outcomes are consistently most robust among vulnerable groups, including children, the elderly, and those with pre-existing illnesses. Another study echoes these findings, describing how health impacts are greater in low-income communities due to health outcomes disparities, location-based exposure, in-home exposure, and

increased vulnerability to the “heat or eat” dilemma (Tan and Jung, 2021). Other studies estimate that health improvements represent as much as 75% of the total return on the investment for the retrofit interventions, with one study from Massachusetts surveying several hundred low-income households in multifamily buildings finding an estimated annual savings of US \$1,537 for these non-energy benefits (NMR, 2021). These benefits extend out to the neighborhood, with a study on the case of a public housing project in Phoenix, AZ, using several tools to calculate different economic, environmental, and health metrics associated with three levels of energy efficiency. Their results demonstrate that avoided health and climate costs could total around 40% direct utility savings, in addition to energy-saving strategies that cool the neighborhood, make buildings more resilient to heat, improve indoor air quality, and reduce the transmission of airborne disease (Baniassadi et al., 2022). Given the many equity considerations in a just decarbonization transition, local governments will need to create additional tools and outreach materials that help frame benefits and challenges with local values.

Conclusion

Building decarbonization in the US can potentially reduce CO₂ emissions by 72%–78% relative to 2005 levels, just shy of the 80% emissions reductions 2050 goal (Langevin et al., 2019). This can be achieved through a combination of aggressive efficiency measures, electrification, and high renewable energy penetration. Greater political alignment across local, state, and federal levels can enable electrification to play a more significant role as a central component of decarbonization. If the political environment allows more ambitious climate policies, deeper decarbonization could be achieved at a lower average abatement cost (Zhu et al., 2022). Through the combined efforts of energy efficiency upgrades within the building (by reducing the carbon content and use of energy resources and appliances), to the building (with weatherization), and regionally (by shifting energy usage with available technology), decarbonizing buildings can achieve multiple policy objectives, like reaching state climate goals, saving consumers money through reduced energy bills, supporting grid resiliency and reliability, improving indoor and outdoor air quality, and reducing health risks from buildings (California Energy Commission, 2018). Thus, meeting the State's 2050 GHG target is feasible and often desired by multiple constituents. Still, it requires a portfolio of local measures and a commitment to integrating and coordinating policies in the electricity, buildings, transportation, and industrial sectors (Wei et al., 2013).

Table 1. Key Terms

BAU	Business as usual
BEC	Building energy codes, control and regulatory mechanisms that traditionally set minimum requirements for energy use and generation in buildings
Biomass	A plant-based material used as fuel to produce heat or electricity. Includes wood and wood residues, energy crops, agricultural residues, and waste from industry, farms and households.
CCA	Community Choice Aggregation. Allows cities and counties to aggregate the electric loads of residents, businesses and public facilities in order to facilitate purchase and sale of electricity
CEC	California Energy Commission
CHP	Combined Heat and Power
CPUC	California Public Utilities Commission
DE	District Energy
DOE	Department of Energy
Electricity end uses	The energy directly consumed by the user, includes electricity, gasoline, and natural gas.
Energy efficiency gap	Many energy-saving opportunities are not realized even when they are cost-effective
ENERGY STAR	A program which assigns the Energy Star label to appliances that meet specific efficiency standards, administered by the EPA
EPA	Environmental Protection Agency
GHG	Greenhouse gas

Gt CO₂eq/year	Gigaton of carbon dioxide, used to estimate global GHG emissions
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
LED	Light-emitting diode bulb
LEED	Leadership in Energy and Environmental Design, a building energy performance and environmental criteria rating system, overseen by the U.S. Green Building Council
MRT	Mean radiant temperature
PV	Photovoltaic Solar
TWH	Terawatt-hour
WAP	Weatherization Assistance Program
ZCB	Zero carbon buildings

References

- Alexander, M.; Alvarez-Gomez, A.; Bowermaster, D.; Grant, J.; Johnson, B.; Knipping, E.; Krishnamoorthy, S.; Liu, C.; Nopmongcol, U.; Stephens, P.; et al. (2019). Air Quality Implications of an Energy Scenario for California Using High Levels of Electrification; California Energy Commission: Sacramento, CA, USA.
- American Planning Association Policy Guide on Energy. 2004. Accessed January 12, 2022. <https://www.planning.org/policy/guides/adopted/energy.htm>.
- Andrews, C. J. (2008). Energy conversion goes local: Implications for planners. *Journal of the American Planning Association*, 74(2), 231-254.
- Athalye, Rahul A., Sivaraman, Deepak, Elliott, Douglas B., Liu, Bing, & Bartlett, Rosemarie. (2016). Impacts of Model Building Energy Codes. United States. <https://doi.org/10.2172/1334003>
- Atwa, Y. M., El-Saadany, E. F., Salama, M. M. A., & Seethapathy, R. (2009). Optimal renewable resources mix for distribution system energy loss minimization. *IEEE Transactions on Power Systems*, 25(1), 360-370.
- Baniassadi, Amir, Jannik Heusinger, Pablo Izaga Gonzalez, Stephan Weber, and Holly W. Samuelson. (2022). Co-Benefits of Energy Efficiency in Residential Buildings. *Energy* 238: 121768. <https://doi.org/10.1016/j.energy.2021.121768>.
- Bassett, E., and Shandas, V. (2010). Innovation and climate action planning: perspectives from municipal plans. *Journal of the American Planning Association*, 76(4), 435-450.
- Bernstein, S., & Hoffmann, M. (2018). The politics of decarbonization and the catalytic impact of subnational climate experiments. *Policy Sciences*, 51(2), 189-211.
- Bouffaron, P., & Koch, A. (2014). The benefits of combined district energy modelling and monitoring: the case of district heating. *International Journal of Energy, Information and Communications*, 5(1), 21-32.
- Brinkley, Catherine, and Andrew Leach. (2019). Energy next Door: A Meta-Analysis of Energy Infrastructure Impact on Housing Value. *Energy Research & Social Science* 50: 51–65. <https://doi.org/10.1016/j.erss.2018.11.014>.
- Brinkley, Catherine. (2018). The Conundrum of Combustible Clean Energy: Sweden's History of Siting District Heating Smokestacks in Residential Areas. *Energy Policy* 120: 526–32. <https://doi.org/10.1016/j.enpol.2018.05.059>.
- Brinkley, C. (2014). Decoupled: Successful Planning Policies in Countries that Have Reduced per Capita Greenhouse Gas Emissions with Continued Economic Growth. *Environment and Planning C: Government and Policy*, 32(6), 1083–1099. <https://doi.org/10.1068/c12202>
- Brown, Matthew. (2002). An Analysis of Opt-Out Aggregation in Ohio and Massachusetts. Prepared for the National Center for Appropriate Technology's National Energy Affordability and Accessibility Project.
- Brown M, Southworth F, Stovall T. (2005) Towards a Climate-friendly Built Environment Pew Center on Global Climate Change, Arlington, VA, <http://www.pewclimate.org/global-warming-in-depth/> all reports/buildings/index.cfm
- Brown, Marilyn A, and Frank Southworth. (2008). Mitigating Climate Change through Green Buildings and Smart Growth. *Environment and Planning A: Economy and Space* 40, no. 3: 653–75. <https://doi.org/10.1068/a38419>.

- Browning, C. R., Wallace, D., Feinberg, S. L., & Cagney, K. A. (2006). Neighborhood social processes, physical conditions, and disaster-related mortality: The case of the 1995 Chicago heat wave. *American sociological review*, 71(4), 661-678.
- Building Decarbonization Assessment. Assembly Bill 3232 (Friedman) in 2018 (Cal. Gov. code, Chapter 373)
- Building Decarbonization Coalition. (2019). A ROADMAP TO DECARBONIZE CALIFORNIA BUILDINGS. <https://www.buildingdecarb.org/archived/a-roadmap-to-decarbonize-californias-buildings>
- Building Initiative for Low-Emissions Development (BUILD) Program. Assembly Bill 1477 (Stern) in 2019 (Cal. Gov. Code § 921)
- California Energy Commission. (2022). Building Energy Efficiency Standards for Residential and Nonresidential Buildings: For the 2022 Building Energy Efficiency Standards. Title 24, Part 6, and Associated Administrative Regulations in Part 1. https://www.energy.ca.gov/sites/default/files/2022-08/CEC-400-2022-010_CMF.pdf
- California Energy Commission. (2018). Toward A Clean Energy Future, 2018 Integrated Energy Policy Report Update, Volume I. <https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2018-integrated-energy-policy-report-update>
- California Energy Commission. (2015). Tracking Progress: Resource Flexibility, p. 10 https://www.energy.ca.gov/sites/default/files/2019-12/resource_flexibility_ada.pdf
- California Gov. Arnold Schwarzenegger, Executive Order S-3- 05. [http://static1.squarespace.com/static/549885d4e4b0ba0bff5dc695/t/54d7f1e0e4b0f0798ce3010/1423438304744/California+Executive+Order+S-3-05+\(June+2005\).pdf](http://static1.squarespace.com/static/549885d4e4b0ba0bff5dc695/t/54d7f1e0e4b0f0798ce3010/1423438304744/California+Executive+Order+S-3-05+(June+2005).pdf)
- California Public Utilities Commission. (2019). Building Decarbonization: Fact and Fiction. <https://www.cpuc.ca.gov/about-cpuc/divisions/energy-division/building-decarbonization>
- Carbajal, S. (2016). 2015 California Climate Action Planning Conference Keynote Address. *Focus*, 12(1), 8.
- Coffey, Brian, Sam Borgeson, Stephen Selkowitz, Joshua Apte, Paul Mathew, and Philip Haves. (2009). Towards a Very Low-Energy Building Stock: Modelling the US Commercial Building Sector to Support Policy and Innovation Planning. *Building Research & Information* 37, no. 5–6 (November 1, 2009): 610–24. <https://doi.org/10.1080/09613210903189467>.
- Cohn, C., and N. W. Efram. (2022). Building Electrification: Programs and Best Practices. Washington, DC: American Council for an Energy-Efficient Economy. [aceee.org/research-report/b2201](https://www.aceee.org/research-report/b2201).
- Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., and Nielsen, S. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy policy*, 65, 475-489.
- Cook, G. D. (1992). Whole House Fans: Installation.
- Delforge, Pierre. (2021). California Forging Ahead on Zero Emission Buildings. Natural Resource Defense Fund. <https://www.nrdc.org/experts/pierre-delforge/california-forging-ahead-zero-emission-buildings>
- Department of Energy. (2022). DOE Awards \$32 Million to Accelerate Next-Generation Building Upgrades. <https://www.energy.gov/articles/doe-awards-32-million-accelerate-next-generation-building-upgrades>

- Department of Energy. (2015). Chapter 5: Increasing Efficiency of Building Systems and Technologies. QUADRENNIAL TECHNOLOGY REVIEW AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES. <https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf>
- DeRolph, C. R., McManamay, R. A., Morton, A. M., & Nair, S. S. (2019). City energy sheds and renewable energy in the United States. *Nature Sustainability*, 2(5), 412-420.
- EIA, Energy Information Administration. (2004). 2004b Annual Energy Review. US Department of Energy, Washington, DC. DOE/EIA-0383, pages 139 ^ 142, tables A4 and A5
- Environmental and Energy Study Institute. (2011). Fact Sheet: What is District Energy? Accessed September 2019, 2022: https://www.eesi.org/files/district_energy_factsheet_092311.pdf
- Evans, S. D., D. Godoy Shimizu, P. Steadman, and R. Liddiard. (2018). Building Stock Modelling and the Relationship between Density and Energy Use. Proceedings paper. In: Proceedings of 4th Building Simulation and Optimization Conference (BSO 2018). (pp. pp. 161-168). IBPSA: Cambridge, UK. Cambridge, UK: IBPSA. <http://www.ibpsa.org/proceedings/BSO2018/2B-3.pdf>.
- Faddoul, Kristiana. (2021). California's Cities Lead the Way on Pollution-Free Homes and Buildings. Sierra Club. <https://www.sierraclub.org/articles/2021/07/californias-cities-lead-way-pollution-free-homes-and-buildings>
- Fankhauser, S., & Tepic, S. (2007). Can poor consumers pay for energy and water? An affordability analysis for transition countries. *Energy Policy*, 35(2), 1038-1049.
- Fuerst, F. and McAllister, P. (2011), Green Noise or Green Value? Measuring the Effects of Environmental Certification on Office Values. *Real Estate Economics*, 39: 45-69. <https://doi.org/10.1111/j.1540-6229.2010.00286.x>
- Gillingham, Kenneth and Karen Palmer. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*, Association of Environmental and Resource Economists, vol. 8(1), pages 18-38, January.
- Global Warming Solutions Act. Assembly Bill 32 (Nunez) in 2006 (Ca. Health and Safety Code, Chp. 488 § 38500)
- Hampton, Rachel, Adanna Okpala, Marisa Perez-Reyes, Diana Roycroft, and Sunny Sowards. (2017). Fact Sheet: Energy Efficiency Standards for Appliances, Lighting and Equipment. Environmental and Energy Study Institute. <https://www.eesi.org/papers/view/fact-sheet-energy-efficiency-standards-for-appliances-lighting-and-equipmen>
- Han, A. T., Laurian, L., & Brinkley, C. (2021). Thermal planning: what can campuses teach us about expanding district energy?. *Journal of environmental planning and management*, 64(11), 2066-2088.
- Harmelink, M., Nilsson, L. & Harmsen, R. (2008). Theory-based policy evaluation of 20 energy efficiency instruments. *Energy Efficiency* 1, 131–148. <https://doi.org/10.1007/s12053-008-9007-9>
- Hicks, W. (2020). Declining Renewable Costs Drive Focus on Energy Storage. NREL Transforming Energy: <https://www.nrel.gov/news/features/2020/declining-renewable-costs-drive-focus-on-energy-storage.html> adresinden alındı.

- Hoffacker, Madison K., Michael F. Allen, and Rebecca R. Hernandez. (2017). Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States. *Environmental Science & Technology* 51, no. 24: 14472–82. <https://doi.org/10.1021/acs.est.7b05110>.
- Hopkins, A. S., Takahashi, K., Economics, S. E., Lis, D., & Partnerships, N. E. E. (2018). Challenges and Opportunities for Deep Decarbonization through Strategic Electrification under the Utility Regulatory Structures of the Northeast. *Proceedings of the 2018 ACEEE Summer Study on Energy Efficiency in Industry*, 6, 1-14.
- Houde S. (2019). How consumers respond to environmental certification and the value of energy information. NBER working paper series.
- Hulgaard, Tore, and Inger Søndergaard MSc. (2018). Integrating Waste-to-Energy in Copenhagen, Denmark. *Proceedings of the Institution of Civil Engineers - Civil Engineering* 171, no. 5: 3–10. <https://doi.org/10.1680/jcien.17.00042>.
- Hsu, D., Andrews, C. J., T. Han, A., G. Loh, C., C. Osland, A., & P. Zegras, C. (2022). Planning the Built Environment and Land Use Towards Deep Decarbonization of the United States. *Journal of Planning Literature*, 08854122221097977.
- Im, J., Seo, Y., Cetin, K. S., & Singh, J. (2017). Energy efficiency in US residential rental housing: Adoption rates and impact on rent. *Applied Energy*, 205, 1021-1033.
- International Energy Agency (IEA). (2014). Capturing the Multiple Benefits of Energy Efficiency; International Energy Agency: Paris, France.
- International Energy Agency (IEA) (2020), Clean Energy Innovation, IEA, Paris <https://www.iea.org/reports/clean-energy-innovation>, Licence: CC BY 4.0
- Kaiser, M. J., & Pulsipher, A. G. (2003). LIHEAP reconsidered. *Energy Policy*, 31(14), 1441-1458.
- Kammen, D. M. (2006). The rise of renewable energy. *Scientific American*, 295(3), 84-93.
- Kennedy, S. F., & Rosen, B. (2021). The rise of community choice aggregation and its implications for California's energy transition: A preliminary assessment. *Energy & Environment*, 32(2), 262-280.
- Kern, F., P. Kivimaa, and M. Martiskainen. (2017). Policy Packaging or Policy Patching? The Development of Complex Energy Efficiency Policy Mixes. *Energy Research & Social Science* 23: 11–25. <https://doi.org/10.1016/j.erss.2016.11.002>.
- Klinenberg, E. (1999). Denaturalizing disaster: A social autopsy of the 1995 Chicago heat wave. *Theory and society*, 28(2), 239-295.
- Koirala, Bishwa S., Alok K. Bohara, and Robert P. Berrens. (2014). Estimating the Net Implicit Price of Energy Efficient Building Codes on U.S. Households. *Energy Policy* 73: 667–75. <https://doi.org/10.1016/j.enpol.2014.06.022>.
- Kontokosta, C. E., Reina, V. J., & Bonczak, B. (2020). Energy cost burdens for low-income and minority households: Evidence from energy benchmarking and audit data in five US cities. *Journal of the American Planning Association*, 86(1), 89-105.
- Krieger, E. M., Casey, J. A., & Shonkoff, S. B. (2016). A framework for siting and dispatch of emerging energy resources to realize environmental and health benefits: Case study on peaker power plant displacement. *Energy Policy*, 96, 302-313.
- Langevin, Jared, Chioke B. Harris, and Janet L. Reyna. (2019). Assessing the Potential to Reduce U.S. Building CO2 Emissions 80% by 2050. *Joule* 3, no. 10: 2403–24. <https://doi.org/10.1016/j.joule.2019.07.013>.

- Lapin, L., and K. Chelsey. 2015. A New Campus Energy System Cuts Stanford's Greenhouse Gas Emissions by 68 Percent. Accessed January 17, 2020.
<https://news.stanford.edu/features/2015/sesi/>.
- Lee, W.L., & Yik, F.W. (2004). Regulatory and voluntary approaches for enhancing building energy efficiency. *Progress in Energy and Combustion Science*, 30, 477-499.
- Leibowicz, Benjamin D., Christopher M. Lanham, Max T. Brozynski, José R. Vázquez-Canteli, Nicolás Castillo Castejón, and Zoltan Nagy. (2018). Optimal Decarbonization Pathways for Urban Residential Building Energy Services." *Applied Energy* 230: 1311–25.
<https://doi.org/10.1016/j.apenergy.2018.09.046>.
- Leung, Jessica. (2018). Decarbonizing US Buildings. Center for Climate and Energy Solutions.
<https://www.c2es.org/document/decarbonizing-u-s-buildings/>
- Levesque, Antoine, Robert C. Pietzcker, and Gunnar Luderer. (2019). Halving Energy Demand from Buildings: The Impact of Low Consumption Practices. *Technological Forecasting and Social Change* 146: 253–66. <https://doi.org/10.1016/j.techfore.2019.04.025>.
- Less, Brennan D., Núria Casquero-Modrego, and Iain S. Walker. (2022). Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review. *Energies* 15, no. 15: 5590. <https://doi.org/10.3390/en15155590>.
- Lucon O., D. Üрге-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, N. Eyre, A. Gadgil, L.D.D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M.V. Vilariño. (2014). Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. University Press, Cambridge, United Kingdom and New York, NY, USA.
- Lund, Henrik, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, and Brian Vad Mathiesen. (2014). 4th Generation District Heating (4GDH): Integrating Smart Thermal Grids into Future Sustainable Energy Systems." *Energy* 68: 1–11. <https://doi.org/10.1016/j.energy.2014.02.089>.
- Lund, H. (2005). Large-scale integration of wind power into different energy systems. *Energy*, 30(13), 2402-2412.
- Mahone, Amber, Zachary Subin, Jenya Kahn-Lang, Douglas Allen, Vivian Li, Gerrit De Moor,
- Meng, T., Hsu, D., & Han, A. (2017). Estimating energy savings from benchmarking policies in New York City. *Energy*, 133, 415-423.
- Nancy Ryan, Snuller Price. (2018). Deep Decarbonization in a High Renewables Future. *Energy and Environmental Economics* (E3). Prepared for the California Energy Commission.
https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012.pdf
- National Research Council, Division on Earth, Life Studies, Board on Environmental Studies, & Committee on Health Impact Assessment. (2011). *Improving health in the United States: the role of health impact assessment*.
- Metz, Bert & Davidson, Ocen & PR, Bosch & al, E.. (2007). IPCC AR4. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Meyers S, McMahon J E, McNeil M, Liu X. (2003). Impacts of U.S. federal energy efficiency standards for residential appliances. *Energy* 28 755 ^ 767

- NMR Group and ThreeCubed. Low-Income Multifamily Health- and Safety-Related NEIs Study (TXC50). Available online: <http://www.threecubed.org/uploads/2/9/1/9/29191267/low-income-multifamily-health-and-safety-related-non-energy-impact-study>
- Nevin, R. (2010). Energy-efficient housing stimulus that pays for itself. *Energy Policy*, 38(1), 4-11.
- Ortiz, J.; Casquero-Modrego, N.; Salom, J. (2019). Health and Related Economic Effects of Residential Energy Retrofitting in Spain. *Energy Policy*, 130, 375–388. [CrossRef]
- Pacific Consulting Group (2023). “CALIFORNIA ZERO-EMISSION APPLIANCE AWARENESS STUDY What Californians Think About Zero-Emission Appliances, What They Do Not Know (Yet), and What This Means for California’s Climate and Air Quality Goals” <https://www.pcgfirm.com/wp-content/uploads/2023/11/California-Zero-Emission-Appliance-Awareness-Study.pdf>. Accessed 2024/3/10
- Palm, J. (2006). Development of sustainable energy systems in Swedish municipalities: A matter of path dependency and power relations. *Local Environment*, 11(4), 445-457.
- Pitt, D., & Bassett, E. (2013). Collaborative planning for clean energy initiatives in small to mid-sized cities. *Journal of the American Planning Association*, 79(4), 280-294.
- Riahi, L. (2015). District energy in cities. *Unlocking the Potential of Energy Efficiency and Renewable Energy*.
- Rogge, Karoline S., and Kristin Reichardt. “Policy Mixes for Sustainability Transitions: An Extended Concept and Framework for Analysis.” *Research Policy* 45, no. 8 (October 1, 2016): 1620–35. <https://doi.org/10.1016/j.respol.2016.04.004>.
- Roth, M.B., Adams, P.J., Jaramillo, P., Muller, N.Z., 2020. Near term carbon tax policy in the US Economy: limits to deep decarbonization. *Environ. Res. Commun.* 2 (5), 051004.
- Schüler, N., & Cajot, S. (2019). A planning support system using interactive optimization. In *Urban Energy Systems for Low-Carbon Cities* (pp. 51-78). Academic Press.
- Sovacool, B. K. (2009). The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse?. *Utilities Policy*, 17(3-4), 288-296.
- Sovacool, B. K. (2014). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Research & Social Science*, 1, 1-29.
- Starke, Allan R., José M. Cardemil, Rodrigo A. Escobar, and Sergio Colle. (2016). Assessing the Performance of Hybrid CSP+PV Plants in Northern Chile. *Solar Energy* 138: 88–97. <https://doi.org/10.1016/j.solener.2016.09.006>.
- Steinberg, Daniel, Dave Bielen, Josh Eichman, Kelly Eureka, Jeff Logan, Trieu Mai, Colin McMillan, Andrew Parker, Laura Vimmerstedt, and Eric Wilson. (2017). *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization*. *Renewable Energy*, 53.
- Stokes, L.C., Warshaw, C. (2017). Renewable energy policy design and framing influence public support in the United States. *Nat. Energy* 2 (17107), 1–6.
- Summerton, J. (1992). District heating comes to town: The social shaping of an energy system. *Linkopings Universitet (Sweden)*.
- Tan, Y.A.; Jung, B. (2021). Decarbonizing Homes Improving Health in Low-Income Communities through Beneficial Electrification. *RMI*. Available online: <http://www.rmi.org/insight/decarbonizing-homes>

- Tonn, Bruce, Erin Rose, Beth Hawkins, and Brian Conlon (2014). “HEALTH AND HOUSEHOLD-RELATED BENEFITS ATTRIBUTABLE TO THE WEATHERIZATION ASSISTANCE PROGRAM,” n.d., 181.
- Tozer, Laura, and Durham University. (2020). Catalyzing Political Momentum for the Effective Implementation of Decarbonization for Urban Buildings. *Energy Policy* 136: 111042. <https://doi.org/10.1016/j.enpol.2019.111042>.
- Turley, Bethani, Alida Cantor, Kate Berry, Sarah Knuth, Dustin Mulvaney, and Noel Vineyard. (2022). Emergent Landscapes of Renewable Energy Storage: Considering Just Transitions in the Western United States. *Energy Research & Social Science* 90: 102583. <https://doi.org/10.1016/j.erss.2022.102583>.
- UNEP. (2018). District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewables.
- Ürge-Vorsatz, Diana, L. D. Danny Harvey, Sevastianos Mirasgedis, and Mark D. Levine. (2007). Mitigating CO2 Emissions from Energy Use in the World’s Buildings. *Building Research & Information* 35, no. 4: 379–98. <https://doi.org/10.1080/09613210701325883>.
- US Department of Energy. (1976). Weatherization Assistance Program (WAP). Energy Conservation and Production Act, Title IV.
- Velez, Kiki and Merrian Borgeson. (2022). CA Building Decarbonization: What’s Coming in 2022? Natural Resource Defense Council. <https://www.nrdc.org/experts/kiki-velez/ca-building-decarbonization-whats-coming-2022>
- Victor, N., Nichols, C., Zelek, C., 2018. The U.S. power sector decarbonization: investigating technology options with MARKAL nine-region model. *Energy Econ.* 73, 410–425.
- Waite, Michael, and Vijay Modi. “Electricity Load Implications of Space Heating Decarbonization Pathways.” *Joule* 4, no. 2 (February 19, 2020): 376–94. <https://doi.org/10.1016/j.joule.2019.11.011>.
- Walker, I.S.; Less, B.D.; Casquero-Modrego, N. (2022). Carbon and Energy Cost Impacts of Electrification of Space Heating with Heat Pumps in the US. *Energy Build.* 259, 111910. [CrossRef]
- Walker, G., & Day, R. (2012). Fuel poverty as injustice: Integrating distribution, recognition and procedure in the struggle for affordable warmth. *Energy policy*, 49, 69-75.
- Werner, S. (2017). District heating and cooling in Sweden. *Energy*, 126, 419-429.
- Wei, Max, James H. Nelson, Jeffery B. Greenblatt, Ana Mileva, Josiah Johnston, Michael Ting, Christopher Yang, Chris Jones, James E. McMahon, and Daniel M. Kammen. (2013). Deep Carbon Reductions in California Require Electrification and Integration across Economic Sectors. *Environmental Research Letters* 8, no. 1: 014038. <https://doi.org/10.1088/1748-9326/8/1/014038>.
- Whitcomb, R. (2002, April 25). Bundling Municipal Electricity. *Providence Journal-Bulletin*.
- Wheeler, S. M. (2008). State and municipal climate change plans: the first generation. *Journal of the American Planning Association*, 74(4), 481-496.
- Williams, J., Bouzarovski, S., & Swyngedouw, E. (2019). The urban resource nexus: On the politics of relationality, water–energy infrastructure and the fallacy of integration. *Environment and Planning C: Politics and Space*, 37(4), 652-669.
- York, D.; Cohn, C.; Morales, D.; Tolentino, C. (2022). Building Decarbonization Solutions for the Affordable Housing Sector; American Council for an Energy Efficient Economy (ACEEE): Washington, DC, USA.

- Zhao, Bin, Tianyang Wang, Zhe Jiang, Yu Gu, Kuo-Nan Liou, Nesamani Kalandiyur, Yang Gao, and Yifang Zhu. (2019). Air Quality and Health Cobenefits of Different Deep Decarbonization Pathways in California. *Environmental Science & Technology* 53, no. 12: 7163–71. <https://doi.org/10.1021/acs.est.9b02385>.
- Zhu, Qianru, Benjamin D. Leibowicz, Joshua W. Busby, Sarang Shidore, David E. Adelman, and Sheila M. Olmstead. (2022). Enhancing Policy Realism in Energy System Optimization Models: Politically Feasible Decarbonization Pathways for the United States. *Energy Policy* 161: 112754. <https://doi.org/10.1016/j.enpol.2021.112754>.
- Zycher, B. (2016). Subsidizing The Rich Through California's Solar Scheme. *Forbes*. <https://www.forbes.com/sites/realspin/2016/01/15/california-solar-subsidy-net-metering/#4708657a722f>, accessed: September 20, 2023.

Appendix 1C: Reducing Vehicle Miles Traveled (VMT)

The Role of VMT in California Climate Policy

We review the state of research on reducing Vehicle Miles Traveled (VMT) to identify opportunities and barriers for local jurisdictions in California. Reducing VMT refers to an umbrella of strategies to reduce the total number of miles driven by personal cars across a given area. Policies include changes to the built environment to promote compact, walkable places where people can live near places they work and play without reliance on a car. VMT reduction also includes efforts to minimize miles driven through incentive and disincentive programs to bolster multi-modal transit, institute congestion pricing, and regulate parking. To center the needs of the most vulnerable Californians, this review focuses on equity.

VMT Reduction Challenges

One of the main barriers to reducing VMT is that local jurisdictions lack reliable, standardized VMT quantification measures and evaluation tools. Jurisdictions lack clarity on preferred tools to clearly state the amount of VMT generated by a proposed project, the impact of specific mitigation measures, and the overall effectiveness of combined measures over time. Assessment of VMT under California Environmental Quality Act (CEQA) uses varied and varying regional thresholds, creating confusion for local jurisdictions. To better align state and local level policy goals, the development, maintenance, and mandated use of a standard VMT model tool is desired. This tool must account for the size and available resources of metropolitan planning organizations and local jurisdictions, the impact of enhanced transit service levels on vehicle ownership and VMT, regional job-housing balance, and the relationship between land use density and household vehicle ownership. For example, developing new highways and roadways can increase VMT and induce travel. With a standardized VMT assessment tool, local jurisdictions can rethink investments in road diets and other modes of travel. Similarly, a standardized VMT tool can help local jurisdictions better quantify the amount and type of jobs and housing to reduce VMT.

Notably, CEQA does not have a solid existing case law legal foundation for VMT assessment - which has only recently replaced the level of service (LOS) reporting. The lack of relevant case laws for VMT makes it difficult for local governments to know to what extent they can rely on their VMT reduction goals to meet CEQA standards (Alexander et al., 2021). A stronger legal framework for VMT within CEQA would encourage local governments toward development projects that anticipate VMT reductions.

Similarly, there is not a direct and standard VMT-based fee (such as mileage fees, cordon pricing, etc.). A VMT-based fee would discourage VMT, and new funds could help fill the growing gap in transportation funding. This policy would entail charging users a fee based on when and where the vehicle was driven, the impacts of that vehicle on the environment, and the

damage to the infrastructure. Odometer readings during smog checks may be used for monitoring, coupled with financial incentives to encourage mode shift. To ensure that such a fee would not disproportionately burden vulnerable individuals who are often forced to travel long distances due to job-housing mismatches, this fee should have an equity component to both collection and distribution of funds.

Further, technical assistance for designing and implementing VMT reduction strategies is lacking. For example, a limiting factor in California's ability to reduce VMTs is job-home mismatch, resulting in longer distances between centers of employment and places to live. This, coupled with declining employment density, creates challenges for implementing walk/bike and public transit options as housing and job centers are more spread out. Research has shown that employment density matters more than residential density in encouraging transit use as an alternative to driving (Boarnet and Wang, 2019), yet telecommuting with COVID and post-COVID necessitates the creation of new studies to support adequate technical planning assistance. Similarly, there are insufficient financial, informational, and collaborative resources for local governments. The state should, therefore, provide a general body of knowledge about VMT reduction strategies and identify a primary hub for local governments. Such a hub could include parking requirements and model equitable commuter benefit ordinances. Additional programs could include employer-paid benefit programs, whereby the covered employer offers employees a subsidy to offset the monthly commuting cost via public transit, vanpool, or bicycle. Last, technical assistance should also offer more grant programs and funding to VMT projects undertaken at the regional and city level.

How VMT Impacts Greenhouse Gas Emissions

In this review, we first describe why reducing VMT is a priority area for greenhouse gas (GHG) emissions reductions and how policies addressing land use, employment density, active transportation, ridesharing, pricing incentives, and equity are essential policy components. Then, we review the state of the research on VMT reduction policy. Each section is followed by California legislative codes in place to support policy objectives. The conclusion then discusses how effective these methods are at reaching stated GHG emissions reductions goals and where priority areas lie for making these goals a reality.

Reducing VMT is essential in reducing GHG emissions. Polizin et al.(2024) use US National Household Travel Survey information from 2002 to estimate VMT scenarios through simple model formulations, and show that between 1977 and 2001, household vehicle trips increased by 115% and personal miles of travel increased by about 114%, demonstrating a climb in vehicle activity over the past few decades. In California, emissions from passenger vehicles are the source of 28.5% of the total 418.2 million metric tons of carbon dioxide equivalents (MMT CO₂e) emitted annually (CARB, 2022). The upward trend in personal travel miles has resulted in

increases in local and global pollution from particulate matter and GHG emissions (Ward et al., 2019). Even with lower carbon fuels and increased ZEV uptake in the transportation sector, a policy report by the Center for Climate Change estimates that in the absence of substantial reductions in VMT per capita, low-carbon fuels will only slow, not reverse, the rise in per capita CO₂ emissions (Condon, 2008).

To achieve VMT reductions, local actions for planning development are essential. Wheeler et al. (2013) model three 2050 urban-growth scenarios for Yolo County (a predominantly agricultural area near Sacramento, California) and find a scenario that prioritizes efficient land use is able to reduce GHG emissions from transportation and residential building operations by more than 50% in 2050 compared with business-as-usual development (Wheeler et al., 2013). Similarly, Elkind et al. (2017) found infill-focused housing could avert at least 1.79 million metric tons of greenhouse gases annually compared to the business-as-usual scenario, based on reduced driving miles and household energy usage alone. Such housing density and land-use development is the purview of local jurisdictions.

In addition to improvements in the local environment and quality of life, reducing VMT reduces the consumption of fossil fuels needed to run internal combustion vehicles as well as investments and materials in road infrastructure. Both reductions offer solutions to the environmental degradation and resource consumption issues presented by high levels of VMT (Cervro and Murakami, 2010). Reducing VMT will also provide the additional co-benefits of alleviating traffic congestion, vehicle-related fatalities, water pollution, and wildlife mortality, improving public health through alternative transportation and increased exercise, and enhancing interactions within communities (Salon et al., 2012). Further, higher density development can provide local economic development opportunities, conserve natural resources, and preserve farmland. Such benefits motivate VMT reductions beyond GHG emissions reductions alone.

California Code

Terms used in the California legislative code address **transportation control measures**, encompassing any strategy to reduce vehicle trips, vehicle use, vehicle emissions, VMT, vehicle idling, or traffic congestion. In terms of land use and VMT, **transformative capital improvement** is commonly referred to and means investment in rail, bus, or ferry transit projects that will significantly reduce VMT, congestion, and GHG emissions by creating a new transit system or increasing the capacity or ridership of an existing transit system. Another land use term is **transformative planning** and implementation activities, which refers to housing, planning, infrastructure investments supporting infill housing, and other actions that enable meeting housing goals that result in per capita VMT reductions. Strategies may include accelerating infill development, multimodal communities, shifting travel behavior through reducing driving, and increasing transit ridership. Codes also mention vehicle maintenance

practices that can make vehicles run cleaner. Legislative codes define **transportation network companies** as providing pre-arranged transportation services for compensation using an online-enabled application to connect passengers. Codes also describe **emissions per passenger mile traveled**, which means the total miles completed by drivers of shared vehicles divided by the number of passengers. Terms used to describe travel behaviors are average vehicle ridership, single occupant ridership, and transit system ridership.

VMT Regulatory Frameworks

Historically, GHG emissions from vehicles have been regulated in California through fuel efficiency standards, like the Corporate Average Fuel Economy (CAFE) and Low Carbon Fuel standards. These fuel efficiency standards mandate the average miles per gallon for vehicles industry-wide. VMT, however, has not received as much legislative attention and, therefore, has been growing faster than the population or the economy (Fang et al., 2017). Consequently, a "VMT gap" exists in the current regulatory structure for GHG emissions reductions (Litman, 2013). To bridge this gap, Assembly Bill 32 (Nunez, 2006), or the Global Warming Solutions Act, was established to reduce greenhouse gas emissions from passenger travel. AB 32 created a comprehensive multi-year program to reduce GHG emissions to 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050. Since then, additional legislation has supported reduced GHG emissions. For example, AB 1279 (2022) calls for carbon neutrality by 2045. To meet the carbon neutrality goal, the CARB Scoping Plan proposes reducing VMT from 24.6 miles per day in 2019 to 18.4 miles by 2030 (a 25 percent reduction) and to 17.2 miles per day by 2045 (a 30 percent reduction) in keeping with projections by Boarnet and Handy (2017). Since passing AB 32, two additional major laws have been passed that aim to reduce VMT: Senate Bill 375 (Steinberg, 2008) and SB 743 (Steinberg, 2013). SB 375, or the Sustainable Communities and Climate Protection Act, calls on Metropolitan Planning Organizations (MPOs) to prepare a Sustainable Communities Strategy (SCS) that integrates land use, housing, and transportation strategies into the regional transportation plan that reduces GHG emissions through VMT reduction. These SCSs must meet GHG reduction targets set by CARB. Beginning in 2018, CARB has presented a progress report every four years to the legislature, as directed by SB 150, that assesses each MPO's progress in meeting the regional GHG emission reduction targets set by CARB as part of SB 375. The 2022 report includes information in a Data Dashboard.^[23] In the 2022 progress report, CARB also includes for the first time, information about the VMT metric by region, destination accessibility, housing development by income level, units with a density bonus or inclusionary deed restrictions, and Greenhouse Gas Reduction Fund spending. Though 2020 census data were unavailable for the 2022 report, the progress report on SB 375 notes that major trends moved away from limited progress and inequality worsened (CARB, 2022). Obviously, these are not the desired trends and more local capacity building work is needed to meet state targets for VMT reduction and equity. In addition, CARB found that California is still not reducing GHG emissions from personal vehicle travel as needed under SB

375. The report also noted that per capita GHG emissions and per capita VMT continue to increase, though more slowly than in the 2018 progress report. To better reach goals, the state curates a set of Quantification Methodologies and Calculator Tools for estimating GHG emission reductions and co-benefits of new projects. These include the Sustainable Communities Strategy which outlines metrics to track MPO progress across four dimensions: policy commitments, policy implementation, incremental progress, and equity.^[24] In 1992, California enacted legislation (AB 2109, Katz) enabling qualified employers to offer employees the option to choose to “**cash-out**” of firm parking subsidies. Employees who have access to workplace parking are usually more car-oriented (Tscharaktschiew and Reimann, 2022). Where wage income is taxed, employer parking is seen as a fringe benefit in kind that is usually not taxed. Thus, the government loses income tax revenue for each parking space that firms offer, and local governments lose revenue from paid parking. Updates in 2022 with AB 2206 (Lee) expanded the program and added a requirement for employers to inform employees who receive a parking subsidy of their right to receive the cash equivalent of the parking subsidy and maintain records of that communication. Further, the California Climate Investments provides funding from Cap-and-Trade. To evaluate proposals, this program includes Benefit Criteria Tables for determining benefits to priority populations and templates for reporting outcomes. From December 2022 through the end of May 2023, California Climate Investments programs supported 7,326 projects that are expected to reduce greenhouse gas emissions by 3.3 million metric tons of carbon dioxide equivalent over project lifetimes.^[25] Over 84%, or \$436 million, in implemented funds from this period are benefiting DACs and low-income households. Focused on advancing environmental quality in the state, SB 743 (Steinberg, 2013) further revised the guidelines for transportation impacts under the California Environmental Quality Act (CEQA). The bill changes how lead agencies evaluate transportation impacts under CEQA to advance the state’s goals of reducing GHGs and traffic-related air pollution, promoting the development of a multimodal transportation system, and providing clean, efficient access to destinations. SB 743 led to the adoption of vehicle-miles traveled (VMT) to replace level-of-service (LOS) as the standard for transportation impact analysis under CEQA. Local planners broadly support the change to VMT (Volker et al., 2019). Yet, mitigating VMT impacts of new projects creates the opportunity or potential need to conduct mitigation at locations other than the project site to ensure job-housing balance among other concerns. Further off-site VMT mitigation could include off-site banking or exchange programs that let developers fulfill their mitigation obligations without incorporating changes in the immediate project site (Fang et al., 2017). In sum, state-level bills have language that sets goals, but they often lack explicit strategies and quantification tools to accomplish these goals on a city or county basis.

Additional legislative codes enable local strategies to reduce VMT. For example, SB 310 (Hancock, 2012), or the Transit Priority Project Program, provides a process for cities and counties to adopt an ordinance indicating intent to participate and form an infrastructure financing district. To meet the requirements, projects must be located in a designated transit

priority area within one-half mile of a transit station, provide onsite bicycle parking, and provide car sharing in the city or county. Another bill that addresses these themes is Ch. 832, Sec 3 (Added by Stats, 2001), which outlines how each transportation planning agency with a population that exceeds 200,000 persons may prepare at least one “alternative planning scenario” for presentation to local officials, agency board members, and the public during the development of regional transportation plans. The alternative planning scenario shall accommodate the same amount of population growth as projected in the plan but can be based on an alternative scenario that reduces the growth in traffic congestion and VMT, makes more efficient use of existing transportation infrastructure, and reduces the need for costly future public infrastructure. These alternative plans aim to increase housing and commercial development around transit facilities, jobs, and commercial activity centers. This development should encourage public transit usage, ridesharing, walking, and bicycling. An economic incentive program is also encouraged that may include transit vouchers and variable pricing for transportation.

Measuring VMT

There are several methodology options available for calculating and estimating VMT. This includes High-Performance Monitoring System Data published by Caltrans, Vehicle Registration Data and Smog Check Program Data, CEC Retail Fuel Outlet Annual Reporting Data, and travel demand models. CARB developed an estimate of VMT for new projects. Cal EPA also includes a method for assessing current VMT per jurisdiction using motor vehicles registered and operated in California. Each method is described below.

1. Current CARB Auto VMT Reductions Quantification Method (CARB, 2019)

- *Auto VMT Reduced* = $(D) * (ADT) * (A + C) * (L)$
 - D = days of use per year (default is 200 days; units are in days)
 - ADT = annual average two-way daily vehicular traffic on the parallel road (project-specific data, with a maximum of 30,000; units are in trips/day)
 - A = adjustment factor (table lookup value)
 - C = activity center credit (table lookup value)
 - L = walking trip length (1.0 miles/trip in one direction) Miles/trip

Current EPA VMT Odometer Readings (Bureau of Automotive Repair,
2000)

2. VMT results are calculated as a function of:

- Model year: From 1974 to the current model year
- Fuel type: Includes vehicles powered by gasoline, liquefied propane gas, compressed natural gas, methanol, ethanol, or a combination of these fuels
- Vehicle type: Passenger cars, light-duty trucks, medium-duty vehicles, and heavy-duty trucks

Background on VMT Terminology

A term commonly used in transit is **active transportation investment**. This term refers to the amount of money that the federal government, state agencies, cities, and regions spend on transit (capital and operations) with an emphasis on supporting active modes such as biking, walking, skateboarding and others. **Vehicle efficiency standards** is another common term and tool used by the state. This term refers to how much CO₂ per mile is emitted by a vehicle and the fuel efficiency in miles per gallon. VMT policies also rely on the **state gas tax** to disincentivize fueling up on gasoline and to generate revenue for the transportation system. Other terms outlined in VMT policies are **road use fees** in the form of tolls, driving pricing policies, and parking prices. Guidelines target VMT also aim to decrease traffic congestion. For example, mixed-use, high-density development, aims to reduce the **job-housing mismatch** by increasing the compactness and access between residential, office, and commercial land-uses. Several additional designs can be used to promote reduced VMT in high density areas, such as pedestrian-friendly design, which prioritizes narrow streets that slow and alert motorists, and interconnected parks, trails, sidewalks, and pathways. **Transit-oriented design** is similar to pedestrian-friendly design but focuses on compact, mixed-use, pedestrian- and bicycle-friendly designs and how these can be closely integrated with mass transit by clustering jobs, housing, services, and amenities around public transport stations and stops. These designs also rely on coordinated transportation systems, wherein buses, trains, ferries, and biking and walking paths are all well integrated to ensure passengers can reach their destinations without using a private vehicle. This is primarily a concern for addressing the **first mile/ last mile problem** between destinations, where public transit may not directly go. When such inconveniences arise, people are more likely to rely on personal car transit or taxi services. Another term in transportation and land use is *smart growth*, a way to build economically prosperous, socially equitable, and environmentally sustainable cities, towns, and neighborhoods over time. Many smart growth designs aim to embrace **VMT reduction co-benefits**, such as increased exercise and better air quality, with the creation of greenbelts that allow walking and biking but limit outward urban sprawl. Other VMT-related terms address travel behavior, including **average trip length** and **behavioral mode choice**, which together reference the time to a destination in relation to the transportation options available. **Ridesharing** refers to carpooling, on-demand transit, and Transportation Network Companies (TNCs). As TNCs and other new mobility services become more popular in cities through shared vehicles, bikes, and scooters, they enable users to gain short-term access to transportation modes on an “as-needed” basis. Such shared mobility is often made possible through smartphone apps and information technology, which aggregate and optimize mobility options (Shaheen et al., 2020). While they can offered through ridesharing, **micromobility** includes lightweight devices that operate at low speeds, like bicycles, scooters,

and skateboards, and may be either privately owned or publicly owned and shared. These can be either human-powered or electric. The value of micromobility solutions for cities is that they represent a shift towards low-carbon and sustainable modes of transport and can positively disrupt private vehicle use, especially for short-distance travel (Sperling et al., 2020). Last, **parking requirements** also impact VMT.

Research on VMT Reduction Feasibility and Policy

Integrating Land Use and Transportation Decisions

Land use practices are a significant component of VMT, influencing transportation choices, including how far, how frequently, and by which mode people travel. Therefore, most VMT reduction strategies urge tailored local and regional land use decisions to decrease transportation sector emissions through design. The most frequently cited attributes influencing driving behavior are proximity to urbanized areas, development density, mixed-use buildings, and access to alternative transit infrastructure. Addressing these factors can significantly reduce VMT (Malaczynski and Duane, 2009). Yet, with road investments continuing to outpace other aspects of transit investment, it is not surprising that VMT has not been reduced, as shown in the SB 150 draft report (2022). Thus, scholars urge local jurisdictions to consider not only the development of compact, mixed-use TOD, but also the ratio of investment in this infrastructure compared to local, regional, state, and federal spending on road infrastructure such that development works in step with transit planning.

In further support, studies demonstrate that high population densities are strongly and positively associated with lower VMT per capita. One such study uses data from 370 US urbanized areas and structural equation modeling and found that the largest VMT reductions would come from creating compact communities that have below-average roadway provisions, more pedestrian/cycling infrastructure, and in-neighborhood retail activities that invite nonmotorized travel (Cervero and Murakami, 2010). Cervero and Murakami (2010) describe these communities as “sustainable urbanism,” prioritizing more walkable, transit-friendly urban landscape designs. They contend this will reduce VMT, curb GHGs, energy consumption, and local air pollution, and provide more housing and lifestyle choices (Cervero and Murakami, 2010). Similar to sustainable urbanism, transit-oriented development (TOD) and smart growth policy, like the measures proposed in SB 375, are found to be inversely related to per capita VMT. Woldeamanuel and Kent (2014) use multivariate regression to isolate determinants of per capita VMT in California from the National Household Travel Survey (NHTS). In their study they also use the Chow Test to identify structural change between the 2001 and 2009 NHTS. Using two regressions, they find that the most relevant variables were: distance to work, population density, travel day trips, and number of vehicles in household. These findings are consistent with results from other studies (Lui 2007, Ewing and Cervero 2010, Akar and Guldman 2012). These findings contrast the dominant development trend of single, family

housing enclaves far from work and commercial centers. Indeed, this is the dominant pattern of development *planned* for the future of California based on findings from the California Zoning Atlas, a project by the UC Davis Center for Regional Change and UC Berkeley Othering and Belonging Institute (2024). For example, the incorporated areas in Fresno County dedicated to single family zoning comprise 61% of the total area (OBI, 2023). Similarly, over 50% of land is zoned for low-density single family housing development in Sacramento, San Diego, Los Angeles, and the Bay Area regions.

California's current zoning highlights the missed opportunities to reduce VMT through compact, mixed-use development. For example, Heres-Del-Valle et al. (2011) research the impacts of compact development through a multivariate two-part model using survey data on household travel patterns and socio-economic characteristics in California. Their results indicate that when all else remains equal, a 10% increase in *residential* density would reduce VMT by 1.9%. The scale of this impact is limited because of the effects of residential compactness alone. Similarly, Chatman (2008) uses data from a survey of metropolitan households in California and finds that increasing residential density is unlikely to significantly change travel behavior without concomitant policy changes for commercial and office land-uses, like maintaining minimum levels of roadway capacity and parking provisions. Ewing and Cervero (2010) conduct a meta-analysis of the built environment-travel literature. They conclude that density and VMT must also be understood within regional accessibility. For example, many studies that analyze VMT and density fail to consider commute times across the region, regional mass transit options, and job-housing dynamics across paired districts.

In terms of built structures that increase VMT, Noland and Cowart (2000) use the Texas Transportation Institute annual congestion report and metropolitan-level data to determine urbanized land area and lane miles of highway capacity. Their analysis found that road lane expansion accounts for 15% of per capita VMT growth (Noland and Cowart, 2000). These findings should add caution to highways expansion projects, like that currently underway along I-80 in the Sacramento region. Other studies provide strong empirical evidence that household increases in income and number of vehicles, workers, adults, and children all led to higher VMT. Conversely, higher population densities and high gasoline cost negatively affect VMT (Lui, 2007; Ewing and Cervero 2007; Akar and Guldman, 2012). Nelson (2017) uses Tucson, Arizona as a case study, to look at the relationship between urban form and personal travel by assessing the following variables on travel: density, diversity, design, destination accessibility, and distance to travel. Nelson (2017) categorized infill-redevelopment as having all future development occur in existing developed areas. Nelson (2017) finds that with infill redevelopment, the mean distance a person travels from the downtown decreases by 20%; anticipated transit expansions cut the mean distance to transit by half; and there was a 50% increase in job accessibility. Through the infill-development scenario, between 2011 and 2050, VMT per capita was estimated to fall by 42.6%. Although metropolitan Tucson is expected to grow by 52%, its total VMT in 2050 would be less than its VMT in 2011. This scenario could

redirect \$3 billion from building 1,500 lane miles of new roads (to serve the predicted 4 billion more VMT in metropolitan Tucson) to improve existing roads, enhance pedestrian and bicycle ways, expand transit, and make other strategic investments that improve quality of life (Nelson, 2017). The research demonstrates the cost savings as well as numerous other benefits to be had in infill-redevelopment.

Employment Density

Employment density may have more potential to reduce VMT than increases in residential density. Employment density is the ratio of the number of employees divided by land area (e.g., employees per acre or employees per square mile). Boarnet and Wang (2019) identify 46 employment sub-centers in the Los Angeles Combined Statistical Area and calculate access to jobs within and beyond these sub-centers. They measure household VMT using data on employment from the National Employment Time Series (NETS) matched to geocoded firm locations and the 2012 California Household Travel Survey. The results from this study suggest that infill opportunities that are near, but not within, city sub-centers offer the best land use approach to reduce VMT—as opposed to focusing on redeveloping already accessible downtowns (Boarnet and Wang, 2019). Ding et al. (2014) look at the effects of built environment factors on work-related VMT, considering urban form at home and workplace locations. They use the Maryland and Washington DC Regional Household Travel Survey 2008 in a cross-classified multilevel model using the Bayesian approach to study spatial heterogeneity in Washington DC. The results reveal that development densities at the workplace have more critical roles than at home. These studies highlight that policies aiming to reduce work-related VMT through residential density alone will not be as effective at reaching GHG emissions reduction goals through mixed use and commercial densification.

California legislature sought to address such work-related VMT with the Guidebook for Jobs-Housing Balance, Ch. 843, Sec 1 (Added by Stats, 1990). This guidebook aims to describe and evaluate the various tools available to local, regional, and state governments to measure, assess, and improve the balance of jobs and housing to be completed before 1993. The guidebook also describes efforts by cities, counties, and regional agencies to improve the balance of employment and housing, including the methodologies for measuring trip generation and VMT to and from employment centers. While this one-time guidebook has not been updated, researchers have built on its methods. For example, Blumenberg and King (2021) use census data from Longitudinal Employer–Household Dynamics Origin–Destination Employment Statistics (LODES) to find that the majority of California's cities are becoming less self-contained between 2002 and 2015, with more people commuting outside the city. These findings demonstrate that local planning should recommit to higher density job development.

At the same time, scholars caution that the COVID pandemic spurred the creation of mega commutersheds as housing affordability forced lower-wage workers to “drive until they

qualified” for housing rents and mortgages (Wang et al., 2024a). Using mobile phone data for the Bay Area region in Northern California Wang et al. (2024b) show that lower-income and essential workers commuted more during the pandemic while higher-income workers benefited from teleworking. These findings underscore the need to address VMT with an equity approach that centers high density affordable housing near high density job centers.

Parking Requirements

With ample, free curb parking available through **minimum parking requirements** for all development, most rides by private automobile are essentially free. In addition, surface parking lots, curb parking, and parking structures all remove space that could be used for housing, office, commercial, and industrial purposes. With a career focused on studying parking requirements, Shoup recommends removing off-street parking requirements (Shoup, 1995, 1999, 2018, 2021a), charging market rate for curbside parking (Shoup, 2018, 2021a and b), and investment of resulting revenue to improve public services (Shoup, 2018 and 2021a). In sum, the failure to charge market rates for curb parking, increases cruising to find available, low-cost parking, congests traffic, pollutes the air, wastes fuel, and results in greater traffic fatalities. Yet, there are also equity implications as parking is often more restricted for disadvantaged communities and users (Savignano, 2023) and more heavily policed and ticketed in communities of color (Brazil, 2020; Barajas, 2021). Even outside of DACs, low-income, and disabled riders often pay a greater percentage of their budget on parking (Venkataram et al., 2024), necessitating equitable approaches that allow preferential parking (eg. handicap designated parking spots near entrances) and progressive fees for parking until active and public transit can reach convenience, access, and cost parity with driving.

Similar equity concerns apply to cash-out employer-paid parking. In a case study of eight cash out programs that allowed 1,694 employees to receive between \$36 to \$165 per month in lieu of their parking, solo driving to work fell by 17 percent while carpooling increased by 64 percent; transit ridership increased by 50 percent; walking and bicycling increased by 33 percent, and commuter parking demand fell by 11 percent (Shoup, 1997). Yet, local policymakers remain reluctant to enable and require such employer parking policy programs. In an example from the UK Government’s 2000 “workplace parking levy” which enabled local authorities in England to charge employers for the parking they provided for staff, only one jurisdiction has enacted the law in twenty years (the City of Nottingham; Dale et al., 2023). To spur greater adoption of cash out programs, local governments can encourage and address firm parking requirements—with attention to how such benefit programs interface with firm parking requirement bonuses. After all, many workplaces will be incentivized to simply remove parking benefits without increasing wage benefits to employees. To further encourage equitable shifts, all the above efforts will need to be assessed as part of VMT reduction calculations for meeting CEQA requirements.

Active Transportation and Micromobility

Micromobility is increasingly recognized as a promising mode of urban transport for its environmental, economic, and social benefits, including the potential to reduce private vehicle use for short-distance travel and reduce emissions, crashes, and congestion (De Hartog et al., 2010). Micromobility refers to bikeshare, e-scooters, e-bikes, and semi-motorized variants of these modes, such as pedal assist and pedal-electric bikes. The active transit offers benefits in terms of the increased physical activity (DeMaio, 2009). In addition, micromobility services can provide access to suburbs and locations not well-served by public transport or easily accessed by private vehicles (Shaheen et al., 2013). In this manner, micromobility is an essential component in first and last mile connectivity, helping users access services and economic opportunities faster than using public transport, private vehicles, or walking (Milakis et al., 2020). In the US, more than half of the private car trips are used for trips that are less than five miles. As a result, scholars estimate that micromobility can replace about 30% of car trips (Fitt and Curl, 2019). These options also connect residential and commercial areas to public transport hubs, which helps to make public transport commutes more attractive and feasible. Supporting micromobility includes the creation of designated bike lanes, regular pavement upgrades with curb cuts, and bike and scooter parking.

While micromobility options can include personally owned bikes or semi-motorized variants, some cities offer micromobility options maintained by a city or private organizations and operated on a shared, charge-per-trip basis. This kind of micromobility service is often made available on a smartphone app or through a sharing economy model where users are charged a small fee for sharing a bicycle or scooter for short periods.

Studies find that increased micromobility options can result in decreased congestion and improved air quality regionally, with added benefits to users of time saving and convenience. Some studies find that people give up their vehicles altogether as a result of increased micromobility and public transit options. In a systematic literature review of 328 journal articles from 2000 to 2020, Abduljabbar et al. (2021) find that the most micromobility studies focus on quantifying time-savings, accessibility, congestion, and air quality.. This study also finds that emerging micromobility solutions have helped address several transportation challenges by reducing congestion addressing inequality in accessibility to services and opportunities, and were shown to be a positive force for reducing pollution. The study also finds that the main appeal of micromobility options is that they contribute to shifting road users away from private vehicles and high-pollutant modes of transport to more energy-efficient mobility solutions (Abduljabbar et al., 2021). For example, Basu and Ferreira (2021) examine the impact of bikesharing on reducing auto-dependence in Metro Boston. Using a longitudinal dataset containing millions of geo-referenced vehicle registrations and odometer readings in Massachusetts over six years, the researchers ran the data through a spatial DiD (difference in differences) model. The results

show that new bikeshare stations reduce vehicle ownership per household by 2.2%, VMT per person by 3.3%, and per-capita vehicular GHG emissions by 2.9%, with vehicle ownership reduced almost immediately. These results provide strong evidence for local jurisdictions site bikeshare stations. Another study across North America and European cities analyzes mode shift to bikesharing and found that personal car and taxi use both reduced as people were drawn to bikesharing modes of travel (Shaheen et al., 2013).

Broadly, convenience and proximity are significant factors in utilizing alternate modes of transportation according to a study by the San Francisco Bay Area Metropolitan Transportation Commission conducting a survey of residents based on proximity to a rail/ferry station and population density of the area surrounding the household. They report that people who live half a mile or less from a rail or ferry station were four times as likely to use it than all others and ten times as likely to use public transit if they were also working within a half mile of public transit. This access to transit also had behavioral change implications, as these same individuals were twice as likely to walk or bike for short trips (up to one mile) than all others (Metropolitan Transportation Committee, 2006). Comparatively, no state-level California legislative codes address micromobility nor bikesharing.

Ridesharing and Ridesourcing

Ridesharing and ridesourcing services (like Uber and Lyft) are offered by Transportation Network Companies (TNCs) and microtransit to provide on-demand mobility services. This section describes how on-demand mobility is part of a larger transformation of shared mobility that complements and can compete with personal vehicle ownership and public transit use. Shared mobility encapsulates ridesharing and ridesourcing but is a broader term describing modes of transportation where people use vehicles owned by a third party on an as needed basis. This category includes carpooling, bikesharing, and shuttle services.

On-demand shared mobility has contributed to a change in urban travel patterns, affecting energy use and GHG emissions reductions (Ward et al. 2019). Ward et al. (2019) estimate how much ride hailing services impact per-capita vehicle ownership, energy use, travel distances, and emissions in U.S. states from 2005 to 2015, using a difference-in-difference propensity score-weighted regression model. They study find that TNC entry appears to cause an average decline in state per-capita vehicle registrations by 3% (Ward et al. 2019). An effect of this magnitude would correspond to a reduction in vehicle ownership of 4.1%, on average, across all urban areas (Ward et al. 2019). Further, using EPA estimates of passenger transportation emissions, this research estimates that TNC service availability is associated with a reduction in state per-capita VOC emissions by 4.8%. Using the Department of Transportation's (DOT) average per-mile estimates of the externality costs of air pollutant emissions, this emissions reduction level represents social cost savings of \$600 million over the analysis period (Ward et al., 2019).

Martin (2016) surveys car2go members (a shared vehicle company) in five cities in North America to determine the impacts of shared vehicle usage on vehicle ownership, modal shift, VMT, and GHG emissions. In addition to surveys, this study uses vehicle activity data to evaluate the total driving that car2go vehicles travel in a city during a year and a profile of the frequency of use by the broader car2go population. The results show that usage of shared mobility translated into a reduction in GHG emissions, with estimated changes of car2go VMT, impacts at the household level decreasing -6% to -16%, and GHG emissions changing by -4% to -18% per car2go household (Martin, 2016). Overall, the results of this study suggest that car2go car sharing is substantively impacting travel behavior, miles driven, GHG emissions, and the number of vehicles on urban roads within the regions in which they operate. In another study, Martin and Saheen (2011) survey 6,281 people in North America who participated in car sharing programs in the United States and Canada and found that one-quarter of the study participants sold a vehicle due to carsharing, and another quarter postponed a vehicle purchase. The authors estimate that one car-sharing vehicle replaced 9 to 13 cars among carsharing members, with household annual VMT declining from 27% to 43% and household annual GHG emissions declining from 34% to 41% (Martin & Shaheen, 2011).

The only California legislative code that addresses the role of ridesharing and ride-sourcing in reducing VMT is SB 1014 (Skinner, 2019), which established the California Clean Miles Standard and Incentive Program. This program requires CARB to set a baseline for emissions of greenhouse gasses for vehicles used on the online-enabled applications or platforms by transportation network companies on a per-passenger-mile basis. This bill outlines annual goals for increasing passenger miles traveled using zero-emission vehicles and proposes that each transportation network company develop a greenhouse gas emissions reduction plan. This plan shall include an increased proportion of participating drivers with zero-emission vehicles using transportation network companies, an increased proportion of vehicle miles completed by zero-emission vehicles relative to all vehicle miles, decreased gram-per-mile greenhouse gas emissions rates, and increased passenger miles in proportion to overall vehicle miles. The goals of this bill also state that they should have a minimal negative impact on low-income and moderate-income drivers, ensure that the program complements and supports the sustainable land-use objectives, and support the goals of clean mobility for low- and moderate-income individuals.

Pricing Incentives

Even with a focus on compact urban morphologies and alternative transportation mode strategies described in previous sections, research often calls for additional transportation pricing policies to encourage a transition away from auto dependence. This section explains how VMT-based pricing policies and demand management may deter people from using private vehicles more

effectively than the current gas tax. In the book *Driving Change*, published by the Public Policy Institute of California (2011), the authors describe how SB 375 will require pricing policies to accompany any land use and transportation strategies, even though this policy often receives the most public resistance. The gas tax has been stagnant over the past three decades but is also depreciating in relation to inflation and lower reliance on gas due to improved fuel economy and greater use of ZEVs. Consequently, the gas tax revenue contributions to infrastructure are inadequate in relation to the list of priority improvements. An alternate approach includes VMT-based fees, which rely on new electronic toll collecting and geographic positioning system technologies. VMT-based tolls can be more flexible than the gas tax in that they can be varied according to time of day, type of road, household economics, and type of vehicle (PPIC, 2011). Pricing policies may also include congestion pricing and increased parking fees, all of which provide incentives to reduce driving while also helping to fill the growing gap in transportation funding (Rodier, 2009). Kim et al. (2008) conducted a VMT-fee pilot test involving more than 200 vehicles in Oregon. From the pilot test, they conclude that the implementation of a VMT-fee scenario has great potential to reduce GHG emissions. However, it will only become feasible as VMT toll technology improves (Kim et al., 2008). Salon et al. (2012) conducted a literature review for 14 distinct commute factors and VMT. In this review, they identify studies that quantify how much VMT can be expected to change in response to transport policies and programs such as transit improvements, road pricing, and programs aimed at changing people's travel choices. Their findings emphasize four strategies: link or point tolling-where users pay for access to a roadway segment such as a toll road or bridge; cordon pricing-where drivers are charged when crossing the boundary of a predefined tolling area (typically a downtown or central business district); distance charging-where users pay according to distance driven on the road network; and time charging whereby road users are charged for the time spent on a road. Their results show that travelers are most responsive to VMT charges. They cite one example from Sacramento where a simulated 5-cent per mile VMT charge resulted in a 10% VMT reduction (Rodier, 2002). Further support comes from Safirova et al. (2007), who find that a simulated 10-cent-per-mile VMT charge in the Washington DC area would result in a 14.5% drop in VMT. In addition to VMT pricing policies, the literature describes "demand management" incentives such as carpool lanes, employee shuttles, and other employer inducements to use transit. These strategies create financial or time-saving incentives to shift trip timing away from peak periods, making alternatives, such as transit, carpooling, and telecommuting, relatively more attractive (Deakin et al. 1996). One such study by Rodier et al. (2016) reviewed emerging ridesharing systems with the potential for a new demand management strategy that may be more politically palatable while simultaneously reducing the number of VMTs. This study used the California Bay Area activity-based travel demand model to simulate business-as-usual, transit-oriented development, and auto pricing scenarios with high, medium, and low ridesharing participation levels. Their analysis suggests that relatively significant VMT reductions are possible from moderate and high ridesharing participation levels, but at low participation levels, VMT reductions are negligible. Their analysis suggests a potentially

promising policy combination: a regional dynamic ridesharing system with a 10 to 30-cent increase in auto travel per mile cost may reduce VMT by 11% to 19% (Rodier et al., 2016). While many of the codes in previous sections mention pricing policy briefly as part of more extensive programs, the only California legislative code that more explicitly addresses pricing policy and VMT is Ch. 533, Sec. 8. (1989). In this bill, the Legislature declares that each state should have the freedom to develop the kind of highway user tax structure that it determines to be most appropriate and that annual taxes or fixed fees, which are not imposed on an amount used basis, should be apportioned based on VMT within each of the states. Local jurisdictions do not have the authority to implement gas tax changes or the authority to implement cordon pricing but will respond to legislative shifts. Thus, much of VMT pricing policy and decision-making relies on the state—not local action.

VMT and Equity

Generally, larger carbon footprints and increased VMTs correlate with higher income households. The top decile of earners contribute 30%–45% of emissions (Hubacek et al., 2017; Chancel and Piketty, 2015). Nationwide, 3.3% of total household expenditures are for vehicle fuel, and over 50% of annual household expenditures on energy are for transportation. Larger-income households spend a greater total amount on vehicle fuel and energy for transportation; thereby contributing more to travel-related GHG. This is explained, in part, by larger-income households owning more vehicles. In a San Francisco-based survey of 2,207 households (2019), 53% of households with an annual income of less than \$100,000 do not have access to a vehicle. By contrast, for households with incomes at or above \$100,000, 57% have one vehicle and 17% have two or more vehicles (SFMTA, 2019). In addition to higher income earners having more vehicles, higher income households also tend to drive alone more and accrue more VMT per vehicle according to National and Household Travel Trends (2024, Exhibit 3-24; Akar and Guldmann, 2012). While national-level models demonstrate that VMT-based fees may be mildly progressive for all household incomes below \$200,000 (Weatherford, 2011; Metcalf, 2022), several scholars have reviewed additional equity considerations. For example, Larsen et al. (2012) use data from the 2009 National Household Travel Survey to consider the equity impacts of four VMT-fee scenarios in Texas. In this study, Vertical Equity “is concerned with the distribution of impacts between individuals and groups that differ in abilities and needs, in this case, by income or social class” (Litman, 2002, pp 10). Conversely, Horizontal Equity “is concerned with the distribution of impacts between individuals and groups considered equal in ability and need” such that funds received are linked to where the captured revenue will be spent to establish improvements (Toutkoushian and Michael, 2007, pp 396). Each scenario was run statically and dynamically, assuming the VMT fee would replace the state gas tax. All scenarios were Vertically Equitable, and the most Horizontally Equitable VMT fee resulted from the scenario where vehicles would be charged a user fee that would be assessed based on when and

where the vehicle was driven, the impacts of that vehicle on the environment, and the damage to the infrastructure. Horizontal Equitability emphasized that charging different rates for travel on urban roadways and rural roadways corresponding to funding needs associated with that roadway type as well as vehicle type. In support, Yang et al (2016) use travel data from Maryland to show that income-based VMT fees can protect lower-income households while generating greater revenue. Equity-focused policies are also needed as low-income households are often forced to drive long distances due to job-housing mismatch. Restrictive zoning and limited affordable housing near jobs spurs a “drive until you qualify” search for housing that is within rent and mortgage range for lower-income households (Wang et al., 2024a). In comparison, higher income households often chose to drive longer distances for leisure. Reflecting these mismatches, Zhou et al. (2021) use actual VMT with odometer readings to show that lower-income groups spend from 1.2% to 8% of their income on fuel and personal transportation. In contrast, the range for the highest income group (\$125,000+) is from 0.15% to 3.9%. These ranges hint at the range of impacts experienced by different demographic groups while highlighting a need for equity-focused policies that do not exacerbate burdens on already burdened populations. For example, policies that raise the cost of VMT may disproportionately impact low-income households—particularly where the job-housing ratios do not align affordable housing opportunities with available, qualified jobs. In support, Choi and Hu (2008) found that variables like population growth, age, ethnicity, immigration, income, female labor force participation, and household size affect aggregate VMT. Modeling two significant data sets (2035 US and the SCAG region’s population projections by age, sex, and race/ethnicity and age-sex-race/ethnicity-specific VMT), they show that the peak of the VMT level per person (by age) was from the age group of 35-54 (family households with children). These findings are supported by Polizin et al. (2004), and indicate a need for equity-focused pricing that does not result in undue burdens for households with children who may drive longer distances to access higher quality schools. Choi and Hu (2008) also estimate that up to 65% of VMT growth was driven by population growth (Choi and Hu 2008). Thus, growing regions will need particular focus as urban form and affordable housing dynamics shift VMT patterns.

State Funding Programs that Address VMT

Several California State funding programs address transportation and land use through improved public transportation networks, compact housing, and transit-oriented development. The **Transit and Intercity Rail Capital Program** funds transformative capital improvements to modernize California’s intercity, commuter, urban rail, bus, and ferry transit systems. The policy goals of this program are to achieve reduced emissions of greenhouse gasses, expand and improve transit service to increase ridership, integrate the rail service of the state’s various rail operators, including integration with the high-speed rail system, and improve transit safety. The **Affordable Housing and Sustainable Communities Program** funds a variety of programs that include intermodal, affordable rental, or owner-occupied housing projects that support infill and compact

development; transit capital projects and programs supporting transit ridership; active transportation capital projects, including pedestrian and bicycle facilities and supportive infrastructure, and connectivity to transit stations. This program promotes transit-oriented development projects and other projects designed to reduce greenhouse gas emissions and other criteria air pollutants by reducing automobile trips and VMT within a community. Another program that addresses these broad goals of land use and VMT is the **Regional Early Action Planning (REAP) Grants Program**. REAP 2.0 provides a one-time infusion of funding through a largely formula-based approach. The program also includes competitive grants, funding for high impact transformative projects, and support for tribal and rural communities. Funds from this program are meant to address issues in housing, land use, transportation, climate change, equity, and other planning priorities. To receive these funds, a city or region must describe how housing goals will also result in per capita VMT reductions in furtherance of the region's sustainable communities strategy. Any entity that receives an allocation of funds from this program must establish priorities for eligible transformative planning and implementation activities that include accelerating infill development by performing infrastructure planning and investing in upgrading infrastructure, shifting travel behavior through reducing driving, funding the establishment of a local VMT impact fee or regional VMT mitigation bank. Those who receive these funds must also write a report (to be made publicly available) using guidelines^[26] to include land use maps and VMT generation maps produced for their Sustainable Communities Strategy.

Some other funding programs address more specific aspects of VMT, such as traffic congestion. SB 1 allocates two hundred fifty million dollars (\$250,000,000) in the State Highway Account to be made available to the Department of Transportation annually for the **Solutions for Congested Corridors Program**. Projects funded by this program are designed to achieve a balanced set of transportation, environmental, and community access improvements within highly congested travel corridors throughout the state. This program encourages high-occupancy vehicle lanes, increased transportation options for residents, advances to state highways, local streets, and roads, improved public transit facilities, bicycle and pedestrian facilities, and restoration or preservation work that protects critical local habitat or open space.

The Prohousing Designation Program (PDP) creates incentives for jurisdictions that are compliant with the State Housing Element. The program was established with the passage of the fiscal 2019-2020 budget, and Sacramento earned the first designation in 2024. Actions taken by local jurisdictions earn points across four scoring categories: (1) Favorable Zoning and Land Use (2) Acceleration of Housing Production Timeframes (3) Reduction of Construction and Development Costs, and (4) Providing Financial Subsidies.

Local Initiatives

Many of the policy goals outlined in the previous section fall under city, county, and regional planning purview. For example, PDP designation can include but is not limited to the following local actions:

- Eliminate parking requirements citywide for accessory dwelling unit (ADU) developments
- Expand residential and mixed uses allowed by-right
- Eliminate maximum density for mixed-use projects;
- Reduce parking requirements for affordable and senior housing, small lots, and vertical mixed-use developments
- Offer incentives for higher-density developments near transit by eliminating or reducing parking requirements;
- Creation of a Master Environmental Impact Report (EIR) to streamline development;
- Permit multi-unit dwellings by-right;
- Eliminate the requirement for planning and design commission public hearings where projects are consistent with zoning and the general plan;
- already zoned by right;
- Reduce development impact fees for new affordable dwelling units—\$0 rate for regulated affordable units up to 120% of the area median income;
- Eliminate housing impact fees for mobile home parks, owner occupied single-family, affordable units, high-density housing, and ADUs;
- Adopt policy for Enhanced Infrastructure Financing Districts (EIFDs), most recently the Aggie Square EIFD included a 20% set-aside for affordable housing paired with a Community Benefit Agreement;
- Adopted transit-oriented development land use zoning overlay.

Alexander et al. (2021) describe the challenges in implementing these policies at the local level through qualitative interviews with transportation practitioners. Practitioners mention three broad challenges: 1) a lack of reliable, standardized VMT measures and evaluation tools for planning; 2) a lack of strong legal case law for VMT in the CEQA; and 3) the challenge of distributing off-site VMT mitigation equitably. Dr. Susan Handy has reviewed 247 Environmental Impact Reviews (EIRs), finding that most ($\geq 64\%$) estimated VMT, primarily for air quality purposes prior to the implementation of SB 743 (Steinberg, 2013) requiring VMT to be measured for CEQA. None of the EIRs analyzed VMT as an impact by itself. Of those 136 EIRs that estimated VMT, most (86%) used CalEEMOD or URBEMIS, and only 3% used a travel demand model. These challenges highlight the growing pains as local jurisdictions convert to alternate VMT measurement and GHG inventory methodologies.

Additional bills encourage VMT reduction in targeted jurisdictions and regions. For example, both AB 2548 (Friedman, 2019) in Los Angeles County and SB 1128 (Glazer, 2017) in San Francisco outline how MPOs and county transportation commissions are encouraged to work with local employers to adopt policies that encourage commuting by means other than driving

alone. One such strategy in both bills is to adopt a commuter benefit ordinance that offers all covered employees a pretax option program to exclude commuting costs (such as public transportation passes) from their taxable income. SB 1128 in San Francisco goes even further by offering an employer-paid benefit program, whereby the covered employer offers employees a subsidy to offset the monthly cost of commuting via public transit, vanpool, or, in some cases, bicycle. This bill also encourages employer-provided transit, which is transportation furnished by the covered employer at no cost, to the covered employee in a vanpool or bus. Similarly, in Sacramento County, one of the local initiatives is the Air Quality Improvement Strategy (Ch. 1541, Sec. 3, 1988). This bill describes air pollution in the Sacramento metropolitan region caused by the operation of more than 1,000,000 vehicles. To successfully develop and implement a comprehensive air quality plan for the region, the air quality management district in Sacramento County is given additional authority to reduce motor vehicle emissions, implement reduction measures, and expand the use of cleaner-burning fuels. Yet, this code does not describe the air quality management district's strategies to achieve these goals.

Conclusion

This literature review explored policy areas most crucial for reducing GHG emissions through VMT reduction and which policies from the California legislature are currently in place to support them. The literature revealed that VMT could only be substantially reduced through a policy mix of high-density land use, employment density, increased active transportation, transit, and micromobility and ridesharing options, pricing incentives, and equity considerations. These policy areas are strengthened through their combined implementation. However, policies that are currently in place tend to favor specific strategies over others and broadly lack metrics for evaluating local policy adoption or success. This review also found that few bills support local agencies and organizations in transitioning to reduced VMT, nor do they penalize them if they fail to reduce it. The synergy between state and regional VMT policies is crucial for meeting statewide GHG and VMT reduction targets.

Table 1. Key Terms

Behavioral mode choice	The process where the means of traveling is determined, whether that be by private automobile, public transportation, walking, bicycling, or other means
CARB	California Air Resources Board

CEQA	The California Environmental Quality Act of 1970, the state-level environmental protection statute
DOT	Department of Transportation
Employment density	The number of jobs in an area divided by the resident population aged 16-64 in that area.
GHG	Greenhouse Gas
Land Use Mix	Accommodating more than one type of function within a building, a set of buildings, or a specific area. These functions include residential, office, retail, personal services, parks, and open space.
LOS	Level of service; a measure of delay used to relate the quality of motor vehicle traffic service
Micromobility	Lightweight devices that operate at low speeds, like bicycles, scooters, skateboards. Either human powered or electric
Mitigation Bank	A way to offset impact of a development project by compensating/ reducing its impact on an area. Mitigation efforts are converted to credits, which can be exchanged as currency.
Mixed-use development	Characterized as pedestrian-friendly development that blends two or more residential, commercial, cultural, institutional, and/or industrial uses.
MMT CO₂e	Million metric tons of carbon dioxide equivalents

MPO	Metropolitan Planning Organization
Off-site banking	The exchange program allows developers to fulfill their mitigation obligations without incorporating changes in the immediate project site.
Residential density	The number of dwelling units per gross acre of residential land area, including streets, easements, and open space portions of a development
Ridesourcing	On-demand services that do not require users to own the vehicle
Ridesharing	Form of shared vehicles, bikes, and scooters, enabling users to gain short-term access to transportation modes on an “as-needed” basis.
Road use fees	Motorists pay for roadway network use, including tolls, vehicle registration, and parking prices.
Shared Mobility	Mode of transportation where people use vehicles owned by a third party on an as needed basis. This includes carpooling, bike-sharing, and shuttle services.
TNC	Transportation Network Company
TOU	Time of Use rate for electric charging
VES	Vehicle Efficiency Standards: how much CO2 per mile can be emitted by a vehicle, and the fuel efficiency of vehicles miles per gallon.
VMT	Vehicle-Miles Traveled: a measure of how many miles a person has driven

VMT based fees	Charging users a fee based on when and where the vehicle was driven, the impacts of that vehicle on the environment, and the damage being done to the infrastructure
ZEV	Zero Emissions Vehicle

References

- Abduljabbar, R. L., Liyanage, S., & Dia, H. (2021). The role of micro-mobility in shaping sustainable cities: A systematic literature review. *Transportation Research Part D: Transport and Environment*, 92, 102734. <https://doi.org/10.1016/j.trd.2021.102734>
- Air Quality Improvement Strategy. Ch. 1541, Sec. 3 (Added by Stats.) in 1988 (Cal. Health & Saf. Code § 41016)
- Akar, G., & Guldmann, J.-M. (2012). Another Look at Vehicle Miles Traveled: Determinants of Vehicle use in Two-Vehicle Households. *Transportation Research Record*, 2322(1), 110–118. <https://doi.org/10.3141/2322-12>
- Alexander, Serena E, Mariela Alfonzo, and Kevin Lee. (2021). Safeguarding Equity in Off-Site Vehicle Miles Traveled (VMT) Mitigation in California. Mineta Transportation Institute Publications. <https://doi.org/10.31979/mti.2021.2027>
- Aslanyan, T., & Jiang, S. (2021). Examining Passenger Vehicle Miles Traveled and Carbon Emissions in the Boston Metropolitan Area. In *Urban Informatics and Future Cities* (pp. 319-340). Springer, Cham.
- Barajas, J. M. (2021). Biking where Black: Connecting transportation planning and infrastructure to disproportionate policing. *Transportation research part D: transport and environment*, 99, 103027.
- Basu, Rounaq, and Joseph Ferreira. (2021). Planning Car-Lite Neighborhoods: Does Bikes sharing Reduce Auto-Dependence? *Transportation Research Part D: Transport and Environment* 92: 102721. <https://doi.org/10.1016/j.trd.2021.102721>.
- Bedsworth, Louise W., and Ellen Hanak. (2010). Adaptation to Climate Change. *Journal of the American Planning Association* 76, no. 4: 477–95. <https://doi.org/10.1080/01944363.2010.502047>.
- Blumenberg, E., & King, H. (2021). Jobs–housing balance re-re-visited. *Journal of the American Planning Association*, 87(4), 484-496.
- Boarnet, Marlon, and Susan Handy. (2017). A Framework for Projecting the Potential Statewide Vehicle Miles Traveled (VMT) Reduction from State-Level Strategies in California. <https://escholarship.org/uc/item/2z48105j>.
- Boarnet, M. G., & Wang, X. (2019). Urban spatial structure and the potential for vehicle miles traveled reduction: The effects of accessibility to jobs within and beyond employment subcenters. *The Annals of Regional Science*, 62(2), 381–404. <https://doi.org/10.1007/s00168-019-00900-7>
- Brazil, N. (2020). The unequal spatial distribution of city government fines: The case of parking tickets in Los Angeles. *Urban Affairs Review*, 56(3), 823-856.
- Bureau of Automotive Repair. (2000). *Methodology for Calculating Vehicle Miles Traveled (VMT)*. Smog Check Performance Evaluation, Report 2000-06. Engineering and Research Branch. <https://19january2017snapshot.epa.gov/sites/production/files/2016-06/documents/vmt.pdf>
- California Air Resources Board. (2022). *California Greenhouse Gas 2000-2019 Emissions Trends and Indicators Report*. https://ww2.arb.ca.gov/sites/default/files/classic/cc/inventory/2000_2019_ghg_inventory_trends_20220516.pdf

- California Air Resources Board. (2019). *Quantifying Reductions in Vehicle Miles Traveled from New Pedestrian Facilities*. https://ww2.arb.ca.gov/sites/default/files/auction-proceeds/pedestrian_facilities_technical_041519.pdf
- California Air Resources Board. (2022). *Draft 2022 Progress Report California's Sustainable Communities and Climate Protection Act*. <https://ww2.arb.ca.gov/resources/documents/tracking-progress>
- California Clean Miles Standard and Incentive Program. Senate Bill 1014 (Skinner) in 2019 (Ca. Public Utilities Code, Chapter 710, §5450)
- California Zoning Atlas (2024). <https://www.zoningatlas.org/california> Accessed 4/23/2024
- Cervero, R., & Murakami, J. (2010). Effects of Built Environments on Vehicle Miles Traveled: Evidence from 370 US Urbanized Areas. *Environment and Planning A: Economy and Space*, 42(2), 400–418. <https://doi.org/10.1068/a4236>
- Chancel L and Piketty T. (2015). Carbon and inequality: from Kyoto to Paris Paris School of Economics (<http://piketty.pse.ens.fr/files/ChancelPiketty2015.pdf>)
- Chatman, Daniel G. (2008). Deconstructing Development Density: Quality, Quantity and Price Effects on Household Non-Work Travel. *Transportation Research Part A: Policy and Practice* 42, no. 7: 1008–30. <https://doi.org/10.1016/j.tra.2008.02.003>
- Choi, S., & Hu, H. H. (2008). Measuring the Effects of the Changing Demographic Compositions on Vehicle Miles of Travel (VMT) Growth Using the Standardization and Decomposition Techniques. <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.579.4262&rep=rep1&type=pdf>
- Commute Benefit Policies. Senate Bill 1128 (Glazer) in 2017 (Cal. Gov. Code, § 65081)
- Condon P. (2008). Planning for climate change. *Land Lines* 20(1) 2 ^ 7
- Cook, J., D. Salon, J. Sanchirico, and J. Williams. (2012). Driving Intensity in California: Exploring Spatial Variation in VMT and its Relationship to Fuel Prices, Fuel Economy, and the Built Environment. UC Davis.
- Dale, S., Frost, M., & Ison, S. (2023). The theory of change and realistic evaluation applied to the evaluation of a transport intervention: The case of the Nottingham Workplace Parking Levy. *Evaluation and Program Planning*, 98, 102282.
- Deakin, Elizabeth, Greig Harvey, Randall Pozdena, and Geoffrey Yarema. (1996). Transportation Pricing Strategies for California: An Assessment of Congestion, Emissions, Energy. And Equity Impacts. <https://escholarship.org/uc/item/723002kt>.
- De Hartog, Jeroen Johan, Hanna Boogaard, Hans Nijland, and Gerard Hoek. (2010). Do the Health Benefits of Cycling Outweigh the Risks?" *Environmental Health Perspectives*. 118, no. 8: 1109–16. <https://doi.org/10.1289/ehp.0901747>.
- DeMaio, Paul. (2009). Bike-sharing: History, Impacts, Models of Provision, and Future. *Journal of Public Transportation*, 12 (4): 41-56. DOI: <http://doi.org/10.5038/2375-0901.12.4.3>
- Ding, C., Wang, Y., Xie, B., & Liu, C. (2014). Understanding the Role of Built Environment in Reducing Vehicle Miles Traveled Accounting for Spatial Heterogeneity. *Sustainability*, 6(2), 589–601. <https://doi.org/10.3390/su6020589>
- Driving Change: Reducing Vehicle Miles Traveled in California. (2011). Public Policy Instit. of CA. https://www.pplic.org/wp-content/uploads/content/pubs/report/R_211LBR.pdf
- Elkind, E. N., Galante, C., Decker, N., Chapple, K., Martin, A., & Hanson, M. (2017). Right Type, Right Place: Assessing the Environmental and Economic Impacts of Infill Residential Development through 2030.

- Emrath, P., & Liu, F. (2008). Vehicle Carbon Dioxide Emissions and the Compactness of Residential Development. *Cityscape*, 10(3), 185–202.
<http://www.jstor.org/stable/20868678>
- Ewing, Reid & Robert Cervero. (2010) Travel and the Built Environment. *Journal of the American Planning Association*, 76:3, 265-294, DOI: 10.1080/01944361003766766
- Fang, K., Volker, J., & University of California, Davis. I. of T. S. (2017). Cutting greenhouse gas emissions is only the beginning: A literature review of the co-benefits of reducing vehicle miles traveled. <https://rosap.nrl.bts.gov/view/dot/32254>
- Fitt, H., & Curl, A. (2019). E-scooter use in New Zealand: Insights around some frequently asked questions. *University of Canterbury: Christchurch, New Zealand*.
- Global Warming Solutions Act. Assembly Bill 32 (Nunez) in 2006 (Ca. Health and Safety Code, Chp. 488 § 38500)
- Guidebook for Jobs-Housing Balance. Ch. 843, Sec. 1 (Added by Stats.) in 1990 (Cal. Gov. Code, § 65890.5)
- Heres-Del-Valle, David, and Deb Niemeier. (2011). CO2 Emissions: Are Land-Use Changes Enough for California to Reduce VMT? Specification of a Two-Part Model with Instrumental Variables. *Transportation Research Part B: Methodological* 45, no. 1: 150–61. <https://doi.org/10.1016/j.trb.2010.04.001>.
- Hubacek, K, Baiocchi G, Feng K, Muñoz Castillo R, Sun L and Xue J. (2017). Global carbon inequality *Energy, Ecol. Environ.* 2
- Jones, Christopher M., Stephen M. Wheeler, and Daniel M. Kammen. (2018). Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities. *Urban Planning* 3, no. 2: 35–51. <https://doi.org/10.17645/up.v3i2.1218>.
- Kim, D. S., J. D. Porter, J. Whitty, J. R. Svadlenak, N. C. Larsen, D. F. Capps, B. Imholt, J. L. Pearson, and D. D. Hall. (2008). Technology Evaluation of Oregon's Vehicle-Miles-Traveled Revenue Collection System: Lessons Learned. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2079, Transportation Research Board of the National Academies, Washington, D.C., pp. 37–44.
- Larsen, Lisa, Mark Burris, David Pearson, and Patricia Ellis. (2012). Equity Evaluation of Fees for Vehicle Miles Traveled in Texas. *Transportation Research Record* 2297, no. 1: 11–20. <https://doi.org/10.3141/2297-02>.
- Litman, Todd. (2013). Transportation and Public Health. *Annual Review of Public Health* 34, no. 1: 217–33. <https://doi.org/10.1146/annurev-publhealth-031912-114502>.
- Litman, T. (2002). Evaluating Transportation Equity. *World Transport Policy and Practice*, Vol. 8, pp. 3, 4, 10, 21
- Liu, F. H. (2007). Vehicle CO2 Emissions and the Compactness of Residential Development. *National Association of Home Builders, Special Studies*.
- Malaczynski, J. D., & Duane, T. P. (2009). Reducing Greenhouse Gas Emissions from Vehicle Miles Traveled: Integrating the California Environmental Quality Act with California Global Warming Solutions Act. *Ecology Law Quarterly*, 36(1), 71–136.
- Martin, E. (2016). The Impacts of Car2go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities, 26.
- Martin, Elliot, and Susan Shaheen. (2011). The Impact of Carsharing on Household Vehicle Ownership." *ACCESS Magazine* 1, no. 38: 22–27.

Metcalf, G. E. (2023). The distributional impacts of a vmt-gas tax swap. *Environmental and Energy Policy and the Economy*, 4(1), 4-42.

METROPOLITAN TRANSPORTATION COMMISSION, CHARACTERISTICS OF RAIL AND FERRY STATION AREA RESIDENTS IN THE SAN FRANCISCO BAY AREA: EVIDENCE FROM THE 2000 BAY AREA TRAVEL SURVEY, VOLUME I 1 (2006), available at http://www.mtc.ca.gov/planning/smartgrowth/stars/ExecutiveSummary_BATS2000_StationAreaResidents_Study.pdf.

Milakis, Dimitris, Laura Gedhardt, Daniel Ehebrecht, and Barbara Lenz. (2020). Is Micro-Mobility Sustainable? An Overview of Implications for Accessibility, Air Pollution, Safety, Physical Activity and Subjective Wellbeing. *Handbook of Sustainable Transport*, 180–89.

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., & Seto, K. C. (2018). Carbon footprints of 13 000 cities. *Environmental Research Letters*, 13(6), 064041.

Nawaz, Shahan Shaid; Menedian, Stephen; and Gamghir, Samir. (2023) “Single-Family Zoning in the Fresno Region” UC Berkeley Othering and Belonging Institute (OBI) 2023. <https://belonging.berkeley.edu/single-family-zoning-fresno-region> Accessed 4/23/2024

Nelson, Arthur C. (2017). Compact Development Reduces VMT: Evidence and Application for Planners—Comment on ‘Does Compact Development Make People Drive Less? *Journal of the American Planning Association* 83, no. 1 (January 2, 2017): 36–41. <https://doi.org/10.1080/01944363.2016.1246378>.

Noland, Robert, and William Cowart. (2000). Analysis of Metropolitan Highway Capacity and the Growth in Vehicle Miles of Travel. *Transportation* 27 (December 1, 2000): 363–90. <https://doi.org/10.1023/A:1005288826997>.

Oeschger, G., Carroll, P., & Caulfield, B. (2020). Micro Mobility and public transport integration: The current state of knowledge. *Transportation Research Part D: Transport and Environment*, 89, 102628. <https://doi.org/10.1016/j.trd.2020.102628>

Polzin, S, Chu, X, Toole-Holt, L. (2004). FORECASTS OF FUTURE VEHICLE MILES OF TRAVEL IN THE UNITED STATES. *Transportation Research Record*, 1895, p. 147-155.

Regional Early Action Planning Grants Program. Assembly Bill 175 (Amended by Stats.) in 2021 (CA Health & Safety Code § 50515.09)

Rodier, Caroline J, Robert A Johnston, and John E Abraham. (2002). Heuristic Policy Analysis of Regional Land Use, Transit, and Travel Pricing Scenarios Using Two Urban Models. *Transportation Research Part D: Transport and Environment* 7, no. 4: 243–54. [https://doi.org/10.1016/S1361-9209\(01\)00022-0](https://doi.org/10.1016/S1361-9209(01)00022-0).

Rodier, Caroline. (2009). Review of International Modeling Literature: Transit, Land Use, and Auto Pricing Strategies to Reduce Vehicle Miles Traveled and Greenhouse Gas Emissions. *Transportation Research Record* 2132, no. 1: 1–12. <https://doi.org/10.3141/2132-01>.

Rodier, C., Alemi, F., & Smith, D. (2016). Dynamic Ridesharing: Exploration of Potential for Reduction in Vehicle Miles Traveled. *Transportation Research Record*, 2542(1), 120–126. <https://doi.org/10.3141/2542-15>

Safirova, Elena, Kenneth Gillingham, and Sébastien Houde. (2007). Measuring Marginal Congestion Costs of Urban Transportation: Do Networks Matter? *Transportation Research Part A: Policy and Practice* 41, no. 8: 734–49. <https://doi.org/10.1016/j.tra.2006.12.002>.

- Salon, Deborah, Marlon G. Boarnet, Susan Handy, Steven Spears, and Gil Tal. (2012). How Do Local Actions Affect VMT? A Critical Review of the Empirical Evidence. *Transportation Research, Part D: Transport and Environment* 17, no. 7: 495–508.
<https://doi.org/10.1016/j.trd.2012.05.006>.
- San Francisco Metropolitan Transit Authority, Residential Parking Policy Large Building Study, Survey Findings-(2019) <https://www.sfmta.com/projects/high-density-housing-impact-neighborhood-parking>. Accessed 5/8/2024
- Savignano, E. (2023). Change for the Meter: Exploring the Equity Implications of Market-Priced Parking.
- Senate Bill 743 (Steinberg) in 2013 (Cal. Gov. code, Chapter 386 § 65088.1 and 65088.4)
- Shaheen, Susan A., and Adam P. Cohen. (2013). Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends. *International Journal of Sustainable Transportation* 7, no. 1: 5–34.
<https://doi.org/10.1080/15568318.2012.660103>.
- Shaheen, Susan, Adam Cohen, Nelson Chan, and Apaar Bansal. (2020). Chapter 13 - Sharing Strategies: Carsharing, Shared Micromobility (Bikesharing and Scooter Sharing), Transportation Network Companies, Microtransit, and Other Innovative Mobility Modes.” In *Transportation, Land Use, and Environmental Planning*, edited by Elizabeth Deakin, 237–62. Elsevier. <https://doi.org/10.1016/B978-0-12-815167-9.00013-X>.
- Shoup, D. C. (1995). An opportunity to reduce minimum parking requirements. *Journal of the American planning association*, 61(1), 14-28.
- Shoup, D. C. (1997). Evaluating the effects of parking cash out: eight case studies.
- Shoup, D. C. (1999). The trouble with minimum parking requirements. *Transportation research part A: policy and practice*, 33(7-8), 549-574.
- Shoup, D. (2018). *Parking and the City*. Routledge.
- Shoup, D. (2021). *High cost of free parking*. Routledge.
- Shoup, D. (2021). Pricing curb parking. *Transportation Research Part A: Policy and Practice*, 154, 399-412.
- Solutions for Congested Corridors Program. Senate Bill 1 (Added by Stats.) in 2017 (Streets and Highways Code, Ch. 5, §44.)
- Sperling, Daniel and Fulton, Lewis M. and Arroyo, Vicki. (2020). Accelerating Deep Decarbonization in the U.S. Transportation Sector. Zero Carbon Action Plan, Available at SSRN: <https://ssrn.com/abstract=3725841>
- Sustainable Communities and Climate Protection Act. Senate Bill 375 (Steinberg) in 2008 (Cal. Gov. code, Chapter 728 § 65080)
- Transit and Intercity Rail Capital Program. Senate Bill 9 (Committee on Budget and Fiscal Review) in 2015 (Public Resources Code, Chapter 710, § 75220)
- Transit Priority Project Program. Senate Bill 310 (Hancock) in 2012 (Cal. Gov. Code, ARTICLE 9. § 65470)
- Transportation Planning and Programming. Ch. 832, Sec. 3. (Added by Stats) in 2000 (Cal. Gov. Code, § 65080.3)
- Transportation Planning and Programming. Assembly Bill 2548 (Friedman) in 2019 (Cal. Gov. Code, § 65080.9)

- Tscharaktschiew, S., & Reimann, F. (2022). Less workplace parking with fully autonomous vehicles?. *Journal of intelligent and connected vehicles*, 5(3), 283-301.
- Toutkoushian, R. K., and R. S. Michael. An Alternative Approach to Measuring Horizontal and Vertical Equity in School Funding. *Journal of Education Finance*, Vol. 32, 2007, pp. 395–421.
- Venkataram, P. S., Flynn, J. A., Bhuiya, M. M. R., Barajas, J. M., & Handy, S. (2024). Availability and usability of transportation for people with disabilities depending on what the user is expected to do. *Transportation Research Interdisciplinary Perspectives*, 23, 100960.
- Volker, Jamey M. B., Joe Kaylor, and Amy Lee.(2019.) A New Metric in Town: A Survey of Local Planners on California’s Switch from LOS to VMT. *Findings*, November.
<https://doi.org/10.32866/10817>.
- Wang, B. S., Rodnyansky, S., Comandon, A., & Boarnet, M. (2024a) Drive Until You Qualify: Exploring Long Commutes in a High Housing Cost Region. *Available at SSRN 4074809*.
- Wang, B. S., Rodnyansky, S., Boarnet, M. G., & Comandon, A. (2024b). Measuring the impact of COVID-19 policies on local commute traffic: Evidence from mobile data in Northern California. *Travel Behaviour and Society*, 34, 100660.
- Ward, Jacob W., Jeremy J. Michalek, Inês L. Azevedo, Constantine Samaras, and Pedro Ferreira. (2019). Effects of On-Demand Ridesourcing on Vehicle Ownership, Fuel Consumption, Vehicle Miles Traveled, and Emissions per Capita in U.S. States. *Transportation Research Part C: Emerging Technologies* 108: 289–301.
<https://doi.org/10.1016/j.trc.2019.07.026>.
- Weatherford, B. A. (2011). Distributional Implications of Replacing the Federal Fuel Tax with per Mile User Charges. *Transportation Research Record*, 2221(1), 19–26.
<https://doi.org/10.3141/2221-03>
- Wheeler, S. M., Tomuta, M., Haden, V. R., & Jackson, L. E. (2013). The impacts of alternative patterns of urbanization on greenhouse gas emissions in an agricultural county. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 6(3), 213-235.
- Woldeamanuel, Mintesnot, and Andrew Kent. (2014). Determinants of Per Capita Vehicle Miles Traveled (VMT): The Case of California. *Journal of the Transportation Research Forum* 53, no. 3. <https://doi.org/10.5399/osu/jtrf.53.3.4240>.
- Yang, D., Kastrouni, E., & Zhang, L. (2016). Equitable and progressive distance-based user charges design and evaluation of income-based mileage fees in Maryland. *Transport Policy*, 47, 169-177.
- Zhou, Y., Aeschliman, S., & Gohlke, D. (2021). Household transportation energy affordability by region and socioeconomic factors. *Transportation Research Record*, 2675(10), 81-95.

^[11] For more information and updates, please see: <https://ww2.arb.ca.gov/resources/fact-sheets/local-government-zero-emission-vehicle-readiness>

^[12] These programs are further described by CARB 2022 Local Government Zero-emission Vehicle Readiness, <https://ww2.arb.ca.gov/resources/fact-sheets/local-government-zero-emission-vehicle-readiness>.

^[13] For information on federal and state incentives, please see the Alternative Fuel Data Center website for information on federal and state incentives and programs:

<https://afdc.energy.gov/laws>

^[14] For more information and updates, please see: <https://ww2.arb.ca.gov/resources/fact-sheets/local-government-zero-emission-vehicle-readiness>

^[15] For more about the Clean Miles Standard, please see: <https://ww2.arb.ca.gov/our-work/programs/clean-miles-standard>

^[16] <https://ww2.arb.ca.gov/sites/default/files/movingca/projectheavyduty.html>

^[17] A good example of financing solutions is BlocPower: [BlocPower — Smarter, Greener and Healthier Buildings](#)

^[18] The CPUC has approved special residential rates for heat pumps (and EV chargers) for at least one utility (PG&E): [Electric Home \(pge.com\)](#)

^[19] Such as CEC's Equitable Building Decarbonization which provides direct install incentives for low- and moderate-income households: <https://www.energy.ca.gov/programs-and-topics/programs/equitable-building-decarbonization-program>

^[10] Such as the "Switch is On" <https://switchison.org/>

^[11] The Building Decarbonization Coalition: <https://www.buildingdecarb.org/>

^[12] Kenney, Michael, Jacob Wahlgren, Kristina Duloglo, Tiffany Mateo, Danuta Drozdowicz, and Stephanie Bailey. 2022. "Final 2021 Integrated Energy Policy Report, Volume I: Building Decarbonization." *California Energy Commission*. Publication Number: CEC-100-2021-001-V1. Available at: <https://efiling.energy.ca.gov/GetDocument.aspx?tn=241599>

^[13] Reaching Beyond collaborates with cities, counties, and stakeholders to craft reach codes and spur adoption: [Statewide Reach Codes Program: localenergycodes.com](#)

^[14] <https://www.dgs.ca.gov/BSC/CALGreen>

^[15] Evergreen Economics (2022). SJV DAC Pilot Projects Process Evaluation.

https://www.calmac.org/publications/SJV_DAC_Process_Evaluation_Final_Report_102022.pdf

^[16] Kenney, Michael, Nicholas Janusch, Ingrid Neumann, and Mike Jaske. 2021. California Building Decarbonization Assessment. California Energy Commission. Publication Number: CEC-400-2021-006-CMF. <https://www.energy.ca.gov/publications/2021/california-building-decarbonization-assessment>

^[17] <https://www.energy.ca.gov/programs-and-topics/programs/equitable-building-decarbonization-program>

^[18] <https://ww2.arb.ca.gov/resources/documents/2022-state-strategy-state-implementation-plan-2022-state-sip-strategy>

^[19] <https://www.baaqmd.gov/rules-and-compliance/rule-development/building-appliances>

^[20] <http://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan>

^[21] <https://techcleanca.com/>

^[22] <https://sustainability.ucdavis.edu/ffpp>

^[23] <https://ww2.arb.ca.gov/our-work/programs/sustainable-communities-program/sb-150-dashboard-tracking-progress-sustainable>

^[24] <https://ww2.arb.ca.gov/sites/default/files/2019-11/Final%20SCS%20Program%20and%20Evaluation%20Guidelines%20Report.pdf>

^[25] <https://www.caclimateinvestments.ca.gov/>

^[26] <https://www.hcd.ca.gov/docs/grants-and-funding/mpo-reap-2-0-final-guidelines.pdf>

Appendix 2. Community Partner Materials

Partner solicitation/application

With generous support from the California Air Resources Board (CARB), the University of California at Davis (UC Davis) and California Polytechnic State University at San Luis Obispo (Cal Poly SLO) are collaborating on the development and application of tools and training to support local and regional governments in California to reach their sustainability and climate planning goals and align them with the State's climate commitments. We invite you to learn more about these efforts and the opportunity to serve as a project partner organization or in an advisory role. Interested parties may join us for one of two webinars. Details on this opportunity and the webinars are provided below.

Background

Led by Dr. Catherine Brinkley, Faculty Director of the UC Davis Center for Regional Change, this research project seeks to inform communities and state agencies about effective strategies for addressing climate action planning challenges and barriers to implementation at the local level. This effort seeks to engage local governments and their representatives in the implementation of tools to support climate planning, including the first databases of California General Plans and Climate Action Plans. You can learn more about the General Plan Database currently in beta mode here. This project is also supported by Dr. Michael Boswell, Department Head of the Cal Poly SLO Department of City and Regional Planning, who developed the first database of Climate Action Plans.

Objectives

This effort has three major objectives:

- (1) identify barriers that local governments face in implementing climate action policies and ways in which these barriers can be overcome in alignment with the State's climate commitments;
- (2) identify ways for CARB to support local governments and community-based organizations in tackling climate actions at the local level; and

(3) conduct capacity-building sessions for local government and regional government representatives, community-based organizations, climate action advocates, and other stakeholders around implementing priority climate policies, focused on education about state climate goals, resources, and priority policies using existing partnerships and networks.

Partnership Opportunity

UC Davis will contract with approximately five non-profit and community-based organizations for a series of more than a dozen capacity-building workshops for local and regional government agencies targeted for Fall 2023. Potential partner organizations will have a demonstrated track record of community engagement, education, and/or advocacy in one or more of the following cluster areas. Partner organizations will be vetted through a process to ensure an inclusive approach to represent California's geographic and demographic diversity. Contracts are anticipated to be approximately \$10,000 each for the period of May 2023-April 2024.

Focus Areas

Each contracting partner will support approximately two to three workshops in at least one of the cluster areas listed below. Contractors may propose to conduct workshops in more than one of these clusters but should demonstrate familiarity and experience with these areas. The seven cluster areas by county are:

- Southern Coastal: Santa Barbara, Ventura, Los Angeles, Orange, and San Diego
- Southern Inland: Fresno, Inyo, Kern, Kings, Tulare, Riverside, Imperial
- Northern Inland: Butte, Colusa, El Dorado, Glenn, Lassen, Modoc, Nevada, Placer, Plumas, Shasta, Sierra, Siskiyou, Sutter, Tehama, Yuba, Lake, Trinity
- Northern Coastal: Del Norte, Humboldt, Mendocino, Napa, Sonoma
- Bay Area: Alameda, Contra Costa, Marin, San Francisco, San Mateo, Santa Clara, Solano
- Central Valley: Alpine, Amador, Calaveras, Madera, Mariposa, Merced, Mono, San Joaquin, Stanislaus, Tuolumne, Sacramento, Yolo
- Central Coast: Monterey, San Benito, San Luis Obispo, Santa Barbara, Santa Cruz, Ventura

Application Process

It is our intention for the application process to not put undue demands on partner organizations. We recommend that interested parties submit as many of the following documents as they deem necessary to demonstrate how they meet the scoring criteria described below. Applicants should not be discouraged from applying if they have limited or no experience in one or more of the qualification areas.

- Contact information for applicant representative
- Resumes or CVs for team members
- Narrative describing how the organization meets the following scoring criteria, not to exceed three pages.
 - Demonstrated track record of community engagement, education, and/or advocacy in one or more of the cluster areas
 - History of commitment to climate action and/or environmental justice
 - Experience conducting workshops and/or delivering training
 - Experience working with local government officials

- Qualifications of team members on topics of sustainability and climate planning, (such as resilience and adaptation)
- Familiarity with land use planning, including General Plans and the State’s climate change policy framework, including the AB 32 Scoping Plan, SB 375, and other relevant legislation, regulations, and executive orders

Application materials should be submitted via [THIS SUBMISSION LINK](#) by the application period close date. We recommend submitting materials in Word or PDF format.

Interested parties are encouraged to attend an informational webinar or view recordings. Questions can be directed to creinfo@ucdavis.edu. Questions submitted less than three business days before the application close date may not receive an answer before the application deadline.

Table 1. Metrics for Partner Selection

Qualifications	Score
Demonstrated track record of community engagement, education, and/or advocacy in one or more of the cluster areas	25 points
History of commitment to climate action and/or environmental justice	25 points
Experience conducting workshops and/or delivering training	20 points
Experience working with local government officials	10 points
Qualifications of team members on topics of sustainability and climate planning, (such as resilience and adaptation)	10 points
Familiarity with land use planning, including General Plans and the State’s climate change policy framework, including the AB 32 Scoping Plan, SB 375, and other relevant legislation, regulations, and executive orders	10 points
TOTAL	100 points

Webinars

Webinars will be held virtually via Zoom. The presentation portion of one of the webinars will be recorded and posted on the CRC website. A question-and-answer portion will follow the presentation. Please register for a webinar here: [Informational Webinar Registration](#).

Table 2. CBO recruitment deadlines

<i>Application and Project Timeline</i>	Date
Application released	9/19/2022
Webinars	9/ 26 /2022 to 10/ 6/2022
Application period opens	10/03/2022
Application period closes	10/28/2022
Application scoring completed	November 2022
Top candidates notified	12/1/ 2022
Contracting process	January 2023-March 2023
Contract start	May 2023
Contract completed	April 2024

Decarbonization in the built environment;
https://regionalchange.ucdavis.edu/sites/g/files/dgvnsk986/files/inline-files/Decarbonization_DRAFT_for%20CBOs%20%281%29.docx

Building Planning Capacity for Building Decarbonization

Building Decarbonization is an umbrella term for reducing greenhouse gas (GHG) emissions in the building sector through the following actions:

- Increasing energy efficiency and insulation
- Increasing reliance on renewable electricity (utility and distributed generation)
- Electrification of end uses (for example, water heating or air conditioning)
- Implementing distributed energy resources like rooftop solar and batteries
- Switching to climate-friendly refrigerants and improving refrigerant management

State Supports

The State of California aims to achieve an 80% reduction in CO₂ emissions relative to 2005 levels by 2050 and has created the following supports and funding for local governments:

- Senate Bill 100 (De León, 2018) requires that renewable and zero-carbon energy resources supply 100% of the electricity for retail sales to customers by 2045.
- Over 70 jurisdictions have adopted all electric requirements for new construction. Find model building codes in the California's Green Building Standards (CALGreen) Code and at the Statewide Reach Codes Program
- Zero-Emission Appliance Standards – includes support for zero-emission GHG standards for new space and water heaters sold in California as part of the 2022 State Strategy for the State Implementation Plan. It would require new sales of space and water heaters for residential and commercial buildings to be zero-emission starting in 2030.

Regional Challenges

Feasibility: In California, the energy use from buildings is responsible for about one-quarter of statewide greenhouse gas emissions, making it the second largest contributor to emissions after transportation. At the same time, the energy and the built environment sectors are also most responsive to reduction measures for reducing GHG (Brinkley, 2014). Using existing technologies for private, community, and rooftop solar and wind generation, models show that renewable energy can feasibly and cost-effectively provide approximately 72% of electricity generation by 2050 (Langevin et. al, 2019). Local jurisdictions can help by enabling, fast-tracking permitting, and siting more renewable and net-zero energy infrastructure.

Equity: Low-income communities and communities of color are disproportionately exposed to local pollution while living in lower quality housing and bearing a higher proportion of energy costs as a percentage of total household budget. These communities are also highly vulnerable to extreme weather from climate change, and they lack access to cooling and resilient infrastructure (Tan and Jung, 2021). Renters usually pay the utility bills but face the split-incentive of not being able to make energy efficiency upgrades to insulation, boilers, or renewable energy. Low-cost energy improvements could save low-income households about \$1,500 annually (Kontokosta et al, 2020). Property owners, on the other hand, are not directly incentivized to pay for upgrades that would only benefit their tenants.

In considering equity, Building Energy Codes (BECs) have the potential to reduce energy costs by \$125 billion by 2040 and provide households with a 6.47% reduction in monthly energy expenditure. Weatherization and renovation of existing buildings can generate substantial cost savings while improving health, safety, and overall living conditions (Zhu et. al, 2022). When such programs are directed at rental buildings, they have the potential to benefit the most vulnerable community members, particularly with added rent protection programming.

Example Policies

Strong planning at the local level includes setting feasible goals with measurable benchmarks, identifying potential funding sources, dedicating staff, and creating an implementation timeline that can ensure policies move forward even as administrations cycle. Local jurisdictions can include policies in General Plans, climate action plans, and municipal codes. Few General Plans have focused on holistic decarbonization efforts, leaving room for local jurisdictions to celebrate new advances at the leading edge. For example, while decarbonization is a term commonly used by state agencies, local plans favor terms such as “climate neutral” or focus on technologies such as “microgrid” and “heat pump” adoption. Further, few include equity approaches that address decarbonization. We provide sample policies below for further consideration:

Example policies:

Lake Forest, 2020: “Goal PF-6 Energy Management: A community with adequate power, provided through economically and environmentally sustainable means. Policy PF-6.6 Public-

Private Partnerships. Investigate the opportunity to engage in public-private partnerships on energy efficiency, energy storage, and microgrid development to achieve cost savings, reduce energy use, and improve energy reliability.” Timeline: none. Funding: none. Personnel: none.

Rancho Cucamonga, 202:“Goal 3: Green Building. Development practices that demonstrate high environmental performance through decarbonization, sustainable design, and zero net carbon buildings.

Strategy 3.1: Zero Net Electricity for New Residential Buildings

Measure(s):

- Adopt an ordinance or update development code requiring that new single- and multi-family residential development to meet a standard of zero net energy (i.e., on-site generation of energy is equal to on-site energy consumption).
- Encourage future residential development projects to be designed as Net Positive Energy Homes and take advantage of the State’s Net Energy Metering 2.0 policy, allowing customers to receive credits on their electricity bills for excess electricity generated by photovoltaic systems.”

Timeline: 4646 MTCO₂E reduction by 2030; 3380 MTCO₂e reduction by 2040; Funding: none. Personnel: none.

We invite you to search for additional policies and approaches as your community considers actionable steps!

References:

- Langevin, J., Harris, C. B., & Reyna, J. L. (2019). Assessing the potential to reduce US building CO₂ emissions 80% by 2050. *Joule*, 3(10), 2403-2424.
- Brinkley, C. (2014). Decoupled: successful planning policies in countries that have reduced per capita greenhouse gas emissions with continued economic growth. *Environment and Planning C: Government and Policy*, 32(6), 1083-1099.
- Kontokosta, C. E., Reina, V. J., & Bonczak, B. (2020). Energy cost burdens for low-income and minority households: Evidence from energy benchmarking and audit data in five US cities. *Journal of the American Planning Association*, 86(1), 89-105.
- Zhu, Q., Leibowicz, B. D., Busby, J. W., Shidore, S., Adelman, D. E., & Olmstead, S. M. (2022). Enhancing policy realism in energy system optimization models: Politically feasible decarbonization pathways for the United States. *Energy Policy*, 161, 112754.

Zero emission vehicle adoption;

https://regionalchange.ucdavis.edu/sites/g/files/dgvnsk986/files/inline-files/ZEV_DRAFT_for%20CBOs_1.docx

Building Planning Capacity for Zero Emission Vehicle Uptake

Goal: The Governor's Executive Order N-79-201 (2021) aims to achieve 100% light-duty zero-emission vehicle (ZEV) sales by 2035, 100% ZEV medium- and heavy-duty vehicles in California by 2045, and 100% zero-emission off-road vehicles and equipment operations by 2035. To meet these goals, local jurisdictions can support through:

- Adopting voluntary tiers for CALGreen EV-ready charging infrastructure codes.
- Engaging the community in siting charging infrastructure equitably.
- Ensuring streamlined permitting for EV charging.
- Converting public city fleets to ZEVs

State Support: The State offers ZEV guidance and funding programs for local jurisdictions to advance multi-modal ZEV and ZEV infrastructure to achieve its ZEV goals. Key guidance and support are highlighted below:

Guidance

- The Department of Business and Economic Development (GO-Biz) ZEV Resources and Readiness includes GO-Biz Electric Vehicle Charging Station Readiness with a permitting guidebook, best practices, and resources.
- GO-Biz Resources for Transitioning to a Zero-Emission Fleet
- Local Government Multi-Modal ZEV Readiness and Actions defines a “ZEV-ready” community and provides a list of actions that can be tailored to each community’s needs. Includes links to examples of ZEV community readiness plans and blueprints.

Funding Support

- GO-Biz ZEV Funding Resources (includes Clean Cars 4 All, hybrid and electric truck and bus (HVIP), Off-Road Equipment (CORE), infrastructure incentives, utility transportation electrification incentives, financing programs, California budget and funding plans, and federal funding.
- California Air Resources Board (CARB) Low Carbon Clean Transportation Funding Programs
 - Clean Mobility Options (CMO) and CMO funding for zero-emission mobility projects and needs assessments.
 - Planning and Capacity Building, Clean Mobility in Schools (CMiS) and the Sustainable Transportation and Equity Project (STEP)
- California Energy Commission (CEC) Clean Transportation Program funding
 - CALeVIP for regional charging infrastructure

Challenges and Opportunities: ZEV Costs and Equity

ZEVs have been significantly more expensive than gasoline vehicles for many years, however, that gap is closing. ZEV price analysis shows that ZEV costs will drop below the price of gasoline vehicles by 2027, with the lowest range ZEVs reaching price equality with gasoline cars by 2024. To reduce barriers to ZEV ownership and use, local governments can provide outreach and education about state rebates and incentives as well as supporting ZEV car-share programs.

The State has programs that help a community assess its transportation needs and access funding for planning and capacity building, transportation pilots and needs assessments as well.

Over 30% of Californians live in multi-family homes without access to a dedicated charger. This is a significant barrier for many. The State is addressing this issue by providing incentives and grants for multi-family dwelling owners, options for nearby charging hubs, and the CALGreen code has increased requirements for EV chargers in new multi-unit buildings. Some communities lack sufficient charging infrastructure but the State's CALeVIP program provides significant rebates for charging infrastructure in every region of the state. Regions and communities need to be aware of opportunities such as this to increase the density of chargers in their areas.

Example Policies:

Strong planning at the local level includes setting feasible goals with measurable benchmarks, identifying potential funding sources, dedicating staff, and creating an implementation timeline that can ensure policies move forward even as administrations cycle. Local jurisdictions can include policies in General Plans, climate action plans, and municipal codes. Please see examples below:

Port Hueneme City, 2021: “4.1 Policy CAP 2-1: Increase electric/alternative fuel vehicle and equipment adoption to 10% by 2030, and 15% by 2045. Action Number CAP 2-1.1: Adopt EV Charging Reach Code for Commercial and Multifamily Buildings that require all new commercial and multifamily buildings to exceed minimum CALGreen standards for “EV Ready” charging spaces and infrastructure.”

Timeline: Anticipated Reduction (MT CO₂e) - 2030: 3,555; 2045: 4,635. Funding: none.
Personnel: none

City of Burbank Climate Action Plan, 2022: “T.3.1 Increase zero-emission vehicle adoption to 23% of all passenger vehicles by 2030 and 100% by 2045.”

“T-3.1a Adopt an EV Charging Retrofits in Existing Commercial and Multifamily Buildings Reach Code requiring major retrofits, with either a building permit with square footage larger than 10,000 square feet or including modification of electric service panels, to meet CalGreen requirements for “EV Ready” charging spaces and infrastructure.”

Timeline: phase I of plan implementation (1-3 years)

Funding: none

Personnel: anticipate needing staff and consultant time

Reducing Vehicle Miles Traveled;

https://regionalchange.ucdavis.edu/sites/g/files/dgvnsk986/files/inline-files/VMT_DRAFT_for%20CBOs_1.docx

Building Planning Capacity for Reducing Vehicle Miles Traveled (VMT)

VMT measures the distance that vehicles travel. Encouraging walkable communities with more transportation options reduces VMT. Reducing VMT also helps to avoid expensive road expansions, traffic, air pollution, and loss of natural and working lands.

Goals:

To meet California's carbon neutrality goal by 2045, the California Air Resources Board (CARB) 2022 Scoping Plan targets reducing VMT per capita from 24.6 miles per day in 2019 to 18.4 miles by 2030 (a 25 percent reduction) and to 17.2 miles per day by 2045 (a 30 percent reduction). This translates to every California reducing how often or how far they are driving by about 7 miles per day in 2045. The goal of reducing VMT is to reduce greenhouse gas emissions, air pollution, traffic associated with vehicle traveled, and encourage walkable communities with less traffic and more transportation options to destinations. To help support this goal there is a need to:

- **Shift planning and investments** to create a sustainable transportation system that will reduce the need to drive and provide high-quality alternatives that are more convenient, efficient, and low-cost than driving.
- **Improve alignment of land use planning and development** with climate and equity goals to accelerate infill development, affirmatively further fair housing, and increase natural and working lands protection, in furtherance of the State's planning priorities.

State VMT Legislation:

Senate Bill 743 changed the way transportation impacts are measured under the California Environmental Quality Act (CEQA). Replacing the previous Level of Service (LOS) method, which measured vehicle delay in traffic jams- for example, with VMT, which measures the distance vehicles travel. Under CEQA, jurisdictions will use new metrics, thresholds, and develop mitigation measures around VMT that may include:

Transportation Demand Management (TDM) that reduces reliance on the single-occupant vehicle (SOV) by supporting infrastructure for biking, walking, transit, ridesharing and carpooling such as bicycle parking, streetscape improvements (e.g., sidewalks, crosswalks, curb-extensions, lighting, etc.), carshare parking and membership, and transit passes.

Land use management through changes in project design such as including units in the project be affordable to lower-income residents and including a mix of uses within the project to support the provisions of services closer to where people live.

Parking management through reducing or eliminating project parking, unbundling parking from renting or owning a unit, cashing out parking, or pricing parking, which can encourage other forms of transportation and maintain ideal occupancy rates in high value parking spaces. These tools can also educate people about the cost of vehicle trips.

Funding Support:

- The State has a variety of funding programs, such as the Transit and Intercity Rail Capital Program, Low Carbon Transit Operation Program, Active Transportation Program, Clean Mobility Options, Planning and Capacity Building, Clean Mobility in Schools, Sustainable Transportation Equity Project, Affordable Housing and Sustainable Communities Program, Transformative Climate Communities, and Regional Early Action Planning Grants Program 2.0. These address VMT reduction through investments in mobility choices and infrastructure to support public transportation, walking, biking, carsharing, and transit-oriented development.

Challenges and Opportunities:

A potentially limiting factor in California’s ability to reduce VMT is **job-housing balance**, resulting in longer distances between where people work and places people live. This, coupled with the lack of affordable housing and declining **employment density** creates challenges for implementing walk/bike and public transit options as both housing and job centers are more spread out. The COVID-19 pandemic has exacerbated these challenges. To address these regional challenges and support VMT reduction the following actions could be considered:

- Zoning reforms to allow flexible transit-oriented, mixed-use, mixed-income development at higher densities.
- Incentivize employers to locate in housing-rich communities served by transit.
- Encourage affordable and market rate housing near employment centers.
- Transform aging malls, office parks, and publicly owned land into neighborhoods with housing, office, commercial development, and multimodal transportation facilities.

Example VMT Policies:

Strong planning at the local level includes goal setting with measurable actions and benchmarks, identified funding, dedicated staff, and an implementation timeline that can ensure policies move forward even as administrations cycle. Local jurisdictions can include such policies in General Plans, climate action plans, and municipal codes. Achieving VMT reduction requires a complex and synergistic policy approach that combines high density land use, employment density, increased active transportation, transit, new mobility, and ridesharing options, pricing incentives, and equity considerations. These policy areas are strengthened through their combined implementation. Below are a few examples of policy approaches that address VMT.

El Dorado County, 2019: “MEASURE LU-Q Promote Infill Development: The program shall be linked to land-use, housing, air quality, transportation and circulation strategies that support development within existing communities, reduce vehicle miles traveled, increase energy efficiency, and encourage the development of affordable housing.”

Sacramento City, 2023: LUP-1.1: Compact Urban Footprint. The City shall promote a land- and resource-efficient development pattern and the placement of infrastructure to support efficient delivery of public services and conserve open space, reduce vehicle miles traveled, and improve air quality.

Sacramento County, 2017: “Objective: Coordinate private development with the provision of adequate public facilities and services. LU-68. Give the highest priority for public funding to projects that facilitate and encourage infill, reuse, redevelopment and rehabilitation, mixed-use development, particularly in Environmental Justice Communities, and that will result in per-person vehicle miles traveled lower than the County average, and the lowest priority for projects that do not comply with public facilities Master Plan phasing sequences (Sacramento County General Plan, 2017).”

City of San Jose, 2023: Goal LU-5 – Neighborhood Serving Commercial. Locate viable neighborhood-serving commercial uses throughout the City in order to stimulate economic development, create complete neighborhoods, and minimize vehicle miles traveled.

City of Los Angeles, 2016: 5.2 Vehicle Miles Traveled (VMT): Support ways to reduce vehicle miles traveled (VMT) per capita. Reducing VMT requires a combination of sustainable approaches working together:

- Land use policies aimed at shortening the distance between housing, jobs, and services that reduce the need to travel long distances on a daily basis.
- Increasing the availability of affordable housing options with proximity to transit stations and major bus stops.
- Offering more attractive non-vehicle alternatives, including transit, walking, and bicycling
- Transportation Demand Management (TDM) programs that encourage ride-sharing
- Pricing mechanisms that encourage commuters to consider alternatives to driving alone, including:

§ Congestion or cordon pricing, which would charge vehicles entering into a congested area (such as downtown during rush hour)

City of Arroyo Grande, 2013: “TL-7.2: Develop a form-based zoning code for the central business district/downtown. Form-based codes emphasize building form rather than use. This increases flexibility for a variety of complementary uses to be permitted in the same area, and the potential for mixed-use development, which helps to reduce vehicle miles traveled.”

Appendix 3. Links to videos and presentations

Slide deck to learn and share more about climate planning in your community:

<https://regionalchange.ucdavis.edu/sites/g/files/dgvnsk986/files/inline-files/Capacity%20Building%20Presentation%20Draft%20for%20CBOs.pptx>

Best Practices and Capacity Building for Local Governments Implementing Climate Action Plans:

<https://www.youtube.com/watch?v=myrSrX0cyqQ>

Climate Readiness Capacity Building Workshop Summary Form:

https://ucdavis.co1.qualtrics.com/jfe/form/SV_eQf54tsXN7KlgJo

Advancing Climate Readiness Planning in California: Strategies for Local Governments

Abstract:

Climate change poses significant challenges to California, threatening its ecosystems, communities, and economy. Local governments play a pivotal role in climate readiness planning, as they are on the frontline of addressing climate impacts and implementing resilience strategies. This white paper recommends actionable steps that local governments can take to enhance their climate readiness planning efforts. Recommendations draw from three sources: 1.) feedback gathered from over 155 organizations that attended community partner-led workshops, 2.) a literature review of recent research and state-level programs, and 3.) plan evaluation of California's 482 city and 58 county General Plans as well as 251 Climate Action Plans (CAPs).

Introduction:

California faces increasingly severe wildfires, droughts, heatwaves, and sea-level rise. Recognizing the urgency of addressing these challenges, local governments across the state are ramping up their efforts to develop and implement local policies that go beyond state-level mandates. Navigating the complexities of climate readiness requires comprehensive strategies that encompass multiple sectors and stakeholders. This white paper presents a roadmap for local governments in California to bolster their climate readiness planning and build resilient communities. We focus on equity throughout-out as a key consideration. Improving the health and wellness of the most vulnerable community members reduces the risks faced by the entire jurisdiction.

Key Strategies for Climate Readiness Planning:

1. Conduct Assessments:

Local governments should conduct comprehensive asset maps and vulnerability assessments to identify areas and populations most susceptible to climate impacts. These assessments should analyze various factors such as exposure to extreme weather events, socioeconomic vulnerabilities, and critical infrastructure at risk. By understanding these vulnerabilities, municipalities can prioritize resources and interventions where they are most needed.

A climate asset inventory is a visual representation or interactive tool that identifies and catalogs various resources within a community or region related to climate resilience, mitigation, and adaptation. The resulting database serves as a comprehensive inventory of natural, built, social, and economic resources that can help communities prepare for and respond to climate change impacts. A climate asset inventory might include:

Natural Assets:

- **Ecosystems:** Identify key ecosystems such as forests, wetlands, and coastal areas that provide valuable ecosystem services like flood control, carbon sequestration, and biodiversity preservation.
- **Water Resources:** Map rivers, lakes, aquifers, and watersheds critical for drinking water supply, irrigation, and habitat preservation.
- **Land Cover:** Highlight areas of vegetation, open space, and natural habitats that contribute to climate regulation, heat mitigation, and stormwater management.

Built Assets:

- **Infrastructure:** Identify critical infrastructure such as transportation networks, energy facilities, and communication systems vulnerable to climate hazards like sea-level rise, extreme heat, and wildfires.
- **Green Infrastructure:** Locate green infrastructure projects like parks, green roofs, permeable pavements, and urban forests that enhance resilience to climate impacts and improve urban livability.
- **Buildings:** Assess the vulnerability of buildings and structures to climate risks and identify opportunities for energy efficiency upgrades, retrofitting, and resilient design. This section can include respite centers and cooling centers.

Social Assets:

- **Community Organizations:** Map community-based organizations, nonprofits, and advocacy groups engaged in climate resilience, social justice, and community empowerment.
- **Social Networks:** Identify social networks, cultural institutions, and informal networks that foster community cohesion, knowledge sharing, and collective action on climate issues.
- **Public Services:** Catalog public services and amenities such as healthcare facilities, schools, emergency shelters, and community centers critical for disaster preparedness and response.

Economic Assets:

- **Businesses and Industries:** Inventory businesses and industries contributing to local economic vitality and assess their vulnerability to climate risks, supply chain disruptions, and regulatory changes.
- **Employment Opportunities:** Identify job sectors, workforce skills, and training programs relevant to climate resilience, renewable energy, green technology, and sustainable agriculture.
- **Tourism and Recreation:** Highlight tourism destinations, cultural heritage sites, and recreational assets vulnerable to climate impacts and opportunities for sustainable tourism development.

Policy and Planning Assets:

- **Regulatory Frameworks:** Document existing policies, regulations, and planning documents related to climate change adaptation, land use, zoning, and environmental protection.
- **Planning Initiatives:** Highlight ongoing climate resilience planning efforts, hazard mitigation plans, and adaptation strategies at the local, regional, and state levels.
- **Stakeholder Engagement:** Identify key stakeholders, decision-makers, and partnerships involved in climate resilience planning and community engagement processes.

A climate asset inventory provides valuable insights into a community's strengths, vulnerabilities, and opportunities for enhancing resilience to climate change. By visualizing and synthesizing diverse assets, stakeholders can prioritize investments, allocate resources, and develop targeted strategies to build more sustainable and resilient communities.

2. Develop Feasible Plans:

Based on the findings of asset maps and vulnerability assessments, local governments should develop robust sets of policies that outline specific strategies and actions to mitigate risks. Key components of climate ready policies include upgrading infrastructure, enhancing emergency preparedness response systems, promoting carbon capture through conservation of green spaces, and integrating climate considerations into land use planning.

Policies can be implemented on a short time frame with municipal code updates. For example, “reach codes” reach beyond state requirements and can include: building codes for materials, energy codes that regulate appliances, and electric-vehicle charging ordinances. Gather ideas for municipal code updates by reviewing recently adopted ordinances through the Statewide Reach Codes Program.

Jurisdictions use General Plans and Climate Action Plans (CAPs) to create the overarching vision and goal of how municipal codes will work in tandem with other policies and financing. Such plans can require several years of community dialogue. While every jurisdiction is required to adopt and update a General Plan, CAPs are voluntary. Both plan types can reference one another, and both can and do address climate readiness. However, our plan evaluation shows that CAPs include greater attention to climate readiness and stronger policies when compared to General Plans. We also show that CAPs are associated with implementing electric charging stations. We caution that many communities may not have the funding nor consensus base necessary to embark on adopting a CAP. Community partners working across the state recommend that jurisdictions use an approach that best fits their constituents and planning budget. We note that General Plans are commonly utilized for climate readiness planning in rural areas and often include policies that adapt and mitigate without labeling such policies as “climate” actions. Comparatively, CAPs are high-visibility documents that signal policy willingness to neighboring jurisdictions. This can be an advantage. For example, CAPs that promote electrical vehicle charging stations can embolden neighboring jurisdictions to site more

charging stations. Similarly, safety and hazard mitigation plans are typically revised for Federal Emergency Management Agency (FEMA) compliance, also making them optimal avenues for engagement.

To understand local support for policies, jurisdictions should **gather public input** from diverse stakeholders, including community members, businesses, and environmental experts. Effective climate readiness planning requires meaningful engagement with local communities, particularly those disproportionately affected by climate change. Engaging community-based organizations, conducting outreach in multiple languages, and providing education on climate risks are essential steps toward fostering resilient and socially just communities. Such engagement will ensure a plan that is more responsive—especially during emergencies and for those on the frontlines of climate change. One approach to achieve robust community engagement is to advertise public feedback events in partnership with local community-based organizations.

The planning process should **draw from the latest scientific understandings** of what is feasible and economical. The public and local jurisdictions can **look to neighboring jurisdictions** for policies in progress by utilizing the California [PlanSearch](#) tool for General Plans and the [California Climate Action Plan Database](#). We also recommend that communities consider a **One Health** approach that considers the human, animal, and environmental health impacts of any proposed policy. This **Health in All Policies** approach will help foster community dialogues about building equity locally.

With such input from the public, research, and practice, local communities should be emboldened to draft actionable policy language that will ensure timely implementation. This includes:

1. Use of strong policy language such as “the jurisdiction *will* do the following actions” as opposed to “the jurisdiction *may* do the following actions”
2. Policies should include a timeline for implementation to benchmark planning progress
3. A responsible office or staff position should be designated for carrying out the policy
4. To ensure feasibility, policies should identify potential funding sources

3. Enhance Implementation Collaboration and Coordination:

Climate change transcends municipal boundaries, requiring collaborative efforts among neighboring jurisdictions, regional agencies, and other stakeholders. Local governments should foster partnerships with neighboring municipalities, county governments, state agencies, nonprofits, and academic institutions to leverage resources, share best practices, and coordinate climate adaptation initiatives. Regional collaboration can facilitate the development of integrated strategies that address shared climate challenges more effectively. For example, some non-profits, like the Sierra Business Council, offer free greenhouse gas mitigation inventory preparation. Local jurisdictions can grow collaboration efforts with community and non-profit partners through seeking joint funding opportunities, through grants and fundraising.

Conclusion:

As climate change continues to pose significant risks to California's communities and ecosystems, local governments must proactively adapt to these challenges through robust climate readiness planning. By implementing the strategies outlined in this white paper, municipalities can strengthen their resilience to climate impacts, protect vulnerable populations, and foster sustainable development. Building climate-ready communities requires concerted efforts, collaboration, and innovation at the local level, laying the foundation for a more resilient and sustainable future in California.

Enhancing Local Climate Readiness Planning in California: Recommendations for the California Air Resources Board

Abstract:

The California Air Resources Board (CARB) plays a pivotal role in addressing climate change and air quality issues statewide. As climate impacts intensify, there is a growing need for coordinated efforts to bolster local climate readiness planning across California. This white paper outlines actionable recommendations for CARB to enhance its support for local governments in their climate readiness planning endeavors. By leveraging its expertise, resources, and regulatory authority, CARB can empower municipalities to build more resilient communities and mitigate the adverse effects of climate change.

Introduction:

California is at the forefront of confronting the challenges posed by climate change, experiencing increasingly severe wildfires, heatwaves, droughts, and rising sea levels. Local governments bear the frontline responsibility for preparing their communities to withstand and adapt to these impacts. Recognizing the critical role of local climate readiness planning, CARB can serve as a catalyst for enhancing preparedness efforts statewide. This white paper presents actionable recommendations for CARB to support and strengthen local climate readiness planning initiatives across California.

Recommendations for CARB:

1. Deliver Technical Assistance:

CARB should offer regionally relevant technical assistance and guidance to local governments for conducting vulnerability assessments, developing adaptation plans, and integrating equity considerations into climate planning. Community partners recommend that CARB establish a state agency liaison to facilitate direct communication and engagement with counties and cities. Partners underscore that it is essential for state representatives to meet local entities in their communities, reducing the need for local jurisdictions to travel to the state capitol.

CARB should also develop and **equity checklist** to assist jurisdictions in considering a Health in All Policies approach to plan-making. Our review of General Plans and Climate Action plans shows a broad omission of policy benchmarks and equity considerations in current plans. For example, only six of the 126 cities that address “electric vehicles in their General Plans include equity considerations, such as electric vehicle charging for affordable housing (City of Arcata, 2008 General Plan) or converting public fleets to all-electric (City of East Palo Alto, 2016 General Plan). Updates to the CARB Scoping Plan should consider including a list of adopted and recommended equitable actions related to each priority area for local jurisdictions to consider.

2. Tailor Recommendations to the Locale:

To better inform technical assistance, CARB should **review city and county-level plans** and implementation progress to provide more feasible, real-time guidance. For example, CARB technical assistance can take the form of evaluating how other cities within the same county are addressing priorities and mandates. CARB could proactively promote promising local planning approaches by monitoring plan adoption and celebrating newly adopted plans or unique approaches. Partners also recommend that CARB offer a **jurisdiction specific GHG inventory template** that is pre-filled and can be edited based on local context adjustments. CARB should work with local community-based organizations and jurisdictions to assemble preliminary data for this analysis. Local jurisdictions can further modify and update this inventory based on local conditions. This inventory can be used by local jurisdictions to estimate the reductions planned over a specific time horizon. The template can also help CARB better tailor recommendations based on regional actions that have produced results.

3. Develop and Maintain Knowledge-sharing Platforms:

By leveraging its expertise in climate science, air quality management, and regulatory compliance, CARB can provide valuable resources, tools, and best practices to support municipalities in their climate readiness planning efforts. These tools currently include the **California PlanSearch** tool for General Plans and the **California Climate Action Plan Database**. CARB should continue to maintain and update these public-facing platforms to inform inter-agency technical assistance efforts as well as public engagement in plan-making. To more easily update and maintain these platforms, the State of California should provide **guidelines for plan formatting**, including requirements for plans to be accessible as machine readable PDFs with a standard template cover page that details plan metadata: date of adoption, jurisdiction name, plan author, date of CEQA certification, and a digital object identifier (DOI). Community partners also recommend a **greenhouse gas inventory portal**, helping advocates and state agencies evaluate progress.

4. Funding and Incentives:

CARB should **reduce the competitive grant application burden** to support local climate readiness planning initiatives. This may include pre-qualifying local jurisdictions based on an evaluation of their planned actions in municipal code, General Plans, or Climate Action Plans. Such pre-qualification would encourage local jurisdictions to address priorities in plans and code while reducing the qualification burden on the local jurisdiction. CARB and other state agencies should also continue to provide funding and support for jurisdictions to update plans so that they can qualify for such funding. By leveraging state and federal funding sources, CARB can maximize resources and encourage innovative climate solutions at the local level.

5. Capacity Build in Partnership:

CARB should invest in capacity building and training programs in partnership with community-based organizations. CARB piloted this approach in this contract, enabling a feedback loop between state, regional, local, and nonprofit partners. Further fostering such collaboration will

enhance the technical expertise of CARB as well as the knowledge base of local government staff responsible for climate readiness planning. Continuing partnerships may involve co-sponsoring workshops, webinars, and educational resources on climate science, adaptation strategies, and regulatory compliance. By building the capacity of local officials and practitioners, CARB can strengthen the effectiveness and sustainability of climate readiness planning efforts statewide. This approach allows local governments and organizations to hold expertise, maintaining efforts over time. In addition, working in partnership with local organizations bolsters trust in CARB, while helping CARB to update approaches based on new, locally-pertinent information. Such partnerships should compensate local experts for their time and engagement, while allowing time for the relationships to inform one another. For example, through this contract, the first months of engagement with community-based organizations included dialogues to simplify language and minimize technical jargon.

This effort of translating CARB priorities to the local context helped the team collectively enhance the applicability and accessibility of outreach materials tailored to each regional context, ensuring that barriers were not created from the outset. To start, these efforts surfaced areas of terminology confusion. Where CARB is focused on “building decarbonization,” this is not a term commonly used at the local level, necessitating synonyms. Similarly, local jurisdictions often use the term “green building requirement,” which is functionally similar to “reach code.” Next, community partners raised the profile of local priorities—some of which dovetailed with CARB priorities while others did not. In some cases, the mismatch in priorities relegated climate planning to a future consideration. In other cases, CARB priorities could be seamlessly infused in local planning discussions. To this end, partners advocated that CARB support a variety of climate readiness approaches, not limited to CEQA-qualified CAPs. Partners noted that General Plans are commonly utilized for climate readiness planning in rural areas, while CAPs are high-visibility documents that help signal for region collaboration. Safety and hazard mitigation plans are typically revised for Federal Emergency Management Agency (FEMA) compliance, also making them optimal avenues for engagement and future research. By fostering a collaborative ecosystem involved in capacity building, CARB can not only adjust policy language, but also align priority actions and policy approaches, thereby accelerating progress toward building climate-resilient communities across California.

6. Update Regulatory Frameworks:

CARB should develop and implement regulatory frameworks based on local actions. Such integration will require not only reviewing local plans for their actions, but also continuous conversation with local policymakers. More specifically, the CARB Scoping Plan update should include a more robust focus on rural jurisdictions, which can include mitigation measures that consider ecosystem services, allowing for the crediting of natural and working land management practices toward local mitigation mandates. Regulatory updates may also include updating air quality regulations, land use guidelines, and transportation policies to prioritize climate resilience and emission reductions on a more regional and context-specific basis. We note that regular plan review and feedback from community partners can help CARB better tailor target local priorities (e.g. building decarbonization through biomass generation or reducing VMT through new, mixed-use healthcare center development).

To this end, we recommend that CARB adopt concrete policy targets for two priority areas: reducing VMT and building decarbonization. Partners across the state noted that concepts like VMT are unfamiliar or carry negative connotations due to concerns around mileage taxes, or dependence on gas tax funding, in certain regions. Instead, CARB may wish to focus on mixed-use density targets for development, aligning the priority of reducing VMT with updated CEQA metrics. Similarly, while the term “building decarbonization” is common in state policy documents, only one county mentioned “decarbonization” in its General Plan. Scholarly literature also prefers synonyms (e.g., carbon neutral). As an alternate approach, CARB may wish to promote updates to municipal building codes and siting low-carbon energy supplies. By better aligning regulatory requirements with local approaches and measurable benchmarks, CARB can present shared local and state priorities in a planning language that is mutually understood. To create and refine this language, CARB will need to continuously review local approaches and maintain dialogues with local partners across the state.

Conclusion:

As California confronts the escalating impacts of climate change, CARB has a pivotal role to play in supporting local governments in their climate readiness planning efforts. By implementing the recommendations outlined in this white paper, CARB can enhance its support for municipalities, empower communities to build resilience, and advance statewide climate objectives. Strengthening local climate readiness planning is essential for safeguarding public health, protecting vulnerable populations, and ensuring a sustainable future for all Californians.

Appendix 6. Matrix table

Link to matrix table dataset on the UC Davis Center for Regional Change website:

<https://regionalchange.ucdavis.edu/projects/climate-readiness-through-local-planning>

Link to download data:

<https://regionalchange.ucdavis.edu/sites/g/files/dgvnsk986/files/inline-files/County%20and%20City%20Climate%20Readiness%20Data.pdf>

Appendix 7. Example of standardized plan cover page

Plan title:

Jurisdiction:

Link to jurisdictional boundaries/shapefiles:

Date each plan was adopted:

Dates for each element adopted within the plan:

Housing:

Land use:

Conservation:

Open Space:

Transportation:

Noise:

Safety:

Environmental Justice:

Air quality:

CEQA certification date:

Plan authorship: *information about the firm that prepared the plan or authors of the plan*

DOI:

Appendix 8. Plan References

Adelanto North 2035 Comprehensive Sustainable Plan. (2014, August 27). Retrieved January 19, 2023 from <https://www.ci.adelanto.ca.us/DocumentCenter/View/623/Adelanto-North-2035-Sustainable-Plan>.

Alameda General Plan 2040. (2022, June 7). City of Alameda. Retrieved January 19, 2023 from https://irp.cdn-website.com/f1731050/files/uploaded/AGP_Book_June2022_Amend-1.pdf.

Albany City 2035 General Plan. (2016, April 18). City of Albany. Retrieved January 17, 2023 from <https://www.albanyca.org/departments/planning-zoning/albany-2035-general-plan>.

Amador County General Plan. (2016, July). Retrieved January 19, 2023 from <https://www.amadorgov.org/departments/planning/general-plan-update-draft-environmental-impact-report-and-draft-general-plan>.

City of Arcata General Plan. (2008). Retrieved January 19, 2023 from <https://cityofarcata.org/160/General-Plan>.

City of Arcata General Plan: Housing Element. (2019, December 18). Retrieved January 19, 2023 from <https://cityofarcata.org/DocumentCenter/View/9107/2019-2027-Housing-Element>.

City of Azusa General Plan. (2004, April). City of Azusa. Retrieved January 19, 2023 from <https://www.ci.azusa.ca.us/160/General-Plan>.

Beaumont General Plan. (2020, December 1). City of Beaumont. Retrieved January 19, 2023 from https://www.beaumontca.gov/DocumentCenter/View/36923/Beaumont-GPU_Final-rev-22521.

City of Belvedere General Plan 2030. (2010, June 9). Retrieved January 19, 2023 from https://www.cityofbelvedere.org/DocumentCenter/View/1776/Vol-1_--Goals-Policies-and-Actions?bidId=.

Burlingame General Plan. (2019, November). City of Burlingame. Retrieved January 19, 2023 from https://cms6.revize.com/revize/burlingamecity/document_center/Planning/General%20and%20Specific%20Plans/BurlingameGP_Final_Nov2019_COMPLETE%20DOCUMENT.pdf.

Calabasas City 2021 IV-39

Calaveras County General Plan. (2020, September 22). Calaveras County. Retrieved January 17, 2023 from <https://planning.calaverasgov.us/General-Plan>.

The City of Campbell General Plan. (2001, November 6). City of Campbell. Retrieved January 19, 2023 from <https://www.campbellca.gov/DocumentCenter/View/2664/General-Plan-2015>.

Ceres General Plan 2035. (2018, May 14). City of Ceres. Retrieved January 19, 2023 from <https://www.ci.ceres.ca.us/DocumentCenter/View/2538/The-Ceres-General-Plan-2035-PDF>.

Chico 2030 General Plan. (2017, March). City of Chico. Retrieved January 19, 2023 from <https://chico.ca.us/post/chico-2030-general-plan>.

City of Chino General Plan 2025. (2010, July). City of Chino. Retrieved January 19, 2023 from <https://www.cityofchino.org/211/General>.

City of Coachella General Plan Update. (2015, April 22). City of Coachella. Retrieved January 19, 2023 from <https://www.coachella.org/home/showpublisheddocument/3221/635712771850800000>.

City of Commerce 2020 General Plan. (2008, January). City of Commerce. Retrieved January 19, 2023 from <https://www.ci.commerce.ca.us/Home/ShowDocument?id=76>.

City of Corning 2014-2034 General Plan. (2015, September 8). City of Corning. Retrieved January 19, 2023 from <https://www.corning.org/documents/general-plan/>.

City of Corona General Plan. (2004, March 17). City of Corona. Retrieved March 14, 2023 from <https://www.coronaca.gov/government/departments-divisions/community-development/cdbg/general-plan-update>.

Cotati General Plan. (2015, March). City of Cotati. Retrieved January 19, 2023 from http://cotati.generalplan.org/sites/default/files/Cotati%20General%20Plan_Adopted_Final_3-24-15_0.pdf.

Culver City General Plan: Circulation Element. (1995). City of Culver. Retrieved January 19, 2023 from <https://www.culvercity.org/files/assets/public/documents/community-development/advance-planning/general-plan/circulationelement.pdf>.

East Palo Alto General Plan - Vista 2035. (2016, October 4). City of East Palo Alto. Retrieved January 19, 2023 from https://www.cityofepa.org/sites/default/files/fileattachments/community_amp_economic_development/page/2731/epa_full_final_general_plan_reduced_201807271727020784.pdf.

2004 El Dorado County General Plan. (2019, December 10). El Dorado County. Retrieved January 19, 2023 from https://edcgov.us/Government/planning/pages/Adopted_General_Plan.aspx.

City of Elk Grove General Plan. (2021, August 11). City of Elk Grove. Retrieved January 19, 2023 from https://www.elkgrovecity.org/sites/default/files/city-files/Departments/Planning/Projects/General%20Plan/GPU/Amend_2021-08/GP_Complete_web_2021-08.pdf.

Folsom General Plan 2035. (2021, August 24). City of Folsom. Retrieved January 19, 2023 from <https://www.folsom.ca.us/government/community-development/planning-services/general-plan>.

Gilroy General Plan - Chapter Four: Community Design and Development. (2016). City of Gilroy. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Gilroy_2016_IL90DD0YSL.pdf.

City of Greenfield - Chapter 6: Housing Element. (2014). City of Greenfield. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Greenfield_2014_GWMOT89SI7.pdf.

Hayward 2040 General Plan Policy Document (2014, July). City of Hayward. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Hayward_2014_5IY5W296CF.pdf.

City of Hemet General Plan 2030. (2012). City of Hemet. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Hemet_2012_IM4PX2YNOF.pdf.

City of Hermosa Beach: PLAN Hermosa. (2017, August 22). City of Hermosa Beach. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Hermosa-Beach_2017_LKV7J7IO9R.pdf.

Humboldt County General Plan. (2017, October 23). County of Humboldt. Retrieved January 17, 2023 from <https://humboldt.gov/DocumentCenter/View/61984/Humboldt-County-General-Plan-complete-document-PDF>.

Imperial County General Plan - Circulation and Scenic Highways Element. (2008, January 29). Imperial County. Retrieved March 14, 2023 from <https://www.icpds.com/assets/planning/circulation-scenic-highway-element-2008.pdf>.

Lake Forest 2040 General Plan. (2020, June). City of Lake Forest. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Lake-Forest_2020_ZFMBRIVWPS.pdf.

City of Lathrop General Plan. (2022, August). City of Lathrop. Retrieved March 14, 2023 from https://static1.squarespace.com/static/5a26dc6564b05f670d0bf079/t/633375168ec4404a447d886e/1664316715077/Lathrop+General+Plan_Adopted_9-19-22.pdf.

Comprehensive General Plan for the City of Lathrup, California. (2004, November 9). City of Lathrop. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Lathrop_2004_AR6ULQ579C.pdf.

City of Lincoln General Plan. (2008, March). City of Lincoln. Retrieved January 17, 2023 from <https://www.lincolncalifornia.gov/en/business-and-development/resources/Documents/general-plan-2050.pdf>.

City of Long Beach General Plan - Mobility Element. (2013, October). City of Long Beach. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Long-Beach_2013_K0HA85V0WI.pdf.

Los Angeles City - Housing Element. (2021). City of Los Angeles. Retrieved March 14, 2023 from https://static1.squarespace.com/static/5a26dc6564b05f670d0bf079/t/633375168ec4404a447d886e/1664316715077/Lathrop+General+Plan_Adopted_9-19-22.pdf.

City of Los Angeles - Housing Element 2013-2021. (2013, December 3). City of Los Angeles. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Los-Angeles_2013_OE1KEO1S9A.pdf.

Madera County General Plan. (1995, October 24). Madera County. Retrieved March 15, 2023 from <https://www.maderacounty.com/home/showpublisheddocument/2850/636480653563500000>.

Marin Countywide Plan. (2007, November 7). County of Marin. Retrieved January 17, 2023 from https://www.marincounty.org/-/media/files/departments/cd/planning/currentplanning/publications/county-wide-plan/cwp_2015_update.pdf.

City of Menlo Park - Open Space/Conservation, Noise and Safety Elements. (2013, May 21). City of Menlo Park. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Menlo-Park_2013_4XKNYDMC11.pdf.

2030 Merced County General Plan. (2013, December 10). Merced County. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Merced_2013_1H9WLACYH4.pdf.

City of Milpitas General Plan 2040. (2021, March 9). City of Milpitas. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Milpitas_2021_4TXJNT4Q7S.pdf.

Mono County General Plan. (2009). Mono County. Retrieved January 17, 2023 from <https://monocounty.ca.gov/planning/page/general-plan>.

Mono County General Plan - Noise Element. (2015). Mono County. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Mono_2015_CHQWUNN923.pdf.

Mono County - Land Use Element. (2017). Mono County. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Mono_2017_D1RY0STD8Z.pdf.

Mono County - Conservation/Open Space Element. (2020). Mono County. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Mono_2020_V77MW49QI6.pdf.

Plan Morro Bay. (2021, May). City of Morro Bay. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Morro-Bay_2021_MVGEQW68UB.pdf.

Murrieta City - Chapter 3: Land Use Element. (2011). Murrieta City. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Murrieta_2011_XAIK63D1DF.pdf.

Napa County General Plan: Circulation Element. (2019, February 5). Napa County. Retrieved January 17, 2023 from <https://www.countyofnapa.org/DocumentCenter/View/3332/Circulation-Element-PDF>.

City of Norco General Plan - Safety Element. (2013, January 16). City of Norco. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Norco_2013_NJWIT3F73J.pdf.

Oakdale 2030 General Plan. (2013, August 8). Retrieved January 19, 2023 from https://drive.google.com/file/d/0B8bSmVI_fyceWjJTS2g4c2ZvaFU/view?resourcekey=0-IVT_NIY3ccqT5LriVADa5w.

Orange General Plan. (2010 March). Retrieved January 19, 2023 from <https://www.cityoforange.org/our-city/departments/community-development/general-plan>.

Oxnard City General Plan: Housing Element. (2022, October). Retrieved January 19, 2023 from https://www.oxnard.org/wp-content/uploads/2022/10/Oxnard-Housing-Element_October-2022_Clean_Reduced.pdf.

City of Palo Alto Comprehensive Plan. (2017, November 13). Retrieved January 19, 2023 from https://www.cityofpaloalto.org/files/assets/public/planning-amp-development-services/3.-comprehensive-plan/comprehensive-plan/full-comp-plan-2030_with-dec19_22-amendments.pdf.

City of Point Arena 2019-2027 Housing Element Update. (2019, October). City of Point Arena. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Point-Arena_2019_MM43XVAJBY.pdf.

2045 Port Hueneme General Plan. (2021, September). City of Port Hueneme. Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Port-Hueneme_2021_9JLQF3B6N3.pdf.

Rancho Cordova General Plan. (2006, June 26). Retrieved January 19, 2023 from <https://www.cityofranchocordova.org/home/showpublisheddocument/14279/636820350426270000>.

The City of Reedley General Plan 2030. (2014, February 18). Retrieved January 19, 2023 from <https://reedleyweb.s3.us-west-1.amazonaws.com/2019/12/Reedley-General-Plan-2030-Adopted-February-18-2014.pdf>.

Sacramento County General Plan: Circulation Element. (2020, October 6). Retrieved January 19, 2023 from <https://planning.saccounty.net/PlansandProjectsInProgress/Documents/Circulation%20Element%20-%20Amended%2010-06-20.pdf>.

San Bernardino County General Plan: Natural Resources Element. (2020). Retrieved January 19, 2023 from <https://countywideplan.com/policy-plan/natural-resources/>.

County of San Diego General Plan: Chapter 4 Mobility Element. (2011, August). Retrieved January 19, 2023 from https://www.sandiegocounty.gov/content/dam/sdc/pds/docs/MobilityElement_Oct2018.pdf.

San Joaquin County General Plan Policy Document. (2016, December). San Joaquin County. Retrieved January 17, 2023 from https://www.sjgov.org/commdev/cgi-bin/cdyn.exe/file/Planning/General%20Plan%202035/Part%200%20SJC_PRD-PD_cover.pdf.

City of San Marcos General Plan. (2012, February 14). Retrieved January 19, 2023 from <https://www.san-marcos.net/work/economic-development/general-plan>.

City of San Mateo - Land Use. (2015, April 6). Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-San-Mateo_2015_OH0IFUOSEF.pdf.

San Leandro City 2035 General Plan. (2016, September 19). Retrieved January 19, 2023 from <https://www.sanleandro.org/332/General-Plan>.

City of San Luis Obispo General Plan. (2010). City of San Luis Obispo. Retrieved March 15, 2023 from <https://www.slocity.org/government/department-directory/community-development/planning-zoning/general-plan>.

County of San Luis Obispo General Plan: 2020-2028 Housing Element. (2020, November 17). Retrieved January 19, 2023 from <https://www.slocounty.ca.gov/Departments/Planning-Building/Forms-Documents/Plans-and-Elements/Elements/Housing-Element.pdf>.

City of Santa Clara 2010-20235 General Plan. (2010). Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_City-Santa-Clara_2010_NLBQI4ZLBE.pdf.

Santa Rosa General Plan 2035. (2020, November 3). Retrieved January 19, 2023 from <https://www.srcity.org/DocumentCenter/View/24327/Santa-Rosa-General-Plan-2035-PDF---October-2020>.

Shasta County - Housing Element 2007-2014. (2007). Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Shasta_2007_BZE3VCE0Y0.pdf.

Siskiyou County General Plan - Energy Element. (1993, March), Retrieved March 14, 2023 from https://plansearch.caes.ucdavis.edu/static/data/pdfoutput/2023-03-15_CA_county-Siskiyou_1993_MTFM8XAICZ.pdf.

Solano County General Plan. (2008, November 4). Retrieved January 19, 2023 from https://www.solanocounty.com/depts/rm/planning/general_plan.asp.

Sutter County 2030 General Plan. (2011, March 29). Retrieved January 19, 2023 from <https://www.suttercounty.org/government/county-departments/development-services/planning-services/general-plan>.

Tulare County General Plan 2030 Update. (2012, August). Retrieved January 19, 2023 from <http://generalplan.co.tulare.ca.us/documents/GP/001Adopted%20Tulare%20County%20General%20Plan%20Materials/000General%20Plan%202030%20Part%20I%20and%20Part%20II/GENERAL%20PLAN%202012.pdf>.

City of Turlock General Plan: Housing Element. (2016, April 12). Retrieved January 19, 2023 from https://www.cityofturlock.org/_pdf/files/housingelement.pdf.

City of Tustin General Plan. (2018, November). Retrieved January 19, 2023 from <https://www.tustinca.org/DocumentCenter/View/713/City-of-Tustin-General-Plan-PDF>.

Ukiah City General Plan. (2016). Retrieved January 19, 2023 from <https://cityofukiah.com/community-development/policies-documents-maps/>.

City of Vacaville General Plan. (2015). Retrieved January 19, 2023 from <https://www.ci.vacaville.ca.us/government/community-development/advanced-planning/adopted-plans/general-plan/general-plan-documents>.

City of Waterford General Plan Update Vision 2025: Chapter 10 Housing. (2016, April 7). Retrieved January 19, 2023 from https://www.cityofwaterford.org/v5/wp-content/uploads/2018/10/Attachment-2-10-GP-2014-2023-Housing-Element_CC-Adopted_Final.pdf.

Yolo County 2030 Countywide General Plan. (2009, November 10). Yolo County. Retrieved January 17, 2023 from <https://www.yolocounty.org/home/showpublisheddocument/14457/636643925992000000>.

Yountville General Plan Circulation Element. (2015, April 7). Town of Yountville. Retrieved January 19, 2023 from <https://www.townofyountville.com/home/showpublisheddocument/4006/635796981790430000>.

Yuba County 2030 General Plan. (2011, June 7). Yuba County. Retrieved January 19, 2023 from https://www.yuba.org/departments/community_development/planning_department/general_plan.php.

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CHARGING UP THE *Central Coast*

Policy solutions to improve electric vehicle
charging access in Watsonville

JANUARY 2024
Policy Report



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16. Abstract California's goal to eliminate internal combustion engine sales by 2035 poses challenges for lower- and moderate-income residents, hindering their access to electric vehicles (EVs). Barriers include limited EV charging stations, exacerbated by lower home ownership and inadequate grid infrastructure in lower-income communities. To address this, UC Berkeley School of Law's Center for Law, Energy & the Environment (CLEE) partnered with the City of Watsonville. Due to its location, demographics, and ambitious policy goals, Watsonville represents a potential model and case study for other cities around the state grappling with how to boost EV charging infrastructure. CLEE conducted stakeholder interviews and a convening in Watsonville in May 2023, and developed a set of policy recommendations for both state and local entities to accelerate investment in EV charging infrastructure in Watsonville, which could inform other cities facing similar challenges and seeking to meet state targets and residents' needs.				
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JANUARY 2024 | POLICY REPORT

CHARGING UP THE CENTRAL COAST

Policy solutions to improve electric vehicle charging access in Watsonville

ABOUT THIS REPORT

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The Center for Law, Energy & the Environment (CLEE) channels the expertise and creativity of the Berkeley Law community into pragmatic policy solutions to environmental and energy challenges. CLEE works with government, business, and the nonprofit sector to help solve urgent problems requiring innovative, often interdisciplinary approaches. Drawing on the combined expertise of faculty, staff, and students across the University of California, Berkeley, CLEE strives to translate empirical findings into smart public policy solutions to better environmental and energy governance systems.

THE UC INSTITUTE OF TRANSPORTATION STUDIES

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

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EXECUTIVE SUMMARY

As California seeks to achieve a statewide goal of ending the sale of internal combustion engine passenger vehicles by 2035, lower- and moderate-income residents will face acute barriers to accessing zero-emission vehicles, particularly battery-powered electric vehicles (EVs). Among these challenges is lack of access to EV charging stations. Many lower-income communities feature lower home ownership rates and higher rates of tenancy in apartment buildings, which means these residents lack a dedicated parking space with an electric outlet to charge. Those who do own garages and dedicated parking spaces may have less capital to invest in private charging and electrical upgrades. And lower-income areas often have inadequate grid infrastructure to support the electrical loads required for vehicle charging.

To address these challenges and ensure more and equitably distributed chargers across California, state and local policymakers can learn lessons from representative communities and the practical challenges they face to EV charger installation. To further this objective, UC Berkeley School of Law's Center for Law, Energy & the Environment (CLEE) partnered with Watsonville, a diverse city of 50,000 in Santa Cruz County. Due to its location, demographics, and ambitious policy goals, Watsonville represents a potential model and case study for other cities around the state grappling with how to boost zero-emission vehicle charging infrastructure.

Based on stakeholder interviews and a convening in Watsonville in May 2023, CLEE developed a set of policy recommendations for both state and local entities to accelerate investment in EV charging infrastructure in Watsonville, which could inform other cities facing similar challenges and seeking to meet state targets and residents' needs. Additionally, based on these interviews and convening, CLEE developed the following elements for a vision of ideal charging infrastructure deployment in Watsonville:

- Chargers co-located with other essential services and community hubs, such as schools and libraries and as part of microgrids that can help sustain electricity supply during grid outages and support bidirectional charging, promoting resilience in the process.
- Improved access and outreach around the stations, such as through instructions in multiple languages and with verbal guidance as well for those unable to read or unfamiliar with the technology.
- Granular data collected by public charging transactions, collated in a simple manner to encourage better siting decisions.

- Chargers available at the locations and times necessary for users in priority communities.
- Respect for the privacy of those charging, to allow people of all backgrounds to charge without fear of discrimination.

Participants identified the following three key barriers to achieving this vision, along with targeted solutions to address them:

BARRIER 1: INSUFFICIENT PLANNING AND MAPPING TO IDENTIFY AND DEPLOY EV CHARGERS

- Watsonville's City Planning Department and Public Works & Utilities Department could initiate a comprehensive mapping assessment to determine optimal and equitable charger locations based on local needs and transportation patterns.
- Local utility and city staff could explore curbside charging options, including streetlight or utility pole charging.
- City of Watsonville leaders could promote investment in mobile charging infrastructure to better serve agricultural workers or those whose work locations may change frequently.
- Watsonville's City Planning Department could revise zoning and permitting policies to require EV charger installation or EV-ready electrical infrastructure at certain priority locations.
- Watsonville's City Planning staff could encourage charger installers to include physical components that enhance equity, safety, and accessibility.

BARRIER 2: HIGH COST OF INSTALLING, OPERATING AND USING CHARGERS

- The California Public Utilities Commission (CPUC) and utility companies could implement electricity rates that reduce the cost of charging during off-peak hours and improve transparency for consumers about these rates.
- The CPUC could encourage utility companies to offer incentives for home charger installations targeted at priority communities.
- Local organizations and regional governments could continue to coordinate on grant applications to secure state and federal funding for charging infrastructure.

BARRIER 3: LIMITED PUBLIC AWARENESS, EDUCATION, AND OUTREACH

- The state transportation agencies could expand support for community-based organizations in Watsonville that conduct targeted, multi-lingual public awareness campaigns about the potential cost savings and benefits from switching to EVs

- The City of Watsonville could work with community-based organizations to support schools, car dealerships, or other community entities, to expand the distribution of information about how to use EV chargers and what options are available.
- Charging companies and utilities could provide more detailed data on charger use patterns and demographics so that the City of Watsonville can target awareness and education efforts while also informing siting for new infrastructure.



Photo Courtesy of the
City of Watsonville

INTRODUCTION

California has established concrete plans for a transition to electric vehicles (EVs). Following an executive order from Governor Newsom, in 2022 the California Air Resources Board (CARB) introduced regulations to phase out sales of new internal combustion engine vehicles by 2035.¹ Although internal combustion engine vehicles will still be on the roads after 2035, California cities will need to plan for and in some cases invest in charging infrastructure to support the substantial influx of EVs expected in the coming years.

As more Californians of all demographic and socioeconomic backgrounds adopt EVs throughout the next decade, vehicle use might outpace charging infrastructure, the related transition away from gasoline fueling infrastructure, and the complex physical, technical, and political considerations that will go into an effective and equitable infrastructure buildout.

Lower- and moderate-income Californians face particular barriers to electric vehicle and charging access, including higher initial costs; lack of convenient home, workplace and public charging; reduced range compared to gas vehicles; and fewer models available that can carry multiple passengers and equipment.² Deliberate local government-led efforts will be crucial to ensuring that these residents and communities are not left behind. Because cities and counties are more likely to have a deep understanding of local transportation needs and infrastructure, permitting and planning capacities, and challenges such as the state of local electric grids, they are often best positioned to develop and implement the solutions that are tailored to their specific circumstances. As electric vehicles become the dominant technology, available, convenient, and affordable charging will become a necessity for Californians who rely on automobiles for their travel needs. Cities across California will need both more and equitably distributed chargers so that all Californians can participate in the EV transition.

This report focuses on the challenge of inadequate charging infrastructure, which is especially pronounced for low-income individuals and families residing in apartment complexes. About 27 percent of Californians live in an apartment,³ and of that number, approximately 72 percent are within low-income communities.⁴ These multi-unit dwellings may not have a dedicated parking space to charge or ability to install a charger. As a result, residents cannot conveniently take advantage of

the opportunity to reduce air pollution in their communities⁵ and achieve lower fuel and maintenance costs from relying on electricity over gasoline, among other EV benefits.

Given these policy needs, this report focuses on the City of Watsonville for an in-depth assessment of charging infrastructure priorities, based on an evaluation of where, how many, and what types of chargers are needed, given community demographics and input. Watsonville is a diverse mid-size city with limited public transit but ambitious sustainability goals. It is the third-largest city in the Monterey Bay area, south of the San Francisco Bay Area, with a population of 51,525. Of this total, 84.3% identify as Hispanic, making it one of the most significant Hispanic-majority cities in California. The median income in the city is \$67,007, 20% lower than the state median and 30% lower than the county median.⁶ Watsonville also straddles two disadvantaged communities (DACs) as defined under Senate Bill 535 (De León, 2012), covering the majority of the southern part of the city and including the downtown area.⁷ Watsonville's largest employers are the agriculture and construction industries, employing almost 20% and 15% of the workforce respectively.⁸

CLEE partnered with the city after determining it would serve as an example for the rest of the state and had staff capacity and interest in engaging, following a series of initial conversations to align priorities and approaches. City staff agreed that this process could help them advance implementation of their climate and transportation goals.

While this report aims to provide immediate benefit to the residents of Watsonville and its EV planning process, CLEE envisions that these policy recommendations can inform approaches for other California cities facing similar challenges and sharing some of the general attributes of Watsonville, such as demographics and built environment. The outcomes of this project are to enable city government leaders and local community groups across the state to determine funding priorities, more effectively obtain federal and state grant funding, and build public support for EV charging that meets a range of community needs.

PROJECT METHOD

CLEE combined a literature review, stakeholder interviews, and a half-day workshop with city leaders and advocates to inform the policy recommendations presented in this analysis.

Stakeholder Interviews

After CLEE and Watsonville agreed to work together, CLEE conducted approximately 30 informational interviews with key local experts and stakeholders, ranging from local government officials to regional non-profit organizations. Through these interviews, CLEE assessed local EV charging needs, including general locations of charging stations and the types of chargers that might be most appropriate for the needs of different populations in Watsonville (e.g., mobile charging stations for workers who do not have a single location of employment, like agricultural

workers). Additionally, the interviews revealed an initial set of barriers and potential policy and funding solutions for Watsonville.

In-Person Workshop

On May 16, 2023, CLEE and Watsonville staff organized approximately 18 participants for a 4-hour workshop at the Watsonville Civic Plaza Community Room. The goal of the workshop was to discuss key barriers and solutions to charging infrastructure in Watsonville. Prior to the workshop, CLEE had surveyed participants for input on priority EV charging station locations and top barriers to charger installation in Watsonville. CLEE then incorporated the survey results into the meeting agenda and pre-meeting materials. CLEE had also interviewed many of the participants prior to the workshop and given them the opportunity to elaborate on their ideas and engage in conversation with others in the space.

WATSONVILLE'S EV INFRASTRUCTURE DEPLOYMENT COULD FURTHER FEDERAL AND STATE ELECTRIC VEHICLE CHARGING POLICIES AND PROGRAMS

Watsonville's need for equitable electric vehicle charging infrastructure deployment comes in the context of ambitious state and federal support. To help achieve the state's goal of phasing out sales of new internal combustion engine vehicles by 2035, the California Air Resources Board (CARB) has adopted a wide array of complementary policies and programs to stimulate demand and production of EVs and associated infrastructure. As of 2023, the most significant of these policies include:

- **Zero-emission Vehicle Regulation:** Requires light-duty automakers to sell an increasing proportion of zero-emission vehicles, from 4.5% in 2018 to 22% in 2025. In 2022, the agency set requirements for 2026 onwards, increasing from 35% in 2026 to 100% from 2035 onwards.
- **Clean Vehicle Rebate Project:** A rebate of up to \$7,500 for income-eligible customers to buy or lease a new or used zero- or low-emission light-duty vehicle. This program will transition in late 2023 into a new program that helps low- and middle-income Californians access zero-emission vehicles.⁹
- **Clean Cars 4 All:** Grants of up to \$9,500 for income-eligible residents to replace their old vehicle with a new or used zero- or low-emission light-duty vehicle.¹⁰
- **Low Carbon Fuels Standard:** A credit trading scheme that awards credits for the production of low carbon fuels and infrastructure, including the sale of electricity as a transportation fuel.¹¹

At the federal level, the key policy for promoting light-duty EV deployment is the Clean Vehicle Tax Credit, a federal tax credit of up to \$7,500 for income-eligible customers to buy or lease a new or light-duty vehicle.¹² The Inflation Reduction Act of 2022 removed individual manufacturer eligibility caps, expanded the tax credit to cover used vehicles (up to \$4,000) and commercial vehicles (up to \$40,000), while adding a manufacturer’s suggested retail price (MSRP) cap, income cap (\$150,000 for single person households and \$300,000 for families),¹³ local assembly/sourcing requirement, and the option to transfer the credit to a rebate.¹⁴

State and federal agencies have also implemented policies to spur the implementation of public and shared chargers. California’s goal of 100% zero-emission light-duty sales by 2035 may require nearly 1.2 million public and shared chargers to be deployed in-state,¹⁵ while only 93,855 were active as of December 2023.¹⁶ These federal and state policies include:

- **National Electric Vehicle Infrastructure (NEVI) Grant Program:** The Department of Transportation’s (DOT) Federal Highway Administration (FHWA) offers funding to deploy an interconnected network of public or shared electric vehicle charging stations, primarily along Alternative Fuel Corridors (AFCs). Created through the Bipartisan Infrastructure Bill of 2021, metropolitan planning organizations, public authorities, and governments are eligible.¹⁷
- **Charging and Fueling Infrastructure (CFI) Discretionary Grant Program:** The DOT’s FHWA offers funding to deploy publicly-accessible EV charging infrastructure in urban and rural communities, as well as along Alternative Fuel Corridors. The Bipartisan Infrastructure Bill of 2021 created the program and made metropolitan planning organizations, public authorities, and governments eligible to receive the funding.¹⁸
- **Clean Transportation Program:** The CEC offers \$100 million annually, primarily to electric vehicle charging infrastructure, and “will seek to provide more than 50 percent” of funds “towards projects that benefit low-income and disadvantaged communities.” As of April 2022, the agency had awarded 49% of funding to projects in low-income and/or disadvantaged communities.¹⁹ AB 2061 (Ting, 2022) required the CEC to create an assessment of the equitability of access to reliable charging stations by 2025.²⁰ Businesses, vehicle and technology manufacturers, fleet owners, consumers, and academic institutions are eligible.²¹

MEDIUM- AND HEAVY-DUTY POLICIES

Though this report focuses on policy for light-duty vehicle charging infrastructure, medium- and heavy-duty vehicle electrification will also be critical to reducing emissions and achieving EV deployment targets. Many of the policy solutions discussed in this report are applicable to the medium- and heavy-duty context, in particular for agricultural medium- or heavy-duty work vehicles that may do double duty as work transportation. Some critical state heavy-duty EV policies include:

- **Advanced Clean Truck Regulation:** Requires heavy-duty automakers to sell an increasing proportion of zero-emission vehicles, with deficits differing by vehicle class and weight.
- **Heavy-duty Vehicle Incentive Program:** Funding up to \$120,000 for the purchase of a zero- or low-emission heavy-duty vehicle.
- **Phase 2 GHG Emissions Standards:** Requires heavy-duty automakers to adhere to increasing vehicle and engine emissions performance standards until Model Year 2027.

- **Utility-funded Charger Installations:** The California Public Utilities Commission (CPUC) has also authorized the use of ratepayer funding for EV charging infrastructure investments. The three large Investor-Owned Utilities (IOUs) have policies to fund the installation of light-duty EV charging stations at workplaces, multi-unit dwellings, and some destination centers, mostly at level 2. Southern California Edison's (SCE) Charge Ready, and San Diego Gas & Electric's (SDG&E) Power Your Drive program are undergoing their second round while Pacific Gas & Electric's (PG&E) Charge Program 2 has been authorized to install approximately 2,822 chargers to add to their first round total of 4,749.²²

The federal government's Justice40 initiative set a goal to ensure that 40 percent of the overall benefits from specific federal investments benefit disadvantaged communities burdened by pollution.²³ Additionally, California's legislative measures SB 535 and AB 1550 (Gomez, 2016) require that at least 25% of the funds allocated from the Greenhouse Gas Reduction Fund be invested in projects or programs that provide benefits to low-income households and disadvantaged communities. This scope includes initiatives related to sustainable transportation, clean energy, energy efficiency, and other climate-related projects.

The state has also recognised the need to promote the equitable uptake of EVs, given the disproportionate burden of vehicle exhaust on lower-income areas and the financial challenges individuals face in transitioning to EVs. California has taken a number of steps towards promoting EV uptake in these communities, including:

- **2022 CARB Scoping Plan:** CARB stated that it has ensured equity and affordability in its scoping plan, "prioritiz[ing] working with the communities most impacted [by air pollution] to ensure that these strategies address their needs." CARB also highlighted that "the state has an important role to play in providing financial incentives, especially to low-income consumers, to allow for uptake of clean technologies."²⁴
- **2022 CARB ZEV Regulation Update:** The update to CARB's ZEV regulation highlighted the need for a "coordinated, collaborative, and cross-cutting approach" to ensure an equitable transition, including a focus on charging and grid infrastructure.²⁵
- **Executive Order B-44-18:** In 2018, then-governor Jerry Brown declared that electric vehicle charging must be made "affordable and more accessible to all drivers."²⁶
- **Executive Order N-79-20:** In 2020, Governor Gavin Newsom directed state agencies "to accelerate deployment of affordable fueling and charging options for zero-emission vehicles, in ways that serve all communities and in particular low-income and disadvantaged communities."²⁷
- **SB 350 Study, Part B:** CARB's low-income barriers study as mandated by SB 350 (de León, 2015) acknowledged that for clean transportation, "barriers low-income residents and disadvantaged communities face are magnified."²⁸

EV CHARGING INFRASTRUCTURE IS INEQUITABLY DISTRIBUTED

Access to public chargers is increasingly important for low-income consumers, who are more likely to purchase used vehicles if they were to adopt EVs and consequently rely heavily on public chargers due to the typically more limited range of used vehicles. These consumers also often reside in rented housing and multi-unit dwellings where public charger availability is even more lacking.²⁹ For example, state initiatives such as the California Energy Commission's SB 1000 assessment report have found that public chargers are unevenly distributed across state air districts and counties and are co-located with populations and plug-in electric vehicles.³⁰ This uneven deployment of charging stations has perpetuated existing inequities as low-income communities – with fewer current EV drivers – generally attract less infrastructure investment, which discourages these residents from adopting EVs.³¹ Additionally, while about half of all public Level 2 and Direct Current Fast Chargers (DCFCs) in the state are deployed in low-income communities, low-income communities have fewer Level 2 chargers per capita, as represented in figure 1.

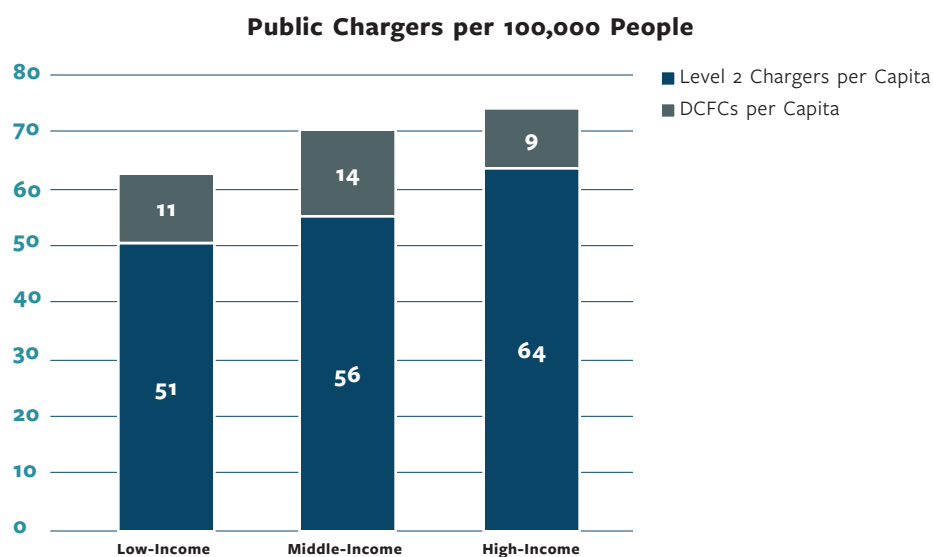


Figure 1: Public Level 2 and DCFC Per Capita by Community Income Level.³² Source: California Energy Commission Staff Analysis using U.S. Census Bureau 2014 – 2018 American Community Survey Median Household Income 5-Year Estimates and U.S. Department of Energy's Alternative Fuels Data Center Station Locator charger data as of July 23, 2020.

Many lower-income communities feature lower home ownership rates and higher rates of tenancy in apartment buildings. Even those residents who do own homes in these communities often face financial constraints that impede their ability to invest in charging infrastructure. Consequently, developers will need to place more charging stations in multifamily building parking lots and public parking areas, presenting barriers related to financing, permitting, and split incentives between landlords and tenants regarding building electrification upgrades. Finally, in lower-income areas, grid infrastructure is sometimes inadequate to support the electrical loads required for vehicle charging. Recent studies have documented

that public charger access disparities are more pronounced in communities with below-median household incomes, as well as those with predominantly Black and Hispanic populations. These disparities are particularly significant in areas with a higher prevalence of multi-unit housing, where residential charging is less common.³³



EV CHARGING AND SUSTAINABILITY GOALS IN WATSONVILLE

Watsonville city leaders have ambitious goals to expand the number and distribution of chargers to encompass residential neighborhoods and business districts, building on the city's sustainability goals. These broader goals include a 2021 action by the Watsonville City Council to achieve net-negative emissions by 2030 as part of the Climate-Safe California Campaign.³⁴ To reach this target, the city developed the 2030 Climate Action and Adaptation Plan (CAAP), which includes a three-pronged approach to the initiatives of climate action, climate adaptation, and climate restoration.

Watsonville will need action to reduce transportation emissions, specifically from gas-powered cars and trucks, which represent the largest source of greenhouse gas emissions at 53% of the city's total (the other main sources include natural gas, electricity use, and food waste disposal).³⁵ As a result, the city set up two CAAP strategies and programs to target carbon emissions from transportation: 'Facilitating EV Infrastructure' and 'Getting People into EVs - Equitably'.³⁶ Planned actions to increase the scale and equitability of EV infrastructure include strengthening public-private partnerships, creating charging station-friendly codes, and working with nonprofits and Central Coast Community Energy (3CE). The immediate actions of 2022 involved installing 13 new EV charging stations. Ultimately, the CAAP had a target of creating at least 20 EV charging facilities in public parking areas, defined as city-owned lots and parking spaces, by 2030.³⁷

As of November 2023, the City of Watsonville has 82 EV charging ports, including 56 Level 2 and 26 DCFCs, out of which 18 DCFCs are Tesla superchargers, and 6 level 2 chargers are at a Cadillac car dealership.³⁸ All of this existing charging infrastructure is either private or concentrated in downtown Watsonville and Watsonville airport, resulting in limited accessibility for residents to charge overnight, the most common and convenient time of day to charge for most EV drivers. To address this gap, participants at the May convening noted aspirational plans to expand the number and locations of chargers across the city to both residential areas and office locations. City staff are also in discussions with the local utility, Pacific Gas & Electric (PG&E), to pilot streetlight and utility pole charging stations to better serve disadvantaged communities, including renters and multi-unit dwelling residents.

To accommodate the transition to EVs, upgrades to the existing city power grid capacity will be necessary – in particular for Level 2 and DCFCs. Meanwhile, Santa Cruz County in general has a total of 476 Level 2 chargers at workplace and public sites and 47 DCFCs. The installers of this charging infrastructure intend to serve roughly 260,000 residents in the county (as of July 2022). The state, through its AB 2127 assessment,³⁹ forecasted a need in the county of 4,230 and 260 publicly accessible chargers for Level 2 and DC Fast respectively by 2030. The city and county will therefore need swift action to establish a robust EV charging infrastructure network in order to successfully meet AB 2127's 2030 and 2035 projections.

This infrastructure build-out will require significant new sources of funding and financing. Current efforts to increase EV charging stations have relied primarily on various grants and rebate programs for the installation. But they do not fund the operational and maintenance costs that agencies incur to sustain the EV charging. For example, the Central Coast Incentive Project, under CALeVIP and in partnership with Central Coast Community Energy (3CE), provided \$700,000 total in rebates for the purchase and installation of EV chargers in the Monterey, San Benito, and Santa Cruz counties.⁴⁰ Rebates were up to \$6,500 per connector and \$80,000 per charger for Level 2 and DC Fast Chargers respectively. Additionally, 41% of the project's total funding was reserved or issued to disadvantaged communities. Another incentive offered by 3CE is the *Electrify Your Ride Program*, which provides transportation electrification rebates and support for EVs (both new and used), Level 2 EV chargers, and EV readiness projects (electrical work associated with charger installation).⁴¹ 3CE customers can qualify to receive up to \$4,700 for equipment and the installation of EV chargers.⁴² More recently, the California Energy Commission established a \$30M incentive project dedicated to building EV charging stations in disadvantaged, low-income, and tribal communities across Eastern California, the Central Valley, and the Central Coast – including Watsonville.⁴³



EV CHARGING VISION FOR WATSONVILLE

Based on the expert interviews and input from the stakeholder convening, CLEE developed the following vision for electric vehicle charging infrastructure in Watsonville. At a larger scale, the California Energy Commission estimated that the Monterey region will need well over 8,000 publicly accessible chargers by 2030, including level 1 and 2 chargers at multi-unit dwellings, workplace and public level 2 chargers, and public fast chargers.⁴⁴ For Watsonville's share of this infrastructure, participants described a roll out that would anticipate future driving trends, where shared vehicles could lead to a reduced number of private vehicles. Policy makers and industry would also seek to identify and anticipate future technologies to avoid the plans becoming outdated as soon charging and vehicle technology advances.

Participants also expressed planning and usage transparency and improved outreach. For example, participants wanted the granular data collected by public charging transactions to be collated in a simple manner to encourage better siting decisions and easier-to-understand pricing. At the same time, they wanted the government to respect the privacy of those charging, to allow people of all backgrounds to charge without fear of discrimination or compromised identity. They also described improving access and outreach around the stations, such as through instructions in multiple languages and with verbal guidance as well for those unable to read. This guidance could also help people otherwise unfamiliar with the technology. Ultimately, they wanted chargers to be available at the locations and times necessary for users of all backgrounds.

In terms of specific locations for chargers, participants described co-locating them with other essential services and community hubs, such as schools and libraries and as part of microgrids that can help sustain electricity supply during grid outages, promoting resilience in the process (though several participants noted that this deployment could require significant upgrades to the existing distribution system). A sufficient number of chargers supporting microgrids could potentially generate their own electricity through bidirectional charging. Participants and city staff also noted that mobile charging and charging in locations other than traditional urban centers or workplaces could be important for Watsonville's large agricultural workforce and other residents who would otherwise struggle to access these fixed chargers. Whereas much of the recent infrastructure deployment has been focused on downtown Watsonville, participants emphasized the importance of distributing and dispersing chargers throughout the city to meet equity goals. Streetlight charging could also be

an option to meet low-income residents where they live and align with known patterns of EV charging.

On the public sector side, any publicly funded chargers require administrative capacity, which can mean significant burden on city staff, both to apply for grants and then administer the funds and maintain the sites. An equitable vision for charging deployment would therefore include sufficient resources for public sector management.



BARRIERS AND PRIORITY POLICY SOLUTIONS

Convening participants identified a number of barriers to achieving this vision for affordable and accessible charging throughout Watsonville, ranging from infrastructure availability to funding cost to the lack of planning and cooperation. This section describes the most significant barriers and top-priority policy solutions that convening participants and expert interviewees identified to overcome them.

BARRIER 1: INSUFFICIENT PLANNING AND MAPPING TO IDENTIFY AND DEPLOY EV CHARGERS

The City of Watsonville currently lacks sufficient and well-distributed EV charging infrastructure to meet the needs of all residents, particularly lower-income ones. Part of the challenge is the lack of comprehensive information about where charging would best support low-income individuals and families to access EVs. These low-income individuals are more likely to reside in multifamily dwellings or housing units without dedicated parking and are less likely to receive employment at workplaces with EV charging infrastructure.⁴⁵ A large number of vehicles parked per housing unit or overcrowding could also make it difficult to access EV chargers. These conditions reduce low-income households' ability to charge in general, and also at preferential times when they can fully reap the cost advantages of EV adoption in their own community. Additional accessibility challenges arise for those with disabilities or limited mobility. The city currently lacks a comprehensive map and set of incentives to address the lack of investment to date in these critical areas.

Solution 1: Watsonville's City Planning Department and Public Works & Utilities Department, with financial support from outside entities, could initiate a comprehensive mapping assessment to determine optimal and equitable charger locations based on local needs and transportation patterns.

To accomplish the mapping, city leaders could form a dedicated working group to design a mapping tool for identifying charging infrastructure sites

that meet the needs of a diverse set of communities. This group could include representatives from organizations such as the Catholic Church, Second Harvest Food Bank, Downtown Watsonville Law Center, social services, and local agencies. The consensus among participants was that such a comprehensive mapping tool could hold significant value in both the planning and implementation phases of charger installations within the city. A collaborative effort among stakeholders and local organizations could:

- Inform grant and funding applications made by the city and nonprofits;
- Attract private investment to underserved communities by demonstrating where charging might be most successful;
- Identify zones where private EV charging companies might expect low near-term revenue and the city might be best positioned to offer zero-cost permitting or potential tax incentives; and
- Allow community groups and stakeholders to see for themselves where charging might be the most useful/beneficial, so they can build public support and push their representatives to make the investment.

City leaders could build on existing mapping work from Community Bridges, a local organization that strives to provide equitable access to resources for the people of Santa Cruz County. The organization is working on providing maps of charging stations in the county. These maps show where the existing chargers are located in the county. Charging companies and utilities could also provide more detailed data on charger use patterns and demographics to the city, to better inform these maps.

Participants noted that city staff could consider a multitude of variables when determining equitable and optimal EV charger sites, including:

- Disadvantaged communities: placement of EV charging infrastructure in disadvantaged communities could help residents who face economic challenges and have limited access to personal charging options. Policy makers could use CalEnviroScreen (a mapping tool) to identify these communities.⁴⁶
- Locations of multifamily residential buildings: Multifamily residential buildings are often home to a significant portion of the population, including renters who may not have home charging options. Placing charging stations near these buildings, as well as potentially public buildings and nonprofit offices, could help ensure more equitable access to EV charging for all residents.
- Grid capacity: policy makers will need to consider grid capacity to ensure that the power infrastructure can handle the increased demand from charging stations without overloading the grid. Upgrades may be necessary to accommodate the additional load.
- High-traffic areas and attractions like parks and schools and shopping malls: People can spend significant “dwell” time at these locations, making them potentially convenient for EV owners to charge their vehicles while engaged in daily activities.

To visually conceptualize charging locations in alignment with the aforementioned considerations, Watsonville's city planning department could create a comprehensive map identifying the types of sites where industry and public sector leaders could prioritize installing chargers. This map would not only identify potential charger sites but also pinpoint specific locales within the city that hold significant promise for successful deployment of chargers for heavy usage. For example, the process could build on the groundwork laid by Santa Cruz Metro Transit's circulator bus route, which connects medical clinics, shopping centers, and essential service locations, by incorporating charging infrastructure at key points to connect along this route and to avoid conflicts with stops.

Participants noted that a significant number of agricultural workers in Watsonville commute from inland areas like San Jose or Santa Cruz, relying heavily on the highway infrastructure rather than the city center. These workers access highways more than downtown city locations. Hence installing EV chargers along the highways surrounding Watsonville could attract heavy usage. Some state routes fall within the purview of the National Electric Vehicle Infrastructure Program (NEVI) grants. In the case of Watsonville, city leaders could concentrate efforts on critical highways including 1, 101, and 152, all integral to California's Deployment Plan for the NEVI grants. To tap into NEVI funding opportunities, the city, state, and other local entities could collaborate in their application efforts. Consequently, the geographical positioning of these highways in and around the city could assume a central role to guide city leaders in strategically directing investment and deployment, both in pursuing federal funding and seeking alternative funding sources.

Solution: Local utility and city staff could explore curbside charging options, including streetlight or utility pole charging

Curbside charging refers to charging on the side of a road or sidewalk. Such charging deployment could be particularly valuable for Watsonville for:

- Supporting multifamily apartment dwellers: many residents of multifamily apartments, often residing in low-income neighborhoods, face challenges in accessing convenient EV charging solutions. Curbside charging can bridge this gap by providing accessible charging points within close proximity to these housing complexes.
- Assisting low-income residents: curbside charging addresses the needs of low-income residents who may be financially unable to install home charging infrastructure due to housing constraints or insufficient power capacity.

While considering charging locations, the city could address diverse needs—workplace, home, corridor, high-traffic areas, transit hubs, workplaces, retail centers, and community gathering places to provide convenient charging options for residents and visitors. The convening participants identified locations that the city could recommend the installation of charging infrastructure to charging companies:

- Existing gas stations
- Middle and high schools
- City Hall parking lot
- Santa Cruz County Fairgrounds
- Public parking lots at restaurants
- Pajaro Church parking lot
- Westridge business park
- Watsonville plaza/downtown center

Utilizing the existing streetlight network for curbside charging represents a promising opportunity for a cost-effective and equitably dispersed charging infrastructure. This approach also has the potential to meet overnight charging needs near homes with minimal expenses by using existing infrastructure. Watsonville leaders could potentially emulate the successful implementation of curbside charging in Melrose, Massachusetts, where pole-mounted EV chargers have been strategically placed throughout the community.⁴⁷ Notably, the use of a drop-down plug design in Melrose has proven effective in minimizing damage from vandalism and flooding, addressing concerns shared by some Watsonville participants. Los Angeles (home to a municipal electric utility) has deployed hundreds of streetlight chargers, as the most ambitious example of a California city program.⁴⁸

To further enhance accessibility and promote equitable distribution, Watsonville could consider committing to a specific number of curbside chargers in each neighborhood where they are needed. The city could identify the optimal and equitable charger locations based on local needs and transportation patterns, as discussed in the mapping assessment solution above. This proactive measure would ensure that charging resources are accessible to all residents across the city. Moreover, such a commitment could stimulate investment in charging infrastructure near key commercial corridors and community facilities, fostering sustainable urban development and supporting the adoption of electric vehicles in Watsonville.

Solution: City of Watsonville leaders could promote investment in mobile charging infrastructure to better serve agricultural workers or those whose work locations may change frequently

Agriculture is one of the main industries in Watsonville. The city is host to several prominent national companies such as Driscoll's Strawberries, Martinelli's, and California Giant, all of which rely heavily on the surrounding expansive agricultural fields. Many agricultural workers commute from outside of Watsonville to work. Some participants suggested that agricultural workers would benefit from the provision of charging facilities near the fields where they work. However, farms are frequently situated in rural or remote areas where access to electrical infrastructure may be limited. However, mobile chargers (portable charging units that can be transported in a vehicle) can reach these remote locations, helping EV users at farms to charge conveniently. These mobile connectors can be deployed in remote or rural locations where installing hard-wired chargers would be impractical or costly. Participants also suggested that farm workers could use services like CalVans,⁴⁹ Miocar⁵⁰ or other vanpool or carpooling services.

Solution: Watsonville's City Planning Department could revise zoning and permitting policies to require EV charger installation or EV-ready electrical infrastructure at certain priority locations.

Lower-income communities tend to have lower home ownership rates and higher rates of tenancy in apartment buildings. To address this dynamic, developers will need to install more charging stations in multifamily buildings and public parking areas, which presents barriers related to financing and permitting.

By revising the zoning and streamlining permitting to require EV charger installations in low-income neighborhoods and other priority locations, the city planning department can take a step towards a more inclusive approach to EV accessibility. The priority locations to consider for rezoning and revising permitting policies could include new multi-family housing, parking lots, and construction of shopping or major employment centers.

Watsonville leaders could potentially look to the City of Portland as an example for updating permitting for public charging. The city updated its code and administrative rules in 2023 to facilitate EV charging in the public right-of-way (PROW). The update included amendments to the Vehicles and Traffic Code, administrative rules for encroachments and utility permits in the right-of-way, and the parking management manual.⁵¹ In March 2023, Portland also launched the ‘Electric Vehicle Ready Code Project’ to amend Portland Zoning Code (Title 33) to require all new multi-dwelling and mixed-use development with five or more units – that include onsite parking – to provide EV-ready charging infrastructure.⁵² City leaders could also look to cities like Portland, Seattle, and Washington, DC which affirmatively permit residents who lack dedicated off-street parking to run Level 1 charging cords across the sidewalk from their home to a parked vehicle, so long as they meet design and safety guidance.

The city could also build on the existing reach code to require EV charging stations or EV-ready electrical infrastructure in buildings that would increase access among low-income residents. A reach code is a local building energy code that “reaches” beyond the state minimum requirements for energy use in building design and construction, creating opportunities for local governments to lead the way on clean air, climate solutions, and the renewable energy economy.

Solution: Watsonville’s City Planning department could encourage charger installers to include physical components that enhance equity, safety, and accessibility

During the discussion, several participants underscored the importance of tailoring charging infrastructure to the specific needs of the lower income communities. By doing so, the city can promote a more inclusive and equitable adoption of electric vehicles, addressing the needs of diverse user groups, including vulnerable populations, and making charging stations safer for all. Features such as well-lit charging areas, built-in lighting and emergency buttons, and accessibility accommodations not only enhance the overall charging experience but also foster a sense of security and convenience, as isolated charging locations can be unsafe for women and other vulnerable groups of people like people with disabilities, senior citizens, children and parents, late-night or shift workers.

Diversifying payment options for EV charging emerged as a key strategy at the convening to make the service inclusive. Participants noted that a number of potential EV drivers in Watsonville are “unbanked” (lacking bank accounts), lack smartphones or credit cards, or may otherwise face difficulties with traditional US-based payment methods for residents with international banking

or phone accounts. An effort in this direction was observed with the introduction of Senate Bill 823 (Smallwood-Cuevas, 2023) which would have created a discounted EV charging payment card competitive grant program aimed to subsidize charging credit cards for low-income Californians.⁵³ Although the bill did not pass in 2023, it highlighted the need for accessible payment solutions to accommodate EV adoption in low-income communities.

In efforts to improve accessibility given the city's linguistic diversity, EV charging companies could incorporate different language options on the chargers, with a particular focus on Spanish, which is one of the most spoken languages in the area. Furthermore, they could augment charging stations with more audio and visual components to aid users in comprehending usage instructions, bridging potential literacy or language barriers. Convening participants also highlighted the complexity of pricing structures for EV charging. To address the pricing, the chargers could suggest prices in terms of dollars per miles covered or time to charge rather than solely kilowatt-hour rates. This addition would simplify public understanding of costs, thus empowering a broader audience to engage with the service. Some participants suggested that the city could focus on providing Level 2 chargers for workplaces and residential areas and DCFCs for select downtown/short-term parking areas and shopping centers.

In addition, participants noted that the city could improve access to chargers through updates to the aforementioned reach codes. When choosing where to put EV charging stations, city leaders could consider the needs of people with disabilities (Americans with Disabilities Act [ADA] requirements). This means making sure that some charging ports are located near spaces that are accessible to people with disabilities. Relatedly, participants noted that some people have safety concerns about EV batteries catching fire, and the city could consider updating the code to reflect fire safety at indoor parking spaces with EV charging stations.

BARRIER 2: HIGH COST OF INSTALLING, OPERATING AND USING CHARGERS

EV charging infrastructure can entail significant costs, including upfront expenses for hardware and installation and long-term expenses for maintenance and power supply. The high cost associated with installing and maintaining chargers can pose a barrier for private investment in charger installation. Installation and site preparation costs can range from \$600 - \$12,700 for Level 2 and \$4,000 - \$51,000 for commercial DCFC.⁵⁴ In addition, according to California Energy Commission data, for projects with one to four connectors, the average unit cost per connector was \$3,658, and the total project cost per connector was \$9,992.⁵⁵ Costs for DCFCs are significantly higher. For one installed DCFC, the average rebate per charger was \$62,516, the average unit cost per charger was \$45,293, and the average total project cost per

EV fast chargers and Level 2 chargers are two common types of charging stations used to charge electric vehicles. They differ in terms of charging speed, power, and use cases:

DCFC (Direct Current Fast Charger): DCFC, or fast chargers, provide rapid charging by delivering high-power direct current to electric vehicles. They are commonly used for long-distance travel and can charge an EV in approximately 30 minutes to an hour. DCFC are significantly more expensive to purchase and install than Level 2 chargers due to their higher power output and specialized technology.

Level 2 Charger: Level 2 chargers offer a moderate charging speed by providing alternating current at a higher rate than standard household outlets. Level 2 chargers are more affordable than DCFCs and have lower installation costs, making them suitable for home, workplace, and public charging locations.

DC fast charger was \$124,665.⁵⁶ Depending on the charging location and type, these costs may be borne or shared by local governments, charging service providers, building and property owners, and charging users. Furthermore, charging an electric vehicle at home is generally more cost-effective than utilizing public charging stations. This cost disparity may inadvertently impose a financial burden on individuals with lower incomes who rely on public chargers.⁵⁷

Solution: The California Public Utilities Commission (CPUC) and utility companies could implement electricity rates that reduce the cost of charging during off-peak hours and improve transparency for consumers about these rates

Watsonville residents who have an electric vehicle but lack access to private driveways or garages will be less likely to benefit from fuel cost savings associated with charging during overnight or daytime off-peak hours as well as from the advantage of receiving subsidized electricity rates for vehicle charging at home. Instead, they are more likely to rely on public charging, including costlier DCFC. To address these disparities, city leaders could encourage the installation of more workplace chargers, enabling individuals to capitalize on off-peak hour daytime charging rates. Furthermore, the CPUC could approve dynamic EV charging rates for drivers who use public charging that are based on the type of EV, the driver's income, and the time of charging (peak/off-peak hours). Some convening participants proposed implementing variable rates based on residents' income levels, or exploring percent income payment plans, to ensure equitable access to affordable EV charging options. This variable rate approach based on income levels could include:

- **Income assessment:** To determine the appropriate rate structure, the CPUC and/or charging companies would need to assess residents' income levels. This assessment could be based on self-reporting, documentation, or data from government assistance programs.
- **Tiered pricing:** Once the CPUC and/or charging companies determine the income levels, the utility could offer tiered pricing structures. Lower-income individuals or households would pay lower rates for EV charging, while higher-income individuals would pay standard or higher rates.

While the CPUC's dynamic rates have the potential to reduce costs, users may not understand the benefits of this reduction without clear communication through a standardized fee structure or pricing unit that facilitates a straightforward comparison of costs. To enhance consumer understanding of the pricing, charging station operators could present prices in easily digestible terms, such as dollars per mile covered or time required for charging, taking into account the tiered pricing structure for individuals.

Solution: The CPUC could encourage utility companies to offer incentives for home charger installations targeted at priority communities

The CPUC can encourage utility companies to create EV charging programs that directly benefit low-income households and underserved communities. PG&E, for instance, has already taken significant steps by introducing two progressive initiatives that offer incentives to low-income households. The utility's Empower EV Program provides one free Level 2 charger and covers up to \$2,000 per eligible single-family household for panel upgrades. The goal is to assist up to 2,000 households with a no-cost Level 2 charger and up to 800 eligible households with panel upgrades through this program.⁵⁸ PG&E has also partnered with Ecology Action on the Multifamily Housing and Small Business EV Charger Program, through which PG&E will install Level 1 and Level 2 EV chargers at multifamily housing (MFH) units, not-for-profit organizations and small businesses, at no cost for sites located in a "priority" community. The program also includes an education campaign for site residents and employees to increase awareness about the charger installation and other EV benefits and incentives.⁵⁹ Utility leaders and CPUC regulators could consider funding mechanisms to bolster and expand these programs.

Solution: Local organizations and regional governments could continue to coordinate on grant applications to secure state and federal funding for charging infrastructure

The City of Watsonville has participated in successful collaborations across different regions and organizations to secure grant funding, which could inform fundraising efforts focused on EV charging infrastructure buildout. Most prominently, Watsonville leaders collaborated with the city and county of Santa Cruz, plus with the counties of San Benito and Monterey, to participate in a multi-agency membership of the Regional Climate Project Working Group (RCPWG). In addition, local environmental community-based organizations such as Ecology Action also contributed to the working group in an advisory capacity. The RCPWG, formalized in 2022, now serves as a collective effort to develop, prioritize, secure funding and advocate for the implementation of regionally beneficial climate mitigation and adaptation projects and programs. Within this framework, the working group has completed two regional grant applications for EV charging infrastructure: "Charging and Fueling Infrastructure Discretionary Grant Program" by the Federal Highway Administration,⁶⁰ and "Advanced Technology Demonstration and Pilot Projects: Municipal Green Zones Grant Program" by the California Air Resources Board.⁶¹ Each of these proposals, if successful, would bring in \$15 million in State and Federal funding to the region, or \$30 million in total for regional EV and EV supply equipment infrastructure.

This collaborative approach, involving multiple regional governments and local organizations, enables the identification and joint application for grants, in turn pooling resources for larger, longer-term, and more cost-effective clean transportation benefits for the community. Moreover, these grants can act as leverage to secure additional funding from federal, state, local, and private sources.

City leaders could also explore dedicating a portion of their CEC grants to advance EV infrastructure installation in Watsonville. Specifically, Ecology Action, a state-wide non-profit with an active presence in Watsonville focused on advancing equitable and climate smart initiatives, received a CEC Reliable, Equitable, and Accessible Charging for multi-family Housing (REACH) grant to cover 100% of costs for EV charger installation (permitting, design, contracting, hardware, maintenance costs) for multi family EV charging in the central coast, central valley and bay area.

Ultimately, the City of Watsonville and RCPWG serve as examples for other cities and regional governments on how to collaborate with each other and local community-based organizations to jointly apply for grants. In order to have a planned and organized approach to grant applications, the cities could appoint a core team to research and identify grant opportunities applicable to and appropriate for them. This team could coordinate across jurisdictions where possible to find and access more regional opportunities. Some funding sources that the city could consider include the Inflation Reduction Act,⁶² Infrastructure Investment and Jobs Act,⁶³ and CALeVIP. Once team members identify these sources or grant opportunities, they could develop a pipeline of opportunities for funding and line up projects. Subsequent grant cycles could support infrastructure maintenance.

BARRIER 3: LIMITED PUBLIC AWARENESS, EDUCATION, AND OUTREACH

Limited access to information about various EV incentive programs offered by state and government agencies, as well as a lack of awareness of available charging options, hinder EV adoption by low-income residents. Language barriers, in particular, can create hurdles to EV purchasing and or disincentivize utilization among residents of disadvantaged communities who do not speak English as a first language. In Watsonville, 84.3% of the population identifies as Hispanic, making it one of the most significant majority Spanish-speaking cities in California. In addition, installers do not always equip charging stations with audio/visual components and different language options, which can limit accessibility for disabled and non-English speaking drivers respectively.

Participants noted that in many cases upfront costs alone do not deter EV adoption among low-income households. Instead, the combination of limited access to financing, lack of awareness of EVs, and general inconvenience of locating EV charging stations can create heightened barriers specific to low-income communities like in Watsonville. As a result, financial education programs and focused outreach that target community-specific barriers and needs can empower low-income individuals to make well-informed decisions about EV ownership.

Solution: The state transportation agencies could support community-based organizations in Watsonville to create a targeted, multi-lingual public awareness campaign about the potential cost savings and benefits from switching to EVs

In addition to financial support, local education and outreach efforts can increase EV adoption in low income and disadvantaged communities. The source of electric vehicle information influences the effectiveness of education and outreach programs. Information ideally would come from trusted sources with ties to the community whenever possible.⁶⁴ Community-based organizations that have already built trust among local residents and understand the specific circumstances of a community may be best positioned to share information about electric vehicles.

Community-based organizations are often under-resourced in terms of funding and staff capacity. These organizations could use state and other outside funding to hire additional staff, broaden their outreach efforts, strengthen organizational capacity, and extend staff positions for longer periods of time, among many other uses. Such organizations in the region could partner with the local government to create public awareness programs on EVs. For example, Ecology Action's initiative EVs for Everyone is aimed at assisting low-to-middle-income residents in the region through the entire process of buying EVs. They are also staffed by bilingual community-based organizations and professional advisors to serve English and Spanish speaking low-income communities.⁶⁵ PG&E's *Empower Electric Vehicle Charger Incentive and Education Program* offers education-based outreach, in addition to EV charger installation rebates, to low- and moderate-income customers on EV education and available incentives through utility and state programs.⁶⁶

In Watsonville, 12.9% of the population lives in poverty and cannot afford a car.⁶⁷ For such populations, the campaign could advertise EV ride share programs and the financial benefits associated with it. The campaign could also offer income-based incentives with EV advance payment grants that would help non-car owners to purchase a used EV. The city could also work with bus transportation agencies to help people who do not own cars, to provide them with reliable, convenient, and affordable access to transportation.

Participants emphasized the importance of having information available in other widely spoken languages in the region in addition to English, like having literature that shows all the charging stations in Spanish.- By conducting a thorough mapping assessment, the city could identify areas where Spanish is the primary language and actively involve Spanish-speaking communities in the development of EV charging brochures in Spanish.

Solution: The City of Watsonville could work with community-based organizations to support schools, car dealerships, or other community entities, to expand the distribution of information about how to use EV chargers and what options are available

By leveraging the knowledge, reach, and influence of schools, car dealerships, and community entities, the City of Watsonville can effectively coordinate a city-wide information network that empowers residents with the knowledge they need to make informed decisions about electric vehicle adoption, charging and usage. Collaborating with local car dealerships offers a practical platform for potential EV buyers to learn about various EV models, charging infrastructure, and available incentives. Dealerships could organize workshops, open-house events, or test drives that not only showcase EVs but also provide guidance on charging protocols and options.

Participants encouraged such engagement efforts to include educating community members about the technical use and availability of EV chargers along with the potential economic and environmental benefits and cost structure associated with EVs. Because knowledge gaps can vary across low-income communities, city leaders and advocates could conduct surveys to identify what locals currently do not understand or misconceive about EVs in order to provide more tailored and relevant educational programs to users. Partnering and collaborating with community-based organizations and local governments can also strengthen EV adoption by addressing the unique challenges faced by low-income residents.

Collaborative efforts among the city and community-based organizations can involve hands-on workshops and practical demonstrations of how to use EV chargers. These events can be held at central locations, such as community centers or popular gathering spots, and provide attendees with the chance to ride EVs and experience EV charging in a supportive and informative environment. Alongside physical outreach, the city can harness the power of online platforms and social media to share instructional videos, infographics, and step-by-step guides on EV charging. Leaders can tailor engaging content to different age groups and demographics in widely spoken languages, catering to a broader audience's learning preferences.

Solution: Charging companies and utilities could provide more detailed data on charger use patterns and demographics so that the City of Watsonville can target awareness and education efforts while also informing siting for new infrastructure

By receiving detailed data on charger use patterns and demographics from charging companies and utilities, the City of Watsonville would gain valuable insights on how the residents are engaging with EV charging infrastructure. Analyzing usage patterns, peak times, and popular locations can guide the creation of targeted awareness and education campaigns. For example, if the data reveal a surge in charging demand during specific hours or at particular charging stations, the city can tailor its educational efforts to coincide with these trends, ensuring that the information reaches those who need it most.

The charging companies and utilities could connect with Central Coast Community Energy to collect Watsonville-specific data on the demographics of the residents buying their cars, as well as what percent of their incentive dollars is used each year. They could distribute materials to educate people on the different types of chargers available, their locations, costs, capabilities and simplified explanations of which ones are best suited for each situation or driver, as well as a map of different charging locations in the city. This information could either be through an app, on a website, or displayed by the station.

In addition to obtaining data from utilities, the city could also survey residents to understand their needs and current knowledge of EVs and charging infrastructure. Accurate data on charger use patterns can inform policy decisions related to charging rates, time-of-use pricing, and infrastructure expansion. These data-driven policies could contribute to a more efficient and user-centric EV charging ecosystem.

CONCLUSION

Addressing the barriers to EV charging access for lower- and moderate-income individuals is crucial for fostering a more equitable and sustainable transportation future. This report puts forth recommendations to achieve this goal, including:

1. Watsonville's City Planning Department and Public Works & Utilities Department could initiate a comprehensive mapping assessment to determine optimal and equitable charger locations based on local needs and transportation patterns.
2. Watsonville's City Planning Department could revise zoning and permitting policies to require EV charger installation or EV-ready electrical infrastructure at certain priority locations.
3. The CPUC and utility companies could implement electricity rates that reduce the cost of charging during off-peak hours and improve transparency for consumers about these rates.
4. The state transportation agencies could expand support for community-based organizations in Watsonville that conduct targeted, multi-lingual public awareness campaigns about the potential cost savings and benefits from switching to EVs.

By removing financial, logistical, and infrastructure obstacles, Watsonville city leaders (with support from state government, the region, and the private sector) can empower the local community to benefit from cleaner and more affordable transportation options. Remedying this problem will require the

city to develop inclusive processes and implementation plans for the needed EV infrastructure. The infrastructure is too often not viable to install, due to factors such as onerous permitting, lack of a willing site host, expensive electrical upgrades, and lack of likely revenue needed to justify the investment. Local leaders will therefore need state and industry support to address these challenges, such as through improved business models, expanded industry investment, and targeted state subsidies. Ultimately, to ensure California's path toward equitable EV deployment is achievable, leaders at both state and local levels must prioritize charging access.



APPENDIX I

List of convening participants:

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Amanda Marino SANTA CRUZ COUNTY REGIONAL TRANSPORTATION COMMISSION	Dennis Osmer CENTRAL COAST ENERGY SERVICES	Jane Barr EDEN HOUSING	Suzi Merriam CITY OF WATSONVILLE
Amaury Berteaud ASSOCIATION OF MONTEREY BAY AREA GOVERNMENTS	Felipe Hernandez SANTA CRUZ COUNTY SUPERVISOR; FORMER WATSONVILLE CITY	Nancy Faulstich REGENERACIÓN	Tatiana Brennan COUNTY OF SANTA CRUZ
		Raymon Cancino COMMUNITY BRIDGES	Tonje Wold-Switzer COMMUNITY BRIDGES

List of stakeholder interviews:

Alex Yasbek CITY OF WATSONVILLE	Creighton Randall MOBILITY DEVELOPMENT GROUP	Jane Barr EDEN HOUSING	Patrick Finch ELECTROTEMPO
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		Nancy Faulstich REGENERACIÓN	

APPENDIX II

STATE ELECTRIC VEHICLE POLICIES AND PROGRAMS

POLICY	DESCRIPTION
Zero-emission Vehicle Regulation	Requires light-duty automakers to sell an increasing proportion of zero-emission vehicles, from 4.5% in 2018 to 22% in 2025. In 2022, the agency set requirements for 2026 onwards, increasing from 35% in 2026 to 100% from 2035 onwards.
Clean Vehicle Rebate Project	A rebate of up to \$7,500 for income-eligible customers to buy or lease a new or used zero- or low-emission light-duty vehicle. This program will transition in late 2023 into a new program that helps low- and middle-income Californians access zero-emission vehicles.
Clean Cars 4 All	Grants of up to \$9,500 for income-eligible residents to replace their old vehicle with a new or used zero- or low-emission light-duty vehicle.
Low Carbon Fuels Standard	A credit trading scheme that awards credits for the production of low carbon fuels and infrastructure, including the sale of electricity as a transportation fuel.
Advanced Clean Truck Regulation	Requires heavy-duty automakers to sell an increasing proportion of zero-emission vehicles, with deficits differing by vehicle class and weight.
Heavy-duty Vehicle Incentive Program	Funding up to \$120,000 for the purchase of a zero- or low-emission heavy-duty vehicle.
Phase 2 GHG Emissions Standards	Requires heavy-duty automakers to adhere to increasing vehicle and engine emissions performance standards until Model Year 2027.

FEDERAL AND STATE ELECTRIC VEHICLE CHARGING POLICIES AND PROGRAMS

POLICY	DESCRIPTION
National Electric Vehicle Infrastructure (NEVI) Grant Program	The Department of Transportation's (DOT) Federal Highway Administration (FHWA) offers funding to deploy an interconnected network of public or shared electric vehicle charging stations, primarily along Alternative Fuel Corridors (AFCs). Created through the Bipartisan Infrastructure Bill of 2021, metropolitan planning organizations, public authorities, and governments are eligible.
Charging and Fueling Infrastructure (CFI) Discretionary Grant Program	The DOT's FHWA offers funding to deploy publicly-accessible EV charging infrastructure in urban and rural communities, as well as along Alternative Fuel Corridors. The Bipartisan Infrastructure Bill of 2021 created the program and made metropolitan planning organizations, public authorities, and governments eligible to receive the funding.
Clean Transportation Program	The CEC offers \$100 million annually, primarily to electric vehicle charging infrastructure, and "will seek to provide more than 50 percent" of funds "towards projects that benefit low-income and disadvantaged communities." As of April 2022, the agency had awarded 49% of funding to projects in low-income and/or disadvantaged communities. AB 2061 (Ting, 2022) required the CEC to create an assessment of the equitability of access to reliable charging stations by 2025. Businesses, vehicle and technology manufacturers, fleet owners, consumers, and academic institutions are eligible.
Utility-funded Charger Installations	The California Public Utilities Commission (CPUC) has also authorized the use of ratepayer funding for EV charging infrastructure investments. The three large Investor-Owned Utilities (IOUs) have policies to fund the installation of light-duty EV charging stations at workplaces, multi-unit dwellings, and some destination centers, mostly at level 2. Southern California Edison's (SCE) Charge Ready, and San Diego Gas & Electric's (SDG&E) Power Your Drive program are undergoing their second round while Pacific Gas & Electric's (PG&E) Charge Program 2 has been authorized to install approximately 2,822 chargers to add to their first round total of 4,749.

ENDNOTES

- 1 California Air Resources Board (CARB), Advanced Clean Cars II Regulations, available at <https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii>
- 2 Chih-Wei Hsu and Kevin Fingerma, “Public electric vehicle charger access disparities across race and income in California,” Transport Policy Vol. 100, 59-67 (January 2021), available at <https://www.sciencedirect.com/science/article/pii/S0967070X20309021>; CARB, Low-Income Barriers Study, Part B: Overcoming Barriers to Clean Transportation Access for Low-Income Residents, available at https://ww2.arb.ca.gov/sites/default/files/2018-08/sb350_final_guidance_document_022118.pdf
- 3 U.S. Census Bureau 2014 – 2018 American Community Survey Total Population in Occupied Housing Units by Tenure by Units in Structure 5-Year Estimates
- 4 California Energy Commission staff analysis using U.S. Census Bureau 2014 – 2018 American Community Survey Estimates. Low-income communities are defined as census tracts with median household incomes at or below 80 percent of the statewide median income or with median household incomes at or below the threshold designated as low income by the Department of Housing and Community Development’s list of state income limits adopted pursuant to Section 50093
- 5 Garcia et al, “California’s early transition to electric vehicles: Observed health and air quality co-benefits”, Science of The Total Environment, Volume 867, 2023 available at <https://www.sciencedirect.com/science/article/pii/S0048969723003765>
- 6 City of Watsonville census data, available at <https://www.census.gov/quickfacts/fact/table/watsonvillecitycalifornia,CA/PST04522>
- 7 DACs are defined as the top 25% of communities experiencing disproportionate amounts of pollution, environmental degradation, and socioeconomic and public health conditions according to the CalEnviroScreen tool (<https://oehha.ca.gov/calenviroscreen>). Low-income communities and households are those with incomes either at or below 80% of the Statewide median or below a threshold designated as low-income by the Department of Housing and Community Development. More information on <https://oehha.ca.gov/calenviroscreen/sb535>
- 8 Watsonville demographics data, available at <https://www.watsonville.gov/1441/Demographics>
- 9 CARB, Clean Vehicle Rebate Project, available at <https://cleanvehiclerebate.org/en>
- 10 CARB, Clean Cars 4 All, available at <https://ww2.arb.ca.gov/our-work/programs/clean-cars-4-all>
- 11 CARB, Low Carbon Fuel Standard, available at <https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard>
- 12 IRS, Credits for New Clean Vehicles Purchased in 2023 or After, available at <https://www.irs.gov/credits-deductions/credits-for-new-clean-vehicles-purchased-in-2023-or-after>
- 13 Electrification Coalition, IRA EV Tax Credits Fact Sheet, available at https://electrificationcoalition.org/wp-content/uploads/2022/08/SAFE_1-sheet_Webinar.pdf
- 14 Electrification Coalition, Inflation Reduction Act Impact on Electric Vehicles, available at <https://electrificationcoalition.org/work/federal-ev-policy/inflation-reduction-act/>
- 15 CEC, Electric Vehicle Charging Infrastructure Assessment - AB 2127, available at <https://www.energy.ca.gov/data-reports/reports/electric-vehicle-charging-infrastructure-assessment-ab-2127>
- 16 CEC, Electric Vehicle Chargers in California, available at <https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/electric-vehicle>
- 17 National Electric Vehicle Infrastructure (NEVI) Formula Program, available at <https://afdc.energy.gov/laws/12744>
- 18 Charging and Fueling Infrastructure Discretionary Grant Program, available at <https://www.fhwa.dot.gov/environment/cfi/>
- 19 CEC, 2022-2023 Investment Plan Update for the Clean Transportation Program, available at <https://www.energy.ca.gov/publications/2022/2022-2023-investment-plan-update-clean-transportation-program-o>
- 20 https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB2061
- 21 California Energy Commission, California Transportation Program, available at <https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program>
- 22 AB-2061 Transportation electrification: electric vehicle charging infrastructure, available at https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB2061

- 23 Justice40, available at <https://www.whitehouse.gov/environmentaljustice/justice40/>
- 24 CARB, 2022 Scoping Plan for Achieving Carbon Neutrality, available at <https://ww2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf>, p.7
- 25 Carb, Public Hearing to Consider the Proposed Advanced Clean Cars II Regulations , available at <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf>, p.24-35
- 26 Governor Brown Takes Action to Increase Zero-Emission Vehicles, Fund New Climate Investments, available at <https://www.ca.gov/archive/gov39/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/index.html>
- 27 State of California, Executive Order N-79-20, available at <https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf>,
- 28 CARB, Low-Income Barriers Study, Part B: Overcoming Barriers to Clean Transportation Access for Low-Income Residents, available at https://ww2.arb.ca.gov/sites/default/files/2018-08/sb350_final_guidance_document_022118.pdf, p.12
- 29 Hsu and Fingerman, *supra*
- 30 Electric Vehicle Infrastructure Deployment Assessment- Senate Bill 1000, available at <https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/electric-vehicle-infrastructure>
- 31 *Ibid.*
- 32 California Energy Commission, SB 1000 Electric Vehicle Charging Infrastructure Deployment Assessment, available at <https://www.energy.ca.gov/publications/2020/california-electric-vehicle-infrastructure-deployment-assessment-senate-bill>
- 33 Hsu, Fingerman, “Public electric vehicle charger access disparities across race and income in California”, available at <https://www.sciencedirect.com/science/article/pii/S0967070X20309021>
- 34 Watsonville Public Works & Utilities, “Watsonville Climate Action & Adaptation Plan”, available at <https://www.watsonville.gov/1764/Learn-About-Climate-Action-Plan>
- 35 *Ibid.*
- 36 *Ibid.*
- 37 *Ibid.*
- 38 US Department of Energy, “Alternative Fueling Station Locator”, available at <https://afdc.energy.gov/stations/#/find/nearest>
- 39 California Energy Commission, “Electric Vehicle Charging Infrastructure Assessment - AB2127”, available at <https://www.energy.ca.gov/data-reports/reports/electric-vehicle-charging-infrastructure-assessment-ab-2127>
- 40 The California Electrical Vehicle Infrastructure Project (CALeVIP), “Central Coast Incentive Project”, available at <https://calevip.org/incentive-project/central-coast>
- 41 Central Coast Community Energy, “Electrify Your Ride – Residential”, available at <https://3cenergy.org/rebates/electrify-your-ride-residential/>
- 42 Central Coast Community Energy, “On Earth Day, Central Coast Community Energy Celebrates Distributing Over 1,000 EV Rebates and Supporting 1,000 New EV Chargers for Region”, available at <https://3cenergy.org/on-earth-day-central-coast-community-energy-celebrates-distributing-over-1000-ev-rebates-and-supporting-1000-new-ev-chargers-for-region/>
- 43 California Energy Commission, “\$30 Million in Incentives Now Available for Shovel-Ready EV Charging Projects Across California”, available at <https://www.energy.ca.gov/news/2023-02/30-million-incentives-now-available-shovel-ready-ev-charging-projects-across>
- 44 The state estimated 8,434 such chargers will be needed in Monterey County by 2028. See Matt Alexander, Noel Crisostomo, Wendell Krell, Jeffrey Lu and Raja Ramesh, “Implementation of AB 2127 Electric Vehicle Charging Infrastructure Assessments,” California Energy Commission, May 2021, at C-14, available at: <https://www.energy.ca.gov/news/2021-06/report-shows-california-needs-12-million-electric-vehicle-chargers-2030> (accessed September 1, 2023).
- 45 Ona Egbue and Suzanna Long, “Barriers To Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions”, Energy Policy Vol. 48 (September 2012), available at <https://www.sciencedirect.com/science/article/abs/pii/S0301421512005162>
- 46 CalEnviroScreen is a mapping tool that helps identify California communities that are most affected by many sources of pollution, and where people are often especially vulnerable to pollution’s effects. More information on <https://oehha.ca.gov/calenviroscreen>
- 47 City of Melrose, Massachusetts, ‘Public EV Charging, available at <https://www.cityofmelrose.org/office-planning-and-community-development/sustainable-melrose/pages/public-ev-charging>

- 48 LA Lights, EV Charging Stations, available at https://lalights.lacity.org/connected-infrastructure/ev_stations.html
- 49 CalVans, available at <https://calvans.org/>
- 50 MioCar, available at <https://miocar.org/>
- 51 Portland Bureau of Transportation, Electric Vehicle Charging In The Public Right-Of-Way Code Project, available at <https://www.portland.gov/transportation/electric-vehicles/documents/electric-vehicle-charging-public-right-way-code-project>
- 52 City of Portland, Electric Vehicle (EV) Ready Code Project, available at <https://www.portland.gov/bps/planning/ev-ready>
- 53 SB-823 Discounted electric vehicle charging payment card competitive grant program, available at https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB823
- 54 Henry Lee and Alex Clark, “Charging the Future: Challenges and Opportunities for Electric Vehicle Adoption”, available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3251551
- 55 CALeVIP Level 2, Average Rebate, Unit Cost, and Total Project Cost Per Connector Installed, available at <https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle/calevip-level>
- 56 CALeVIP DC Fast Chargers, Average Rebate, Unit Cost, and Total Project Cost per Charger, available at <https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle/calevip-dc>
- 57 Hardman et al, “A Perspective On Equity in the Transition to Electric Vehicles, MIT Science Policy Review Vol. 2 (August 30, 2021), available at <https://sciencepolicyreview.org/2021/08/equity-transition-electric-vehicles/>
- 58 Empower EV Program available at https://www.pge.com/en_US/residential/solar-and-vehicles/options/clean-vehicles/electric/empower-ev-program.page
- 59 PG&E Multifamily Housing and Small Business EV Charger Program, available at https://www.pge.com/en_US/small-medium-business/energy-alternatives/clean-vehicles/ev-charge-network/program-participants/multifamily-housing-smb-ev-charger-program.page?
- 60 Federal Highway Administration, Charging and Fueling Infrastructure Discretionary Grant Program, available at <https://www.fhwa.dot.gov/environment/cfi/>
- 61 CARB, Advanced Technology Demonstration and Pilot Projects (2023), available at https://ww2.arb.ca.gov/sites/default/files/2023-07/fy21-23demoandpilot_solicitation.pdf
- 62 Inflation Reduction Act Guidebook, available at <https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/>
- 63 The Bipartisan Infrastructure Deal, available at <https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/>
- 64 Anders Fjendbo Jensen et al., “On the stability of preferences and attitudes before and after experiencing an electric vehicle,” Transportation Research Part D: Transport and Environment, Volume 25, (December 2013), available at <https://www.sciencedirect.com/science/article/pii/S1361920913001077>
- 65 EVs for Everyone, available at <https://evsforeveryone.org/>
- 66 Natural Resources Defense Council, “California Approves Novel Low-Income EV Charger Program”, available at <https://www.nrdc.org/bio/miles-muller/california-approves-novel-low-income-ev-charger-program>
- 67 City of Watsonville census data, available at <https://www.census.gov/quickfacts/fact/table/watsonvillecitycalifornia,CA/PST045222>

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Discussion of Evaluation Year 2024 *Report on SRPs and AB Pilots*

September 17, 2025

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NATIONAL RENEWABLE ENERGY LABORATORY

 ITS UC DAVIS
INSTITUTE OF TRANSPORTATION STUDIES

Agenda

- Introduction
- Medium-Duty and Heavy-Duty Fleets
(SCE Charge Ready Transport, PG&E EV Fleet, and SDG&E Power Your Drive For Fleets)
- Public Charging
(Schools, Parks and Beaches, and PG&E EV Fast Charge)
- Q&A



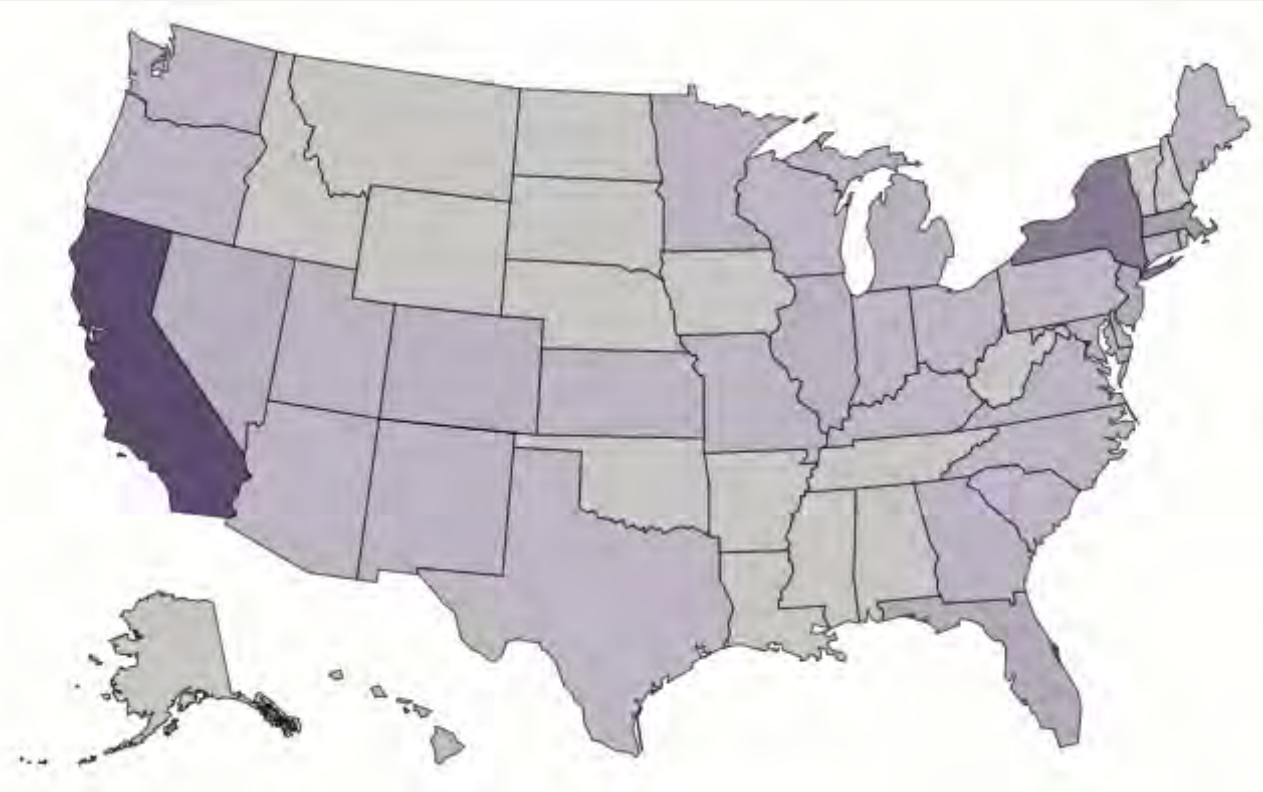
Introduction

Introduction | Programs and Budgets

Total Utility Investment: **\$765M over four to six years**

	Program	Budget (\$Millions)
Liberty	<i>EV Bus Infrastructure Program</i>	\$0.2
	Schools Pilot	\$3.9
	Parks Pilot	\$0.8
Pacific Gas & Electric (PG&E)	EV Fleet Program	\$236.3
	EV Fast Charge Program	\$22.4
	Schools Pilot	\$5.8
	Parks Pilot	\$5.5
Southern California Edison (SCE)	Charge Ready Transport Program	\$342.6
	Schools Pilot	\$9.9
	Parks Pilot	\$9.9
San Diego Gas & Electric (SDG&E)	Power Your Drive for Fleets Program	\$107.4
	<i>Vehicle-to-Grid Pilot</i>	\$1.7
	Schools Pilot	\$9.9
	Parks Pilot	\$8.8
Total		\$765

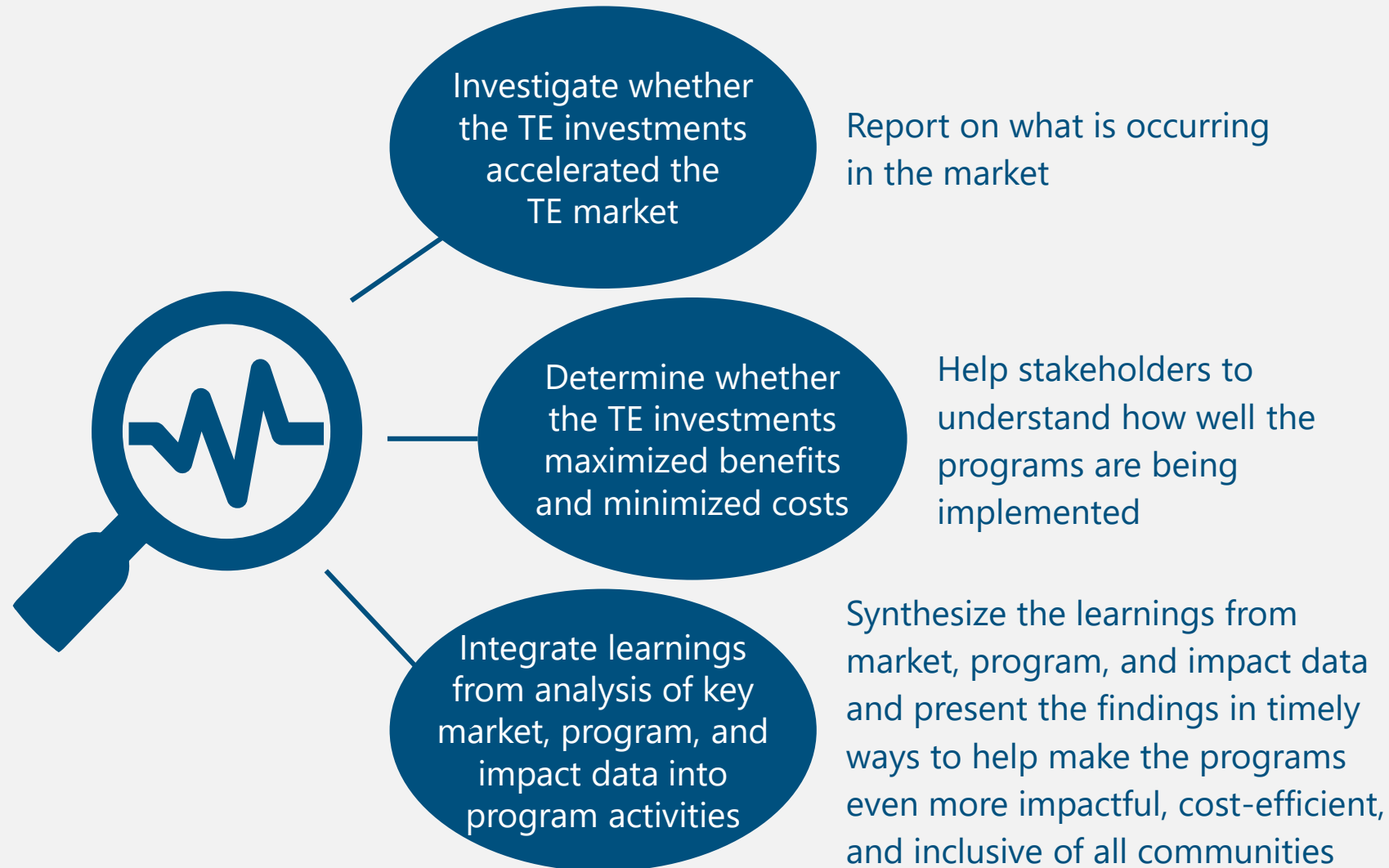
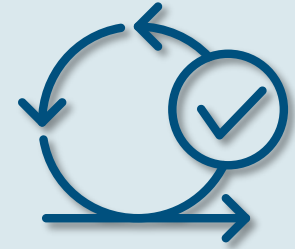
Approved EV Make-Ready Filings (\$ Invested)



Source: Atlas Public Policy, EV Hub
www.atlasevhub.com/materials/electric-utility-filings/

Introduction | Evaluation Objectives

Evaluation Research Objectives



Our approach is based on these core objectives to deliver timely feedback, a durable yet flexible evaluation framework and deep market insights to guide future investments.

Introduction | Evaluation Activities

Data Collection

	MDHD	Public Charging	V2G
 Program Data and Materials	✓	✓	✓
 AMI/EVSP Data	✓	✓	✓
 Site Visits	✓	✓	✓
 Interviews	✓	✓	✓
 Surveys	✓		
 Delphi Panel	✓		

Analysis

	MDHD	Public Charging	V2G
 EV Adoption Regression		✓	
 Grid Impacts	✓	✓	
 Counterfactual Development	✓	✓	
 Petroleum Displacement	✓	✓	
 GHG and Criteria Pollutant	✓	✓	
 Health Impacts	✓	✓	
 Total Cost of Ownership	✓	✓	
 Site Visit Findings	✓	✓	
 Co-Benefits and Co-Costs	✓		
 Interviews/Survey Findings	✓	✓	✓
 Market Effects	✓		

Introduction | Team Partnership

Tasks across evaluation

CADMUS |



- Surveys
- Program Performance
- ME&O
- Interviews
- Total Cost of Ownership
- Health Impacts
- Delphi Panels
- NTG
- Truck Choice Model
- LDV Regression Model



- Site Visits
- Grid Impacts:
 - o AMI Synthesis & Annualization
 - o EVSP Analysis
 - o Billing Data
- Deep Dives
- GHG, Criteria Pollutant
- Petroleum Displacement
- LDV Counterfactual
- MDHD Counterfactual

Introduction | Program Activity

Summary of completed sites as of December 31, 2024

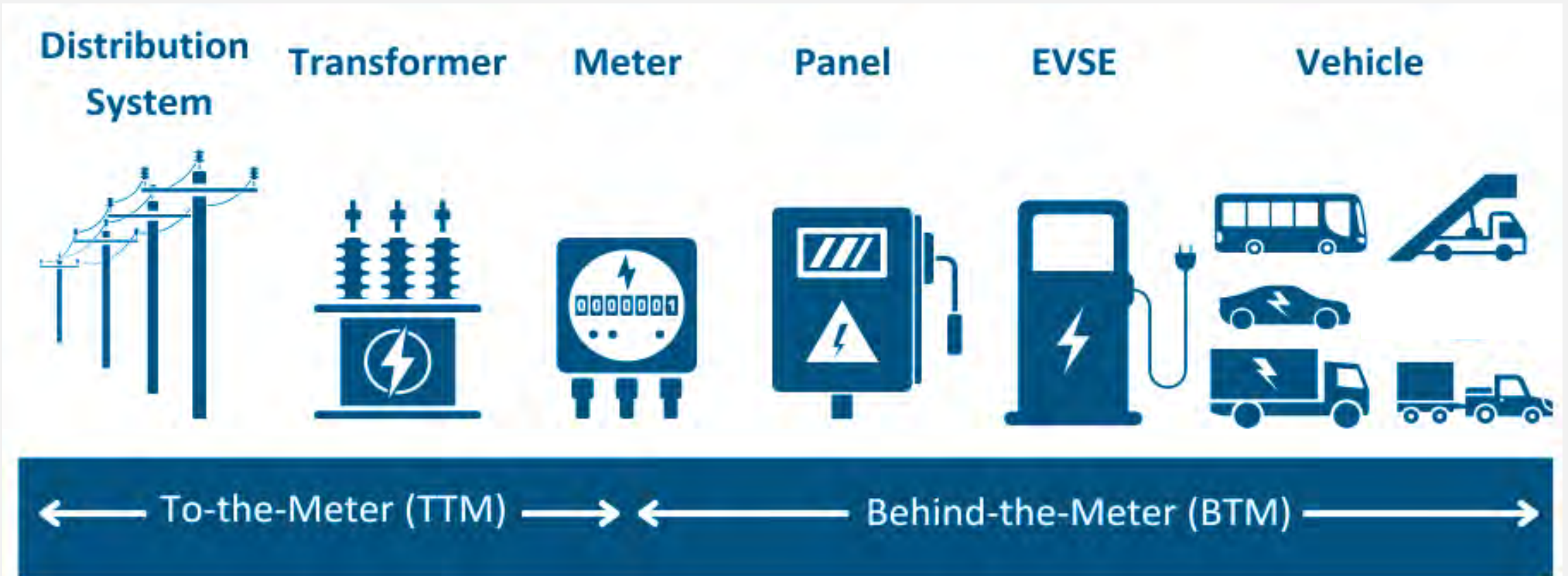
Program-Wide Totals

Utility Construction Complete	
EY2024: 102	PTD: 340
↓	
Activated	
EY2024: 101	PTD: 313
↓	
Operational	
EY2024: 102	PTD: 307
↓	
Closeout	
EY2024: 125	PTD: 249

Activated Totals

		EY2024	PTD
SCE	Charge Ready Transport	31	86
	Schools	1	22
	Parks	0	0
PG&E	EV Fleet	46	108
	Schools	1	12
	Parks	0	0
	EV Fast Charge	11	29
SDG&E	Power Your Drive for Fleets	4	25
	Schools	4	19
	Parks	2	11
Liberty	Schools	1	1
	Parks	0	0

Introduction | Infrastructure



- 14 programs support both to-the-meter (TTM) and behind-the-meter (BTM) infrastructure upgrades
- Utilities pay 100% for TTM infrastructure costs and for some or all BTM costs
- Similar California programs are Rule 29, Rule 45, CAlLeVIP, EnergIZE

Introduction | Unique Contributions



Large volume of **real-world data** in a clean, consistent format (for example, ~25% of electric MDHD in dataset)



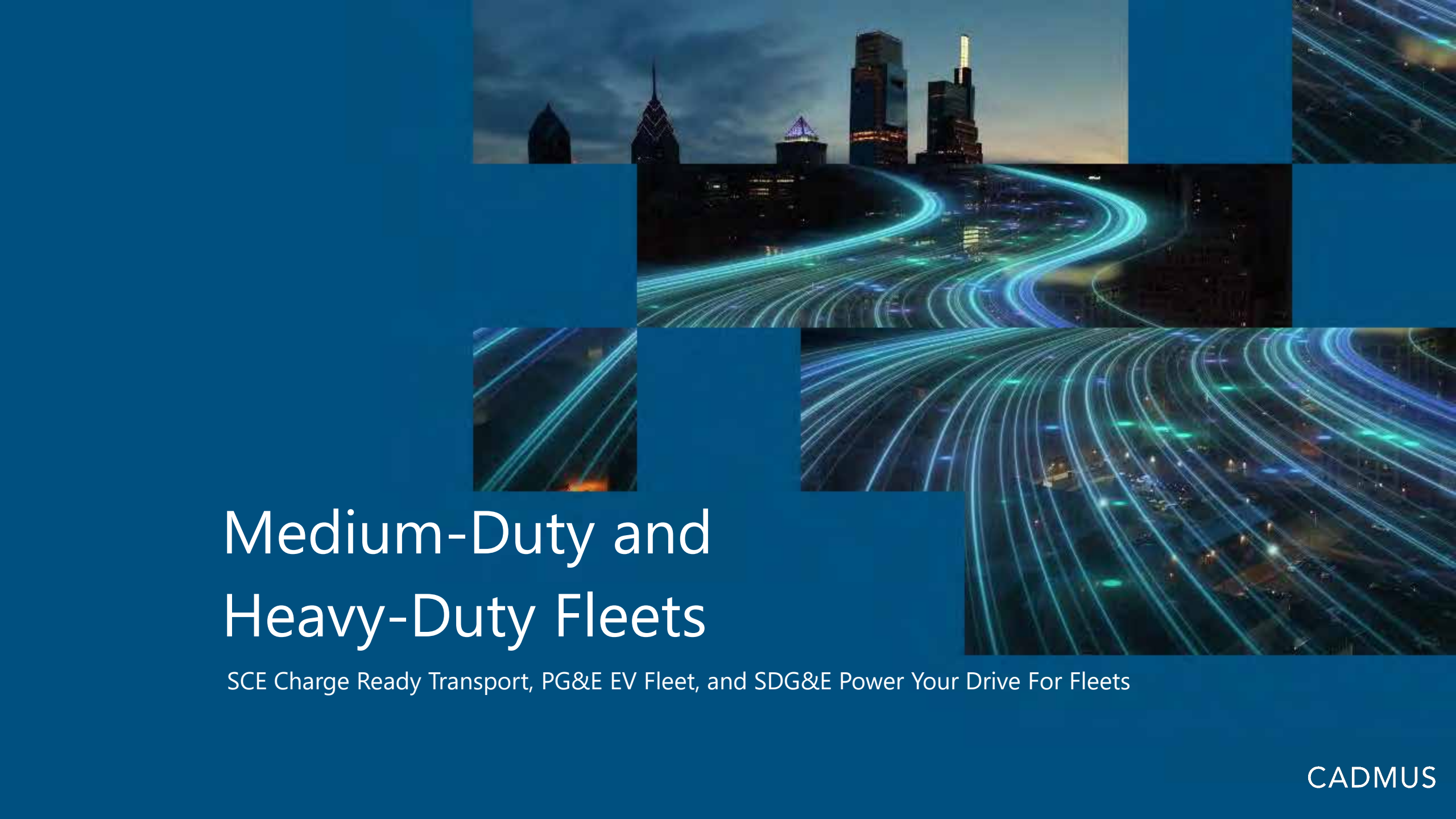
Diversity of vehicle categories, fleet participants, tariffs, etc.



Site cost, meter data, charger data, and billing data



Interactive dashboards on site performance (not public)

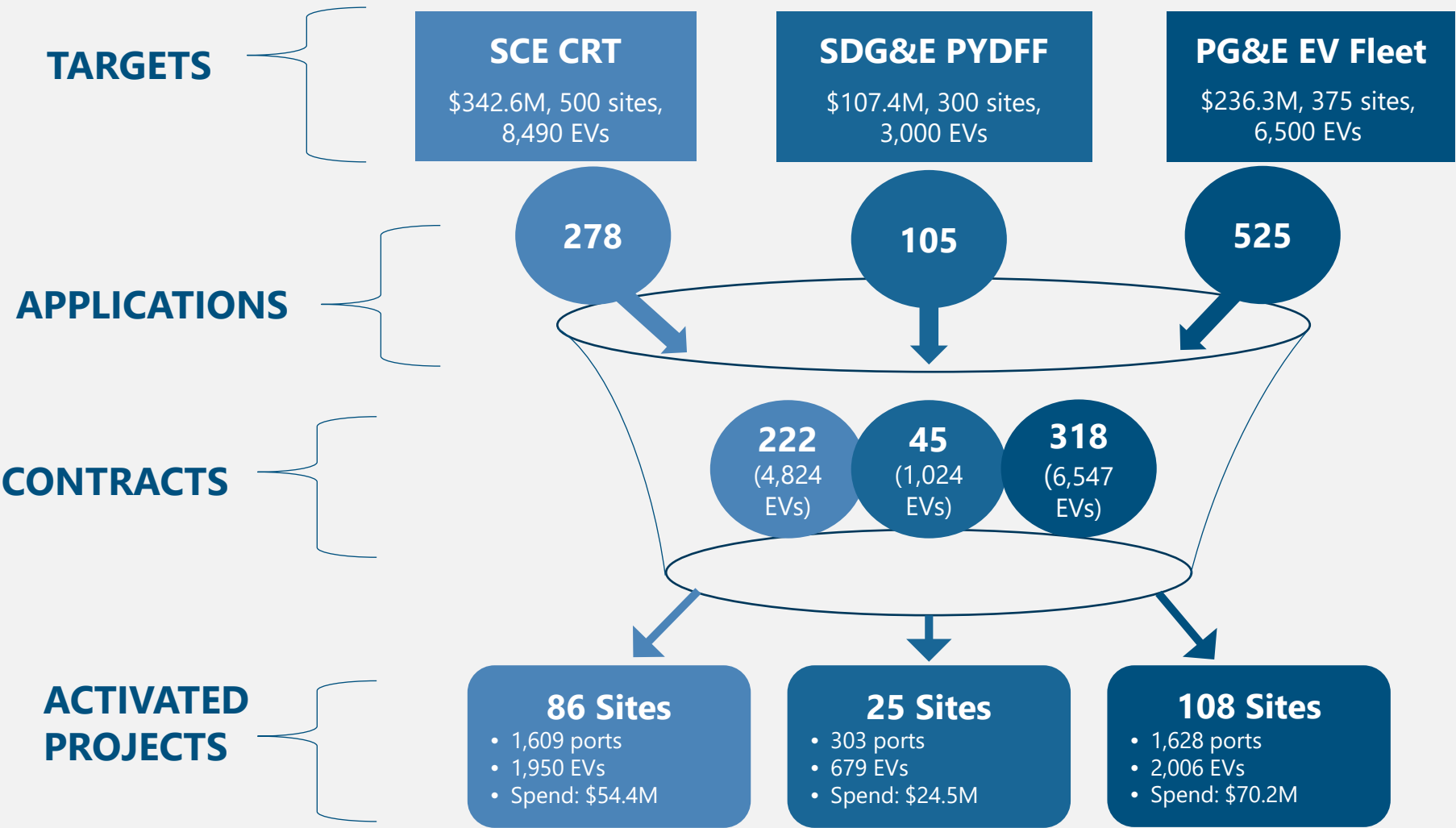


Medium-Duty and Heavy-Duty Fleets

SCE Charge Ready Transport, PG&E EV Fleet, and SDG&E Power Your Drive For Fleets

MDHD | Progress Toward Program Targets

Program Targets (Sites & EVs) / Received Applications / Signed Contracts / Completed Sites



MDHD | 2024 Findings

Positive impacts in fourth year of evaluation; **1,925** MDHD EVs toward goal of **17,990**



Population of Activated Sites in EY2024 (#)

81



Ports Installed in Analyzed Sites (#)

1,590



EVs Supported (#)

1,925



Electric Energy Consumption (MWh)

36,348

The team derived the EVs supported value for MDHD programs from applicants' vehicle acquisition plans (VAP). This value represents the maximum number of vehicles expected to be supported by the charging infrastructure.



Petroleum Displacement (diesel gallons equivalent)

2,861,568



GHG Emissions Reduction (metric ton [MT] GHG)

22,397

GHGs include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) multiplied by their respective Global Warming Potentials (GWP) as defined by the Intergovernmental Panel on Climate Change (IPCC) published fifth assessment (AR5; see the Methodology section for more details).

Local Emissions	Reduction (kg)
Oxides of Nitrogen (NO _x)	15,709
Particulate Matter (PM ₁₀)	159
Particulate Matter (PM _{2.5})	148
Reactive Organic Gases (ROG)	1,055
Carbon Monoxide (CO)	112,575



MDHD | Lessons Learned

Utility Medium-Duty/Heavy-Duty program sites continue to displace petroleum, reduce greenhouse gas and local emissions, and achieve health impacts.

Displaced Petroleum (million gallons)

Program-to-Date Results

7.3

10-Year Expected Results

54.6

Greenhouse Gas Emissions Reductions (MT)

Program-to-Date Results

59,000

10-Year Expected Results

460,000



Utility MDHD programs have achieved a reduction of more than **400,000 kg of local carbon monoxide emissions** to date

Proportion of health benefits in DACs:

- SCE: **32%**
- PG&E: **18%**
- SDG&E: **14%**

MDHD | Market Sector Mix

Market sector diversity continues

EY2024 Takeaways

Medium- and Heavy-Duty Vehicles

have an increasing presence

- National fleet operators and larger sites coming online.

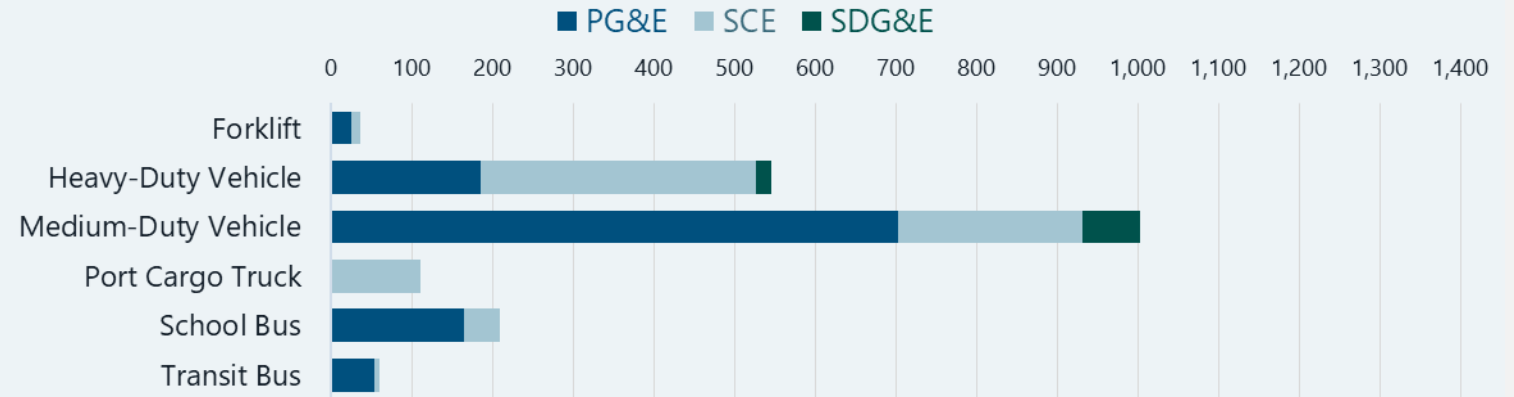
Medium-Duty Vehicles are now the most common across sectors.

- School buses have been the most common in all prior years.

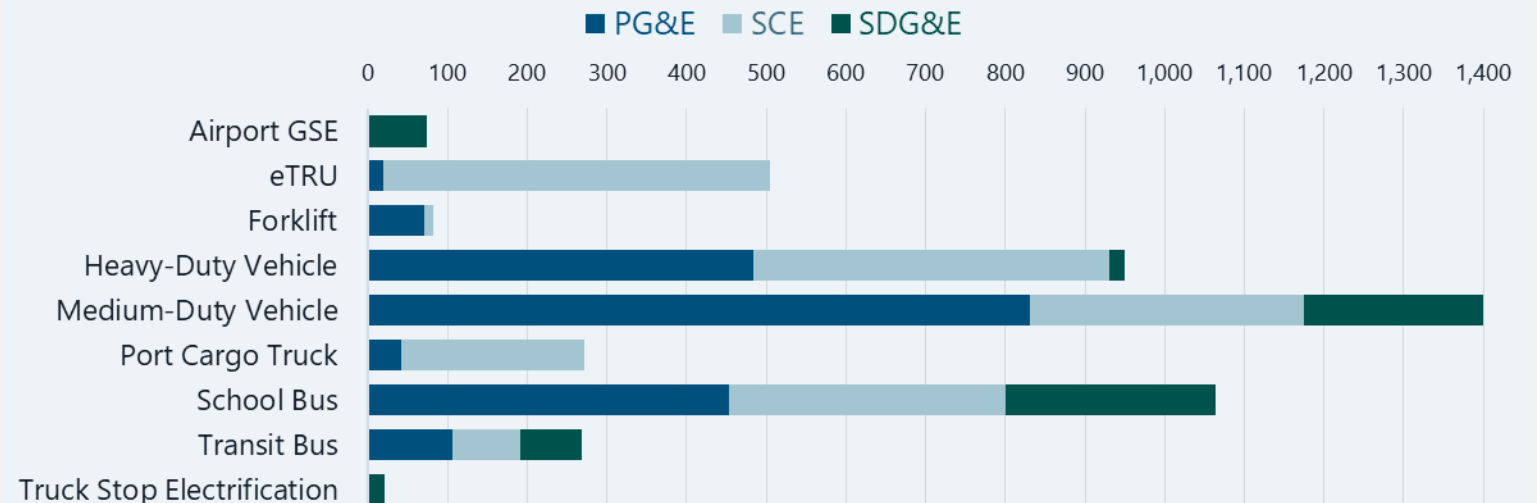
The **School Bus sector** continues to grow.

- Second highest vehicle quantity in the program to date of all market sectors

EY2024 Sites: VAP Vehicle Quantity



Program-to-Date Sites: VAP Vehicle Quantity

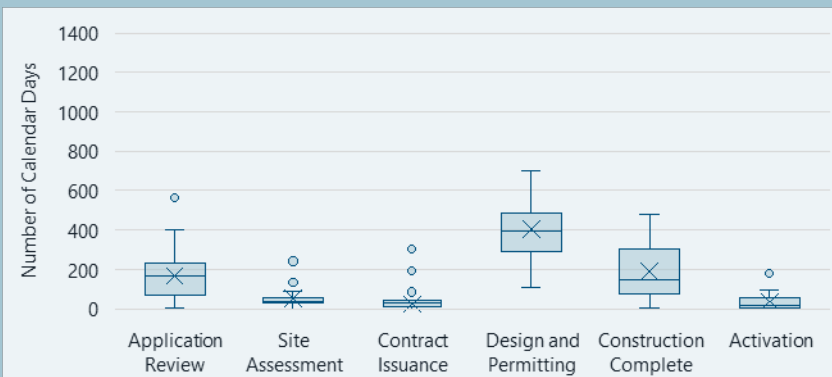


MDHD | Site Timelines

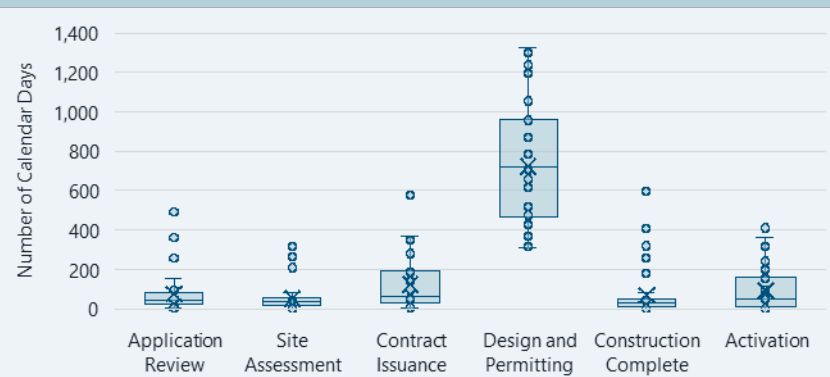
Calendar Days per Phase for EY2024 Activated Sites

- Timelines are generally longer than expected and vary widely by phase
- Original Utility estimates ranged from 11 to 19 months while overall program **medians** are between **24 and 33 months**
- Overall median calendar days have steadily increased in each of the last three years
- The **median start-to-finish** for all 81 EY2024 activated sites was **983 days**
- **Design and Permitting** is **longest phase** with a median of **491 days** in PTD sites, followed by Application Review with a median of 69 days

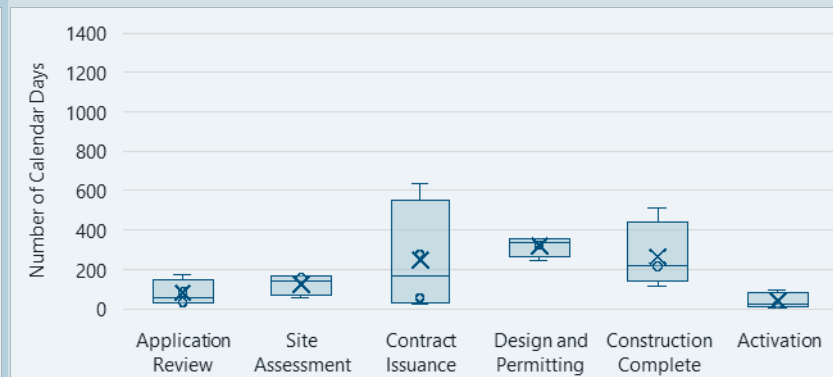
SCE Charge Ready Transport



PG&E EV Fleet



SDG&E Power Your Drive For Fleets

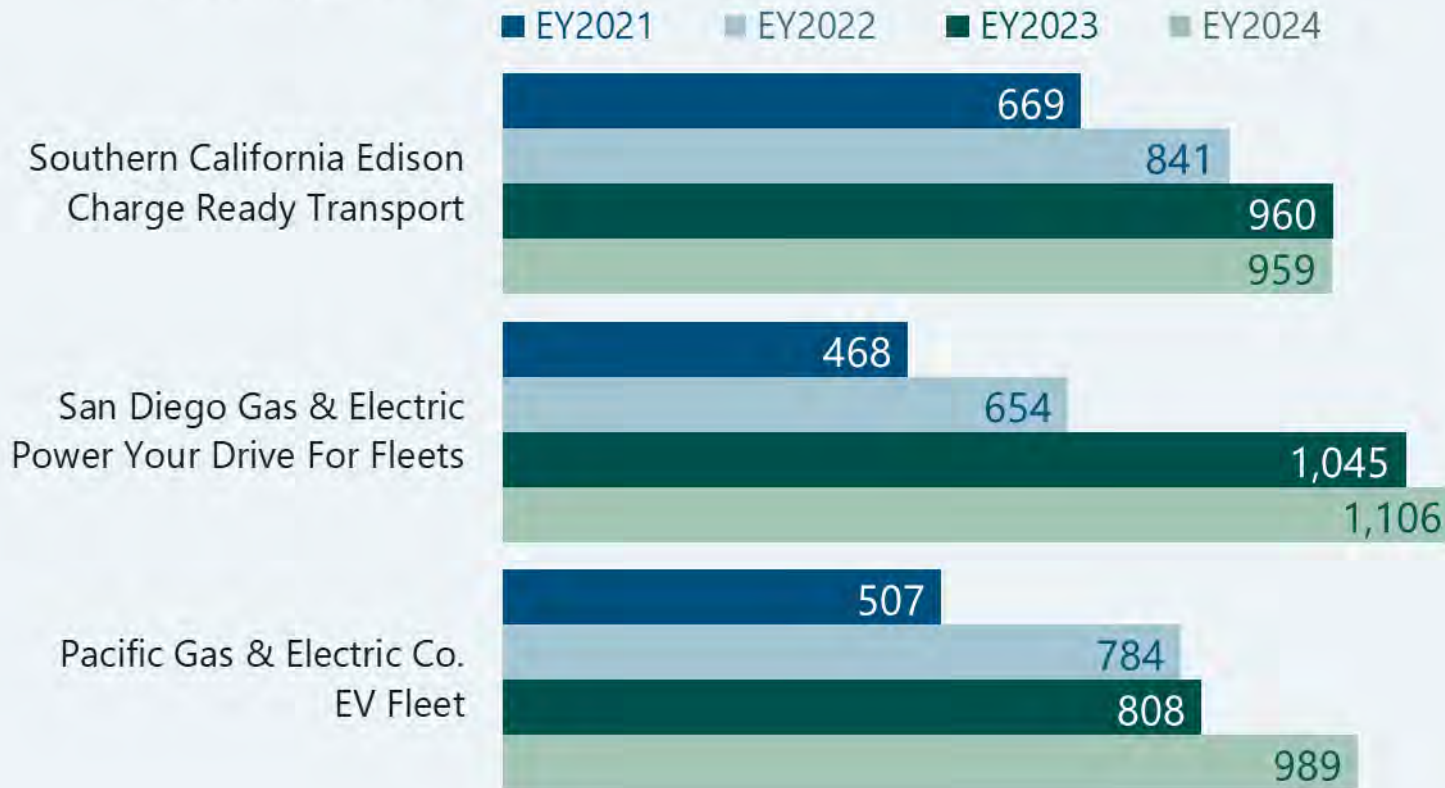




MDHD | Lessons Learned

Site activation timelines continue to increase as larger sites become operational.

Median Calendar Days from Application to Activation



Start-to-finish median calendar days for all MDHD programs:

- EY2021: **600 days**
- EY2022: **725 days**
- EY2023: **862 days**
- EY2024: **983 days**

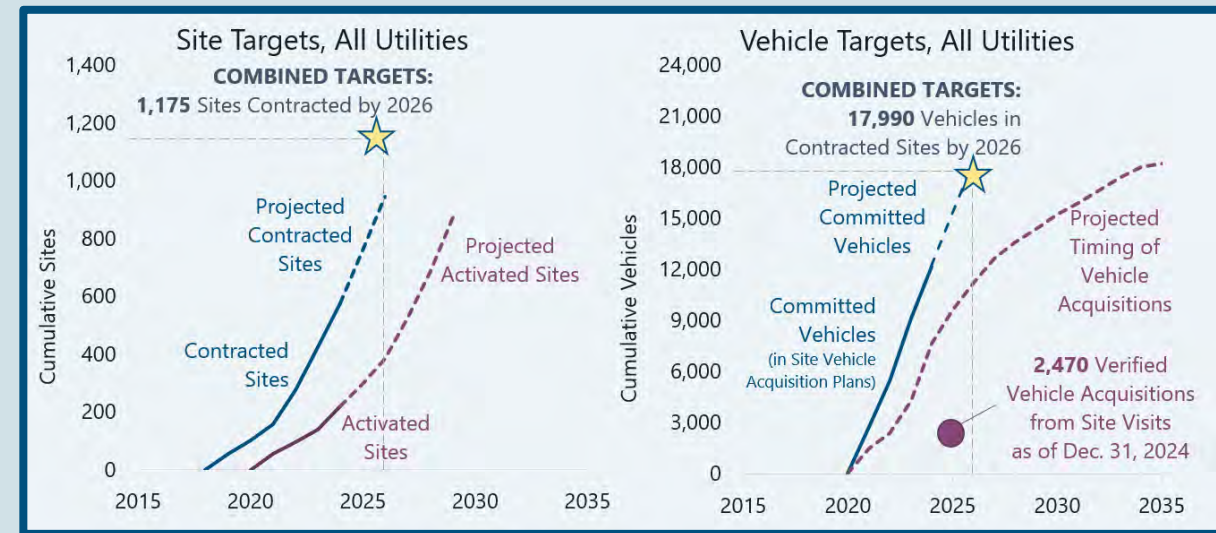


MDHD | Lessons Learned

MDHD programs are having a meaningful impact on EV and charger deployments. However, program participation has been lower than expected in two of the three programs.



When all programs are aggregated, the Utilities will likely **meet the combined vehicle targets** (17,990 vehicles) but **fall short of the combined site targets** (1,175 sites)



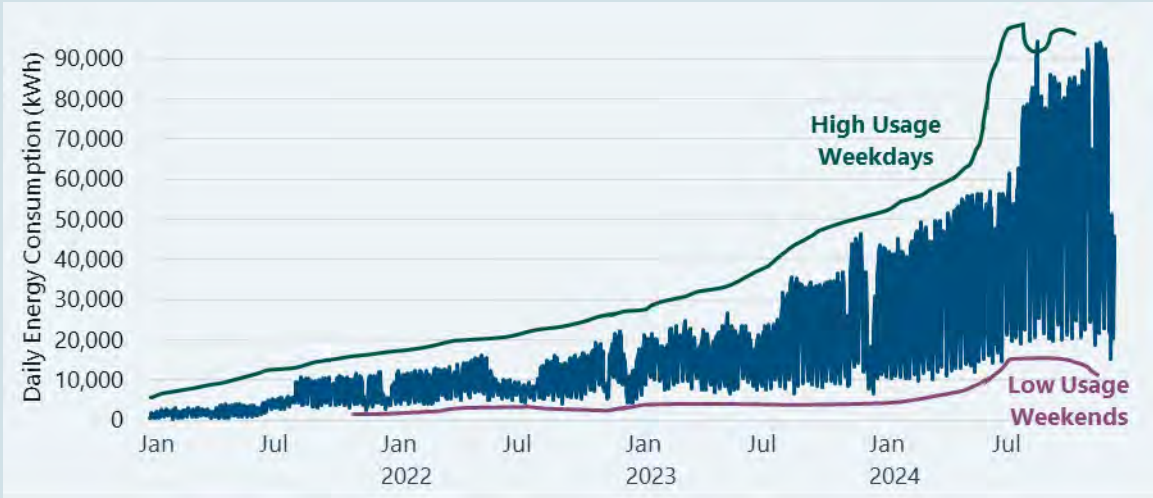
MDHD | Grid Impacts – Consumption

Program Daily Energy Consumption for PTD Sites

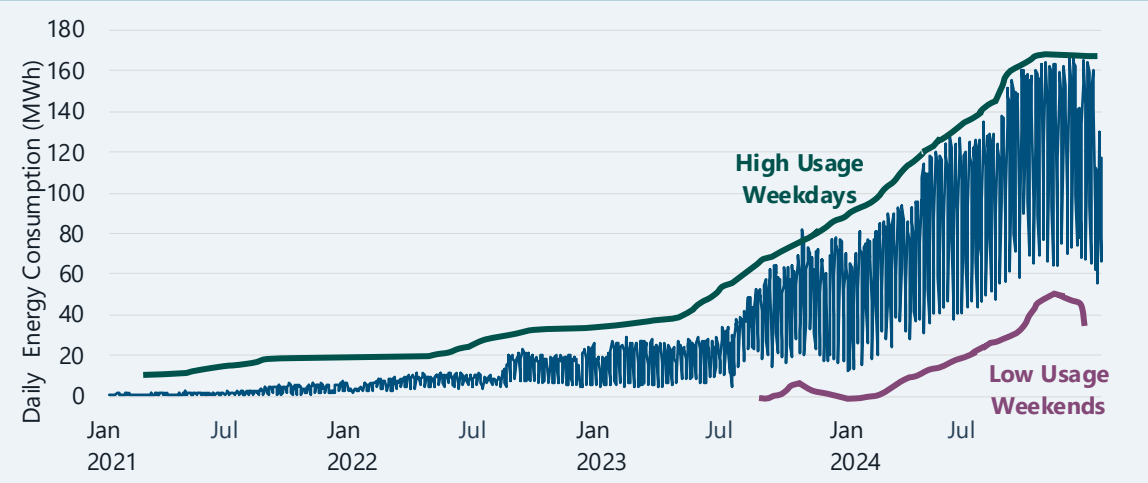
Daily energy consumption across all sites has continued to **increase**, especially as new larger sites have come online.

There are wide variations in daily energy consumed and also in consumption between weekdays and weekends.

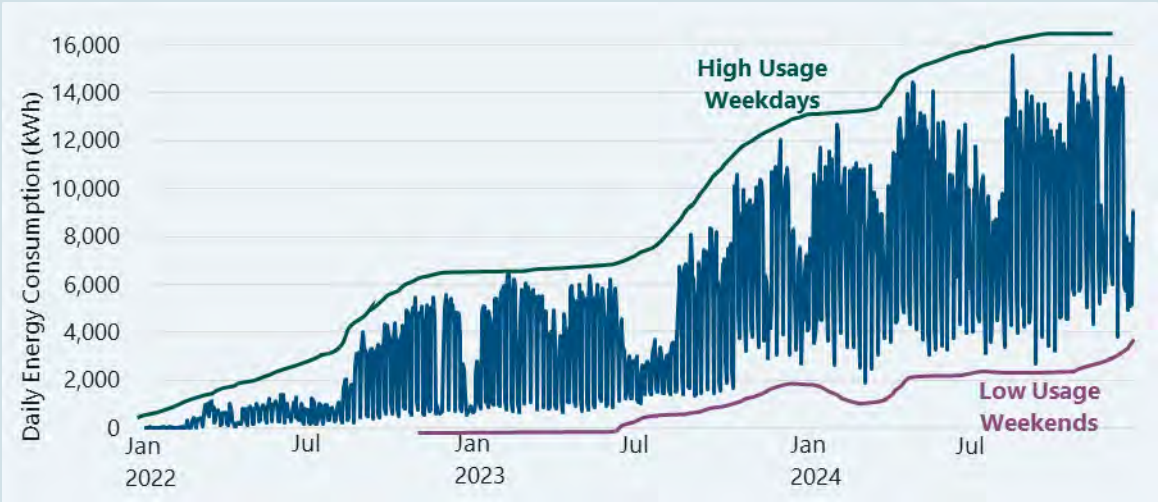
PG&E EV Fleet



SCE Charge Ready Transport



SDG&E Power Your Drive for Fleets

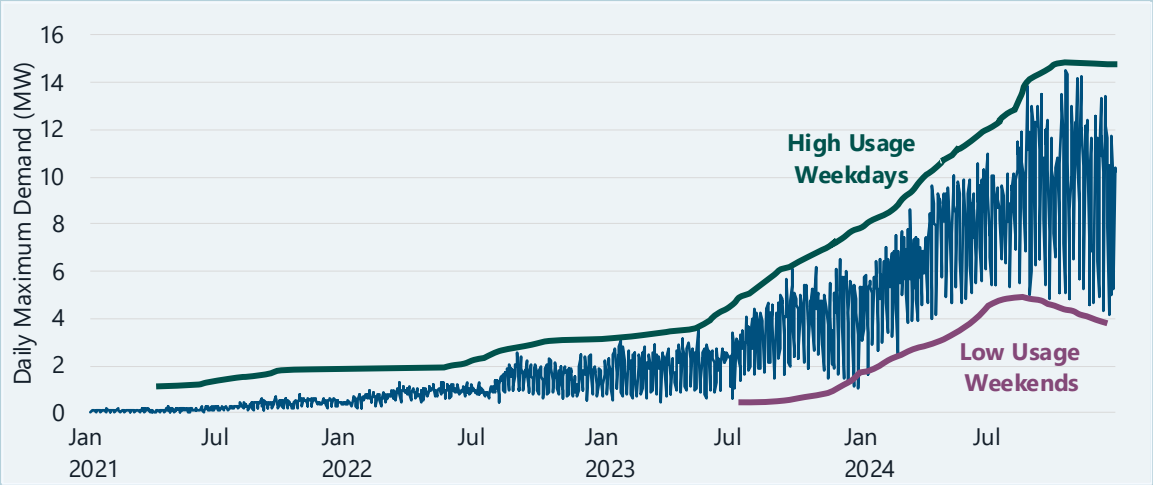


MDHD | Grid Impacts – Demand

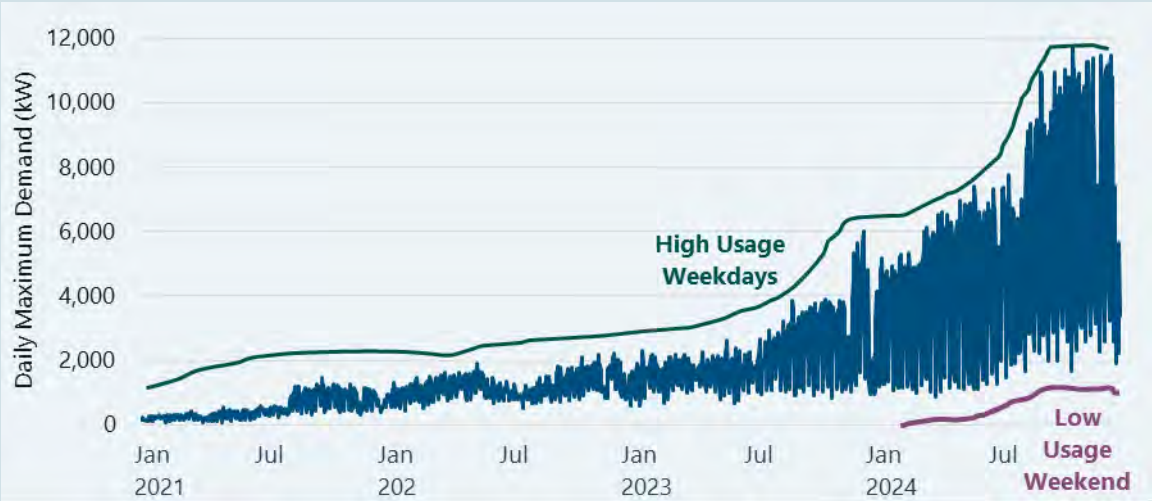
Program Daily Maximum Demand for PTD Sites

SCE and PG&E maximum demand **continues to grow** with time but has been **more consistent** in the second half of 2024.

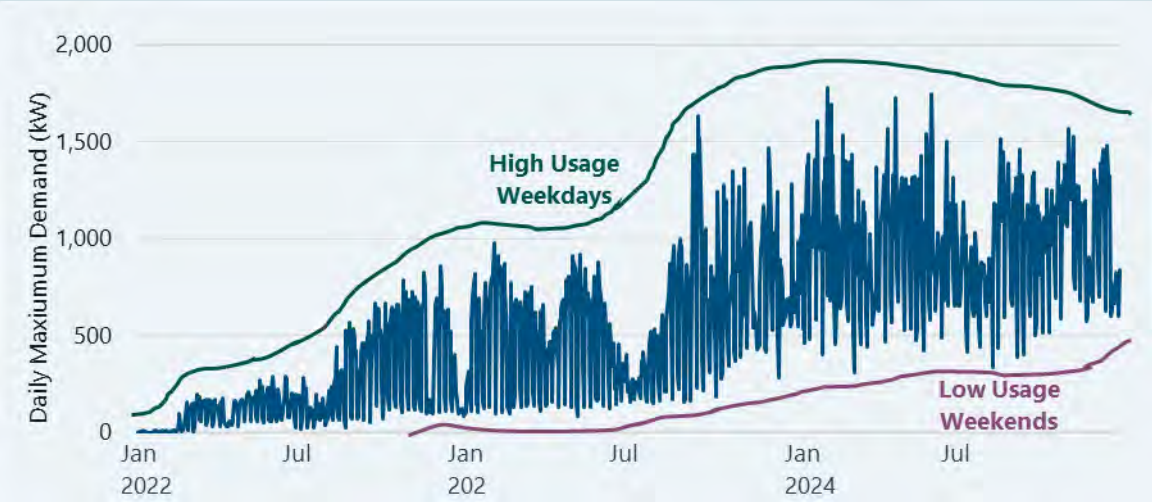
SCE Charge Ready Transport



PG&E EV Fleet



SDG&E Power Your Drive for Fleets



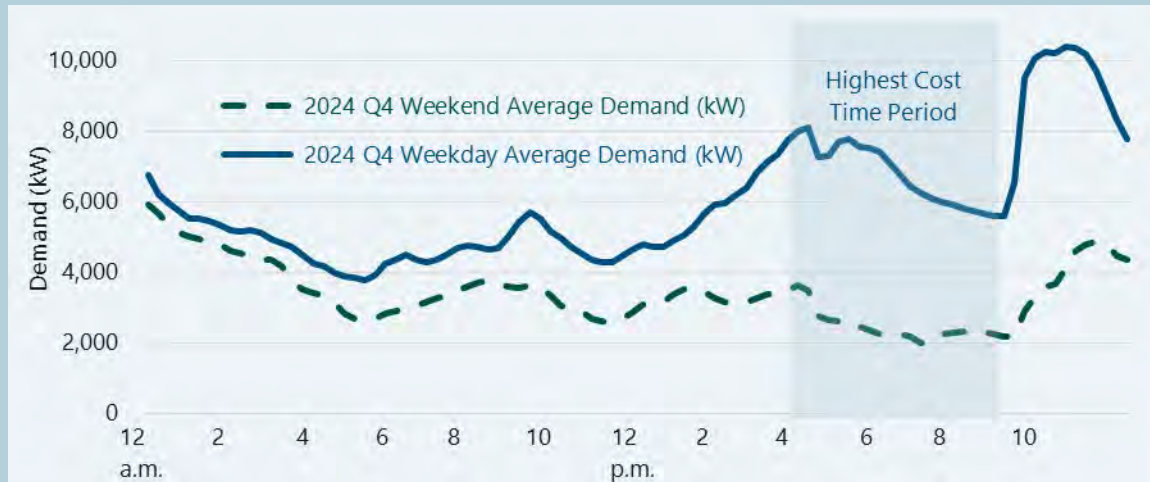
MDHD | Grid Impacts – Load Management

Average Weekday and Weekend Q4 2024 Load Curves

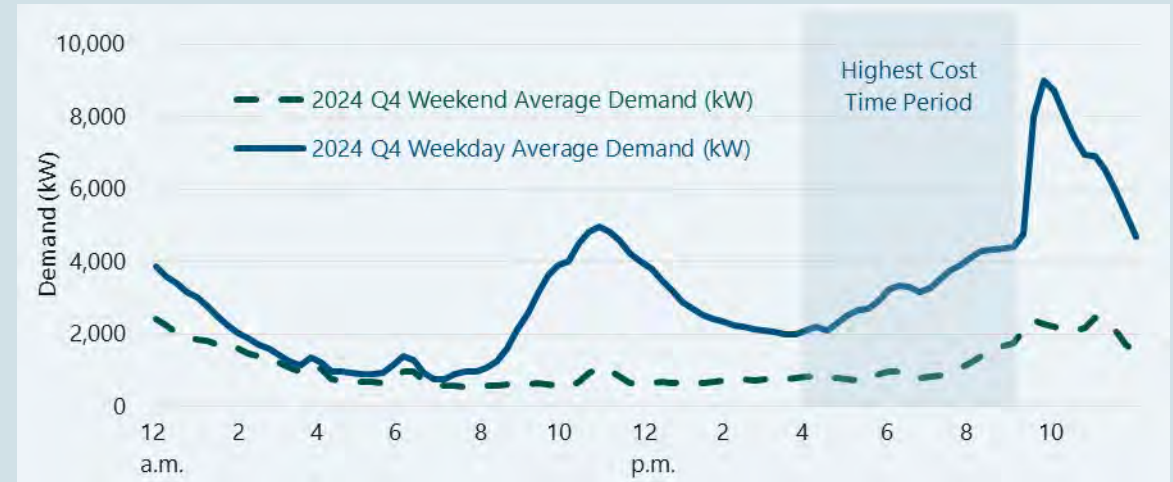
Significant unnecessary consumption from 4 p.m. to 9 p.m.

- **Only 21% of activated sites** (45 of 219) have exhibited the use of **load management** to date
 - **174 out of 219 sites are not using load management**
- A **steep increase in weekday demand at 9 p.m.** indicates that sites are employing load management to avoid high-cost energy
 - Minimizing demand appears less of focus than time-of-use.

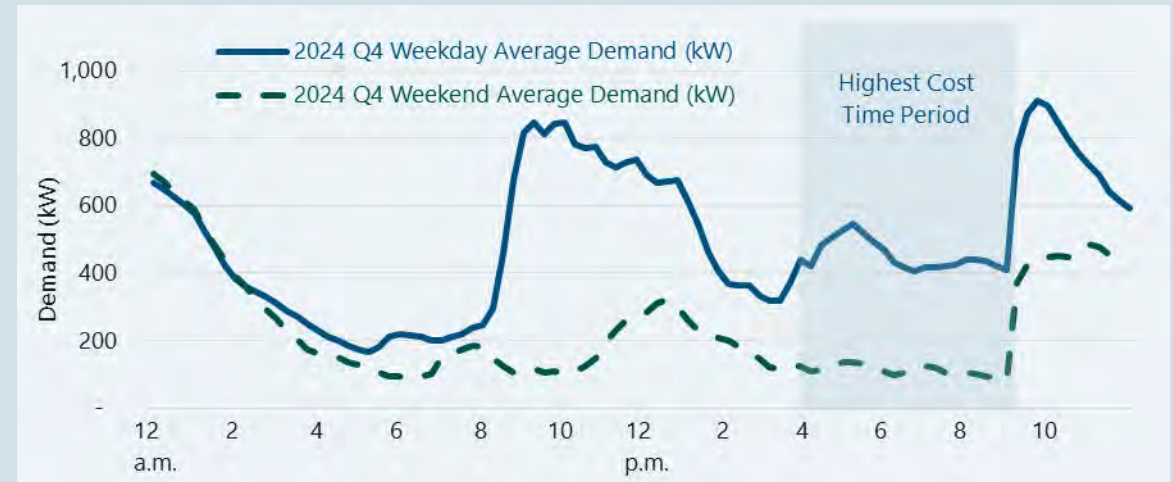
SCE Charge Ready Transport



PG&E EV Fleet



SDG&E Power Your Drive for Fleets



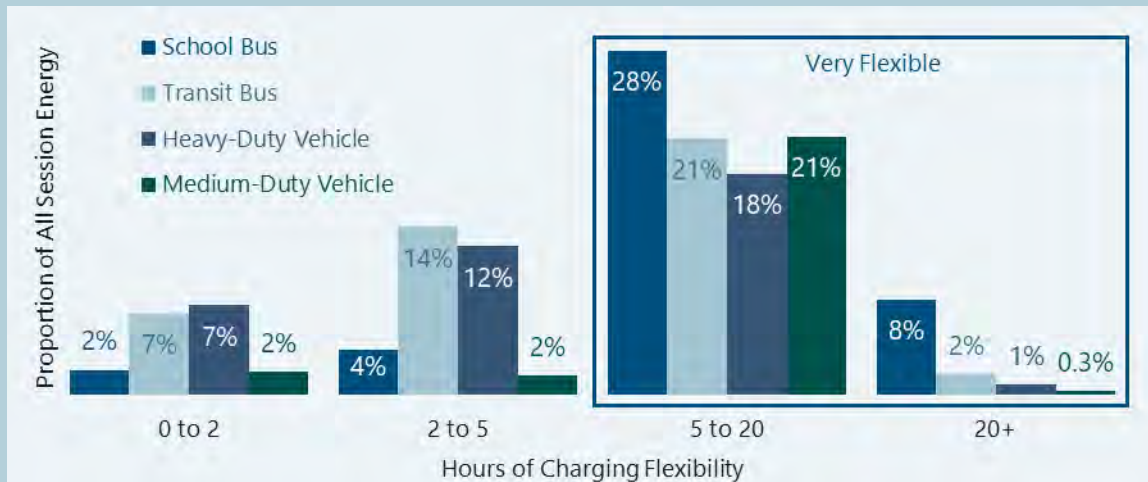
MDHD | Grid Impacts – Load Management

Charging Flexibility for PTD Sites of Sessions Overlapping the Time Period Between 4 p.m. and 9 p.m.

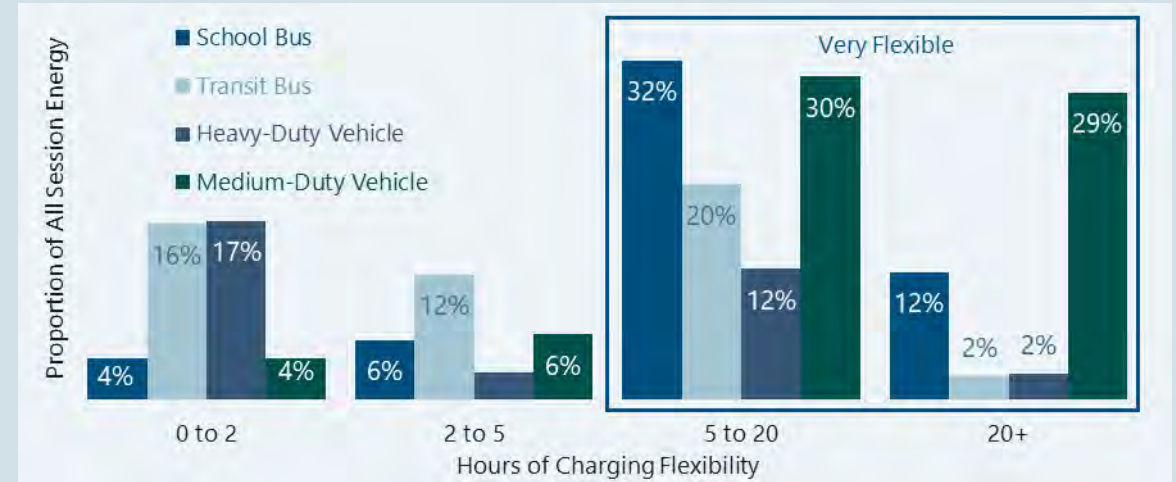
Many charging sessions have enough **flexibility to avoid charging during peak periods:**

- SCE Charge Ready Transport School Bus: **36%**
- PG&E EV Fleet Medium-Duty Vehicle: **59%**
- SDG&E Power Your Drive For Fleets School Bus: **40%**

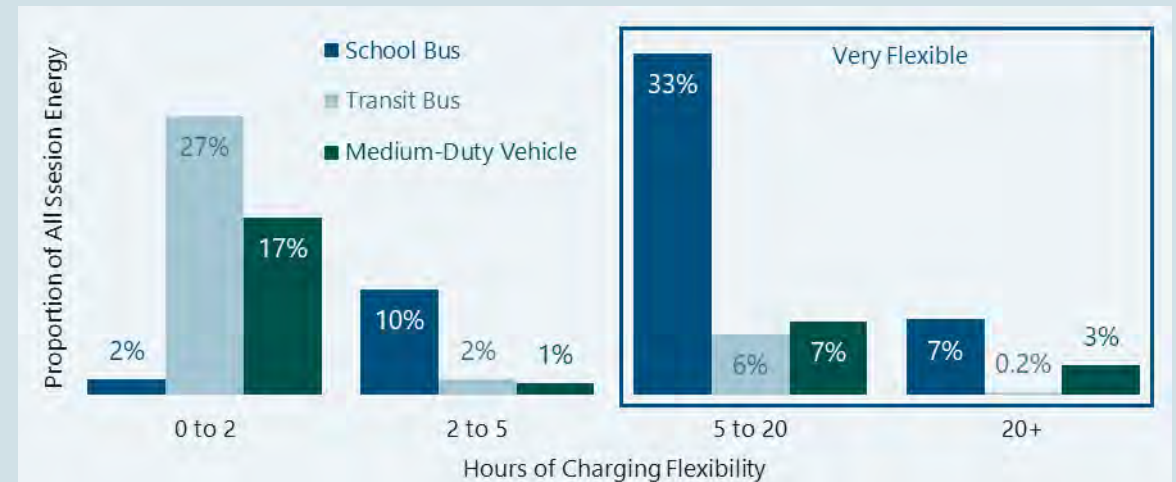
SCE Charge Ready Transport



PG&E EV Fleet



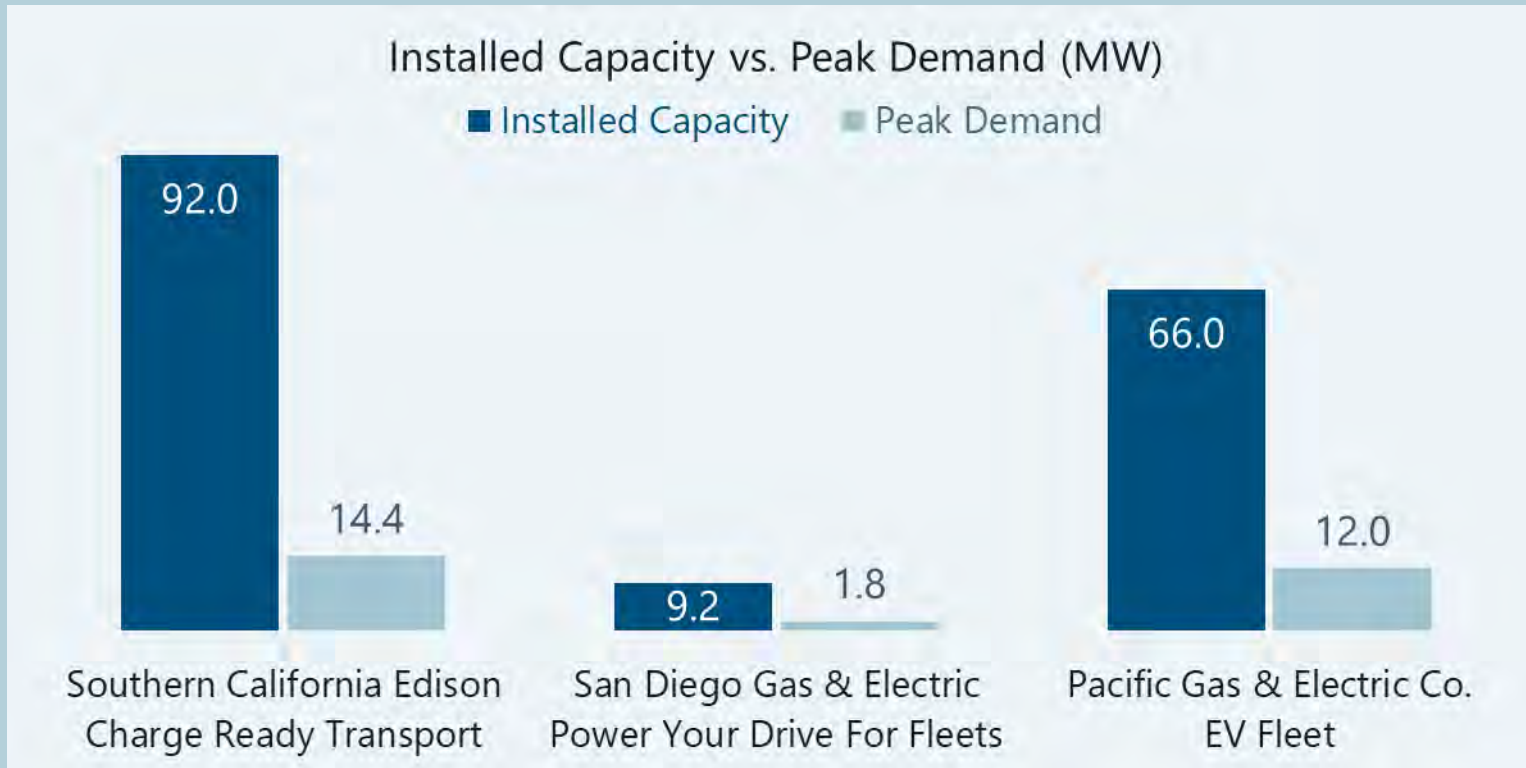
SDG&E Power Your Drive for Fleets





MDHD | Lessons Learned

Though installed capacity and overall consumption for MDHD sites increased significantly, peak demand represents a small portion of installed charging capacity, and most fleet operators have not implemented load management.



- Only **45 of the 219** activated sites (21%) exhibited the use of **load management**
- **Most charging** consumption shows enough flexibility to shift to lower cost time periods

- **Over 56 MWh** of energy consumption in 2024
- This accounted for **64% of PTD consumption** (nearly 88 MWh)
- Maximum demand was approximately 17% of total charging capacity
 - Sites have significant opportunity to grow utilization; most do not appear to mitigate max demand (kW)

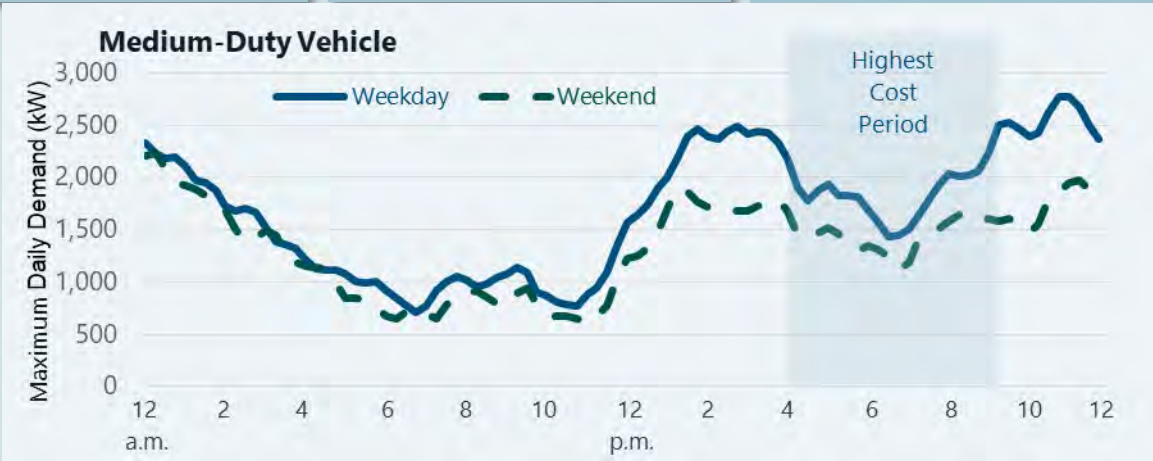
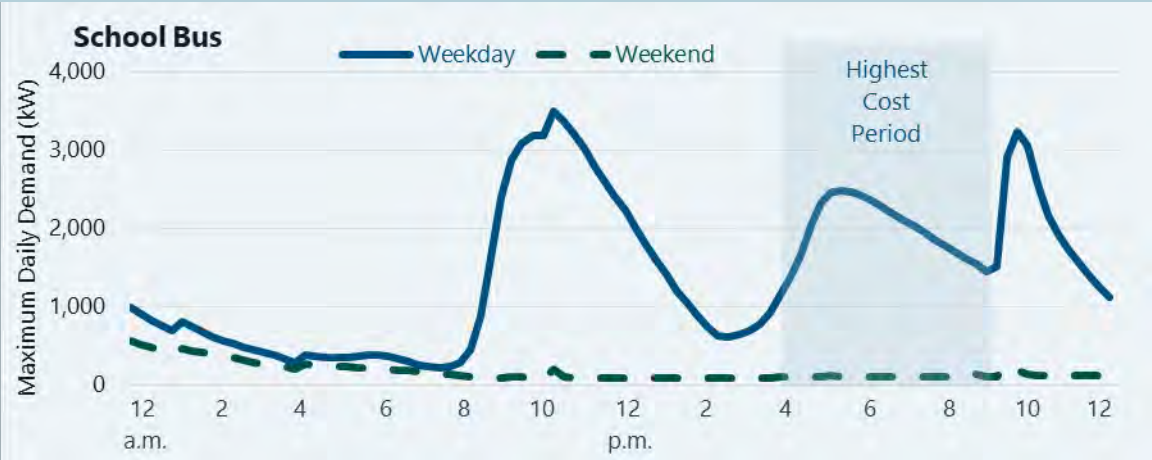
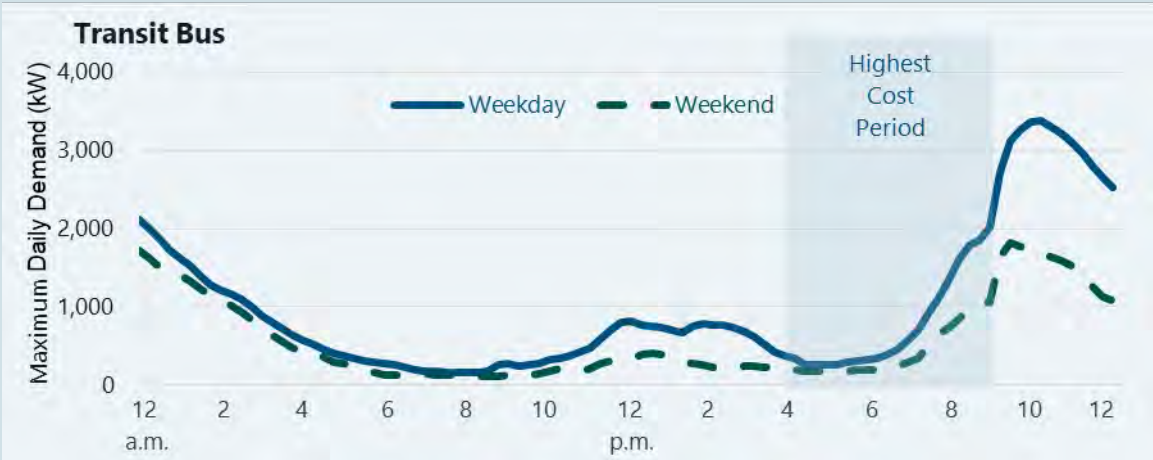
MDHD | Statewide Daily Load Curves

Weekday and Weekend Day Average Load Curves Q4 2024 by Market Sector

School bus charging has most midday consumption; more could move to weekends.

Other sectors show significant energy usage on Saturdays and **less** on Sundays but **~50% less than weekdays**

Most non-school bus fleets are constrained to **weekends for midday charging**



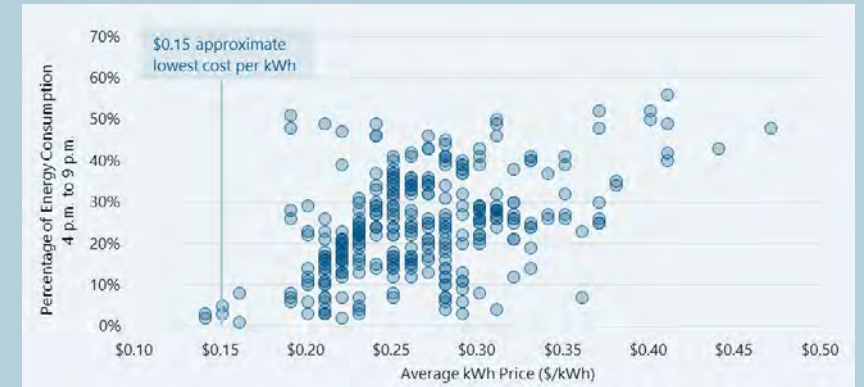
MDHD | Grid Impacts – Billing

These figures show SCE Charge Ready Transport percentage of monthly energy consumed from 4 p.m. to 9 p.m. versus the average energy price for consumption billing months for PTD sites.

High consumption billing months (>20 MWh) show generally lower costs than medium and low billing months. More round-the-clock charging spreads non-volumetric costs and reduces % 4 p.m. to 9 p.m.

Medium consumption billing months (5 MWh to 20 MWh) show average of \$0.20 to \$0.30 per kilowatt-hour. **Cost savings of 30%** for many months averaging \$0.40 or more per kilowatt-hour are achievable.

Low consumption billing months (<5 MWh) show a correlation between the amount of consumption between 4 p.m. and 9 p.m. Due to less energy volume, costs are more heavily impacted by other bill components. This highlights the value of **load management**.

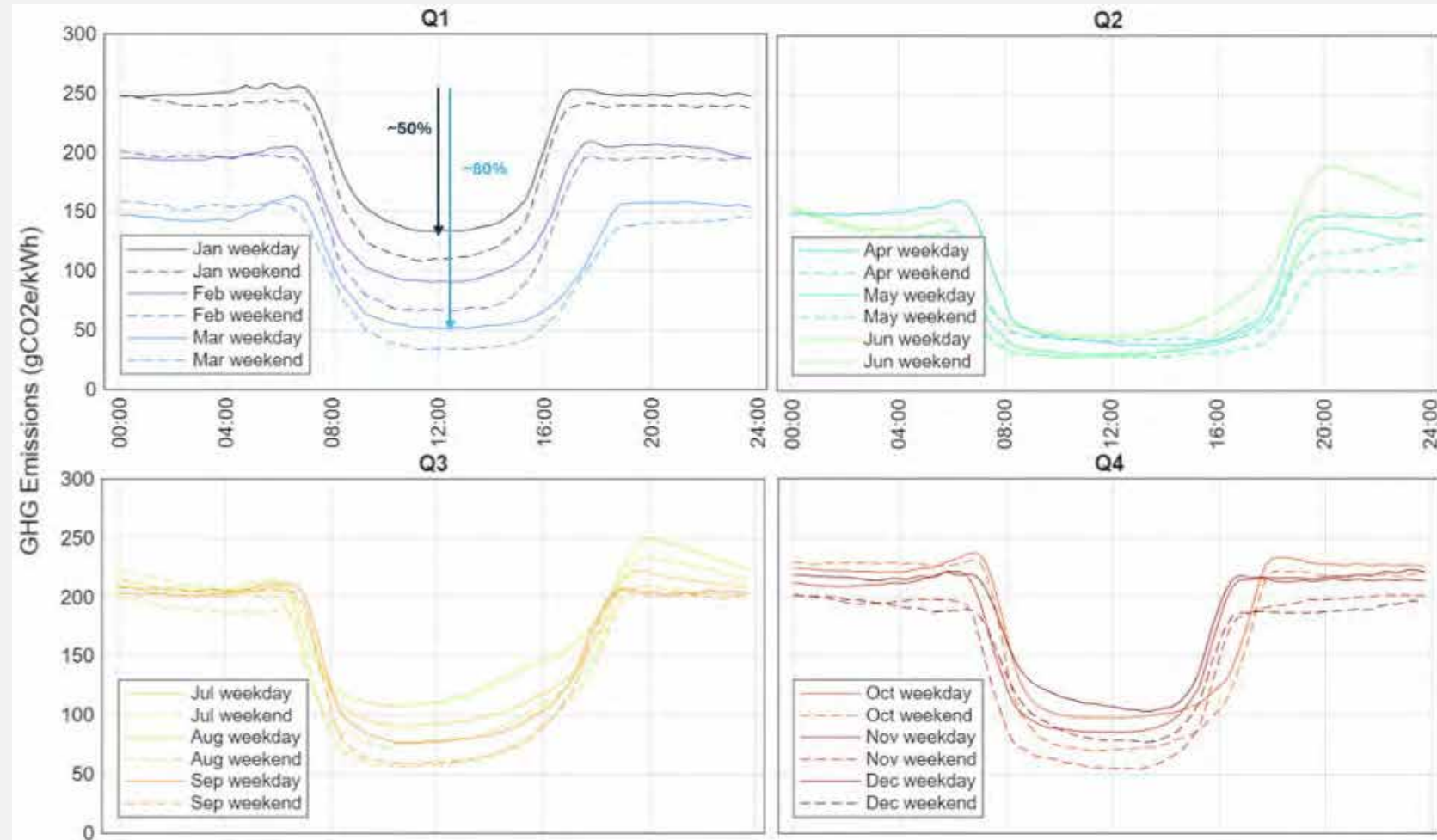


MDHD | NREL Optimization

2024 Weekday and Weekend Average CAISO GHG Emissions by Month

Emissions

- Average emissions generally lowest daily between 9 a.m. and 4 p.m.
- Evening grid electricity generally produces 2x to 4x midday emissions.
- Many fleets have flexibility to delay charging from highest emissions (after 7 p.m.) and highest cost (4 – 9 p.m.) to midday periods



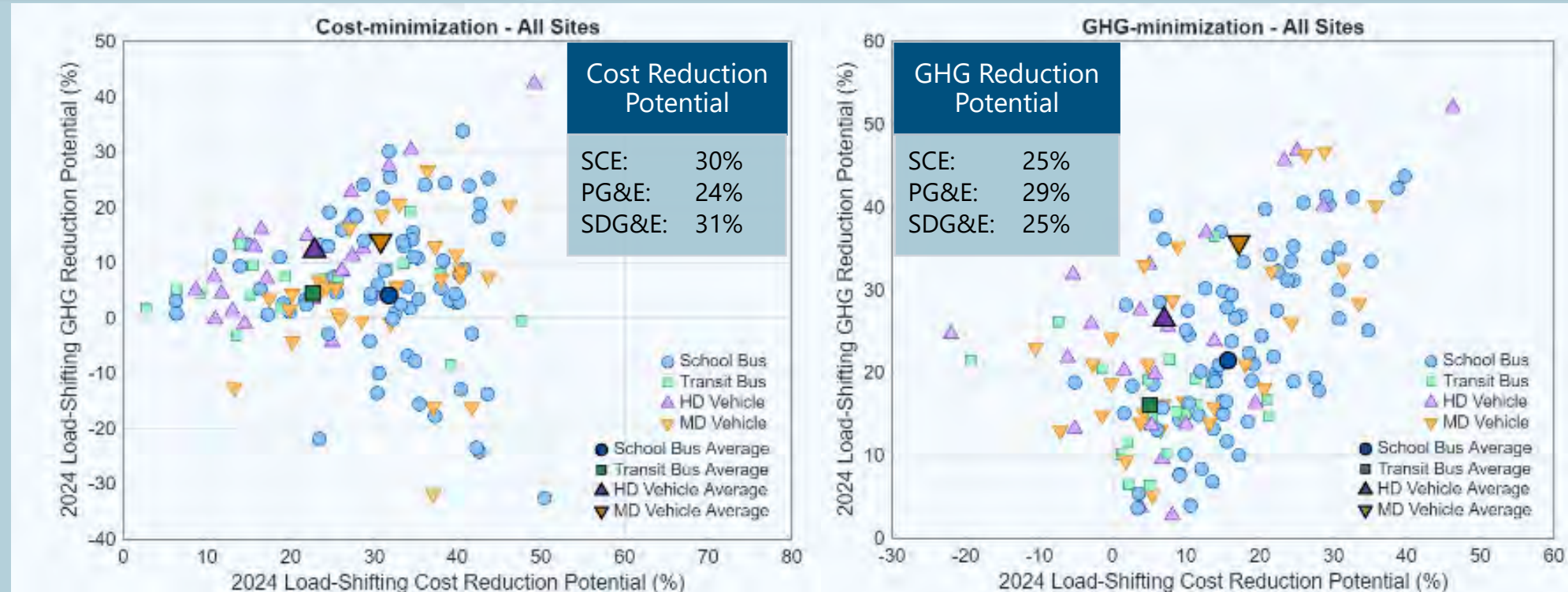
MDHD | NREL Optimization

Available Improvements in Utility Bills and GHG Emissions

- Electricity emissions are much lower during daylight hours than otherwise
- Optimizing charging for costs could save 24% to 31%, and optimizing emissions could save similarly. Both models show that most sites can optimize cost and emissions together.

- SCE and PG&E offer the lowest pricing midday, when emissions are also lowest.
- A **larger midday reduction** in rates by PG&E and SDG&E could create a stronger price signal for fleets to charge their vehicles at that time when costs and emissions are lowest, instead of at 9 p.m., at least part of the week.
- SDG&E's lowest costs are between 12 a.m. and 6 a.m. for most of the year, limiting the emphasis on lower emissions midday.*

* pursuant to ongoing General Rate Case

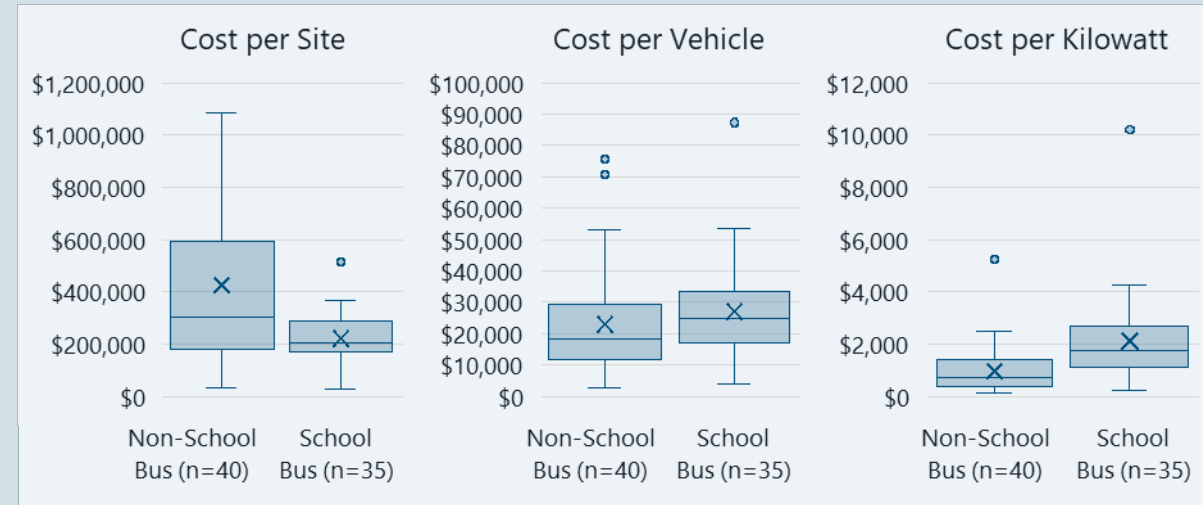


MDHD | Utility Infrastructure Costs

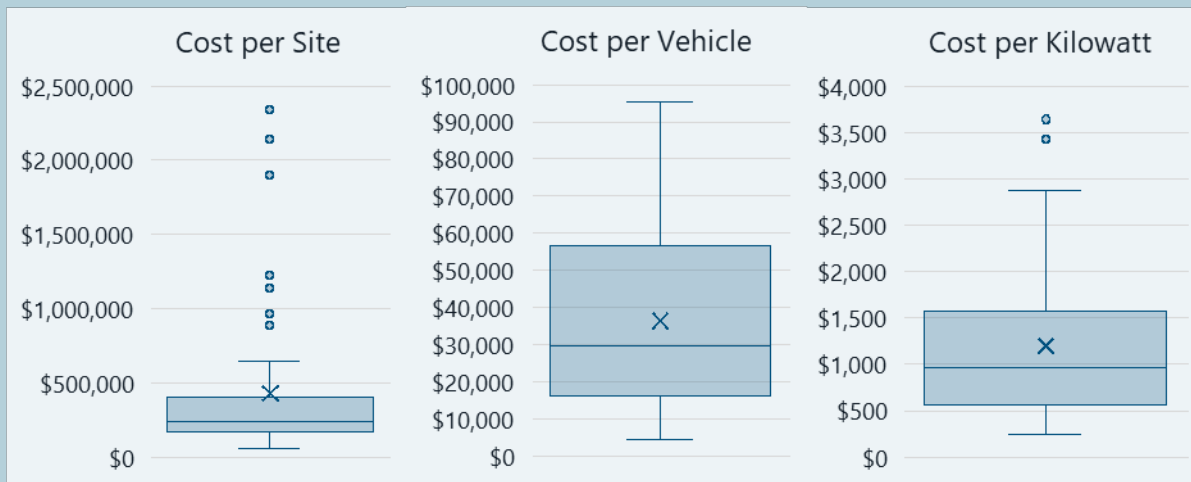
Utility Costs per Site, Vehicle, and Kilowatt for Closed-Out PTD Sites

- **Costs** include Utility-funded **TTM plus BTM** for financially closed-out sites.
- 40% of sites have utility-owned BTM, 60% have customer-owned BTM.
- **Larger sites** have **lower costs** per vehicle and per kilowatt than smaller sites, although the scale effect is relatively modest.
- There is a mix of L2 and DCFC across market sectors.
- School bus sites are cheaper than non-school bus sites

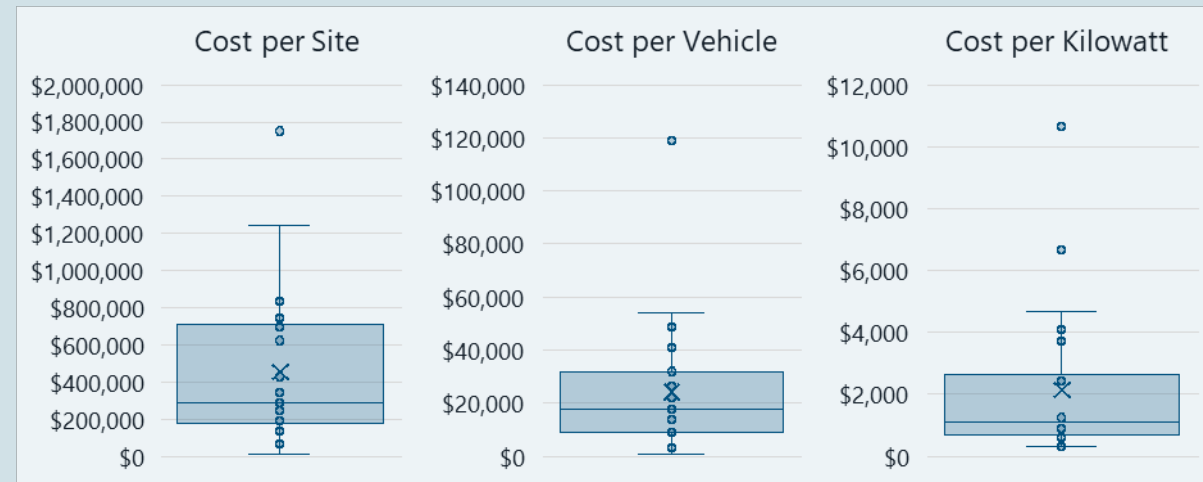
PG&E EV Fleet (75 sites)



SCE Charge Ready Transport (55 sites)



SDG&E Power Your Drive for Fleets (23 sites)



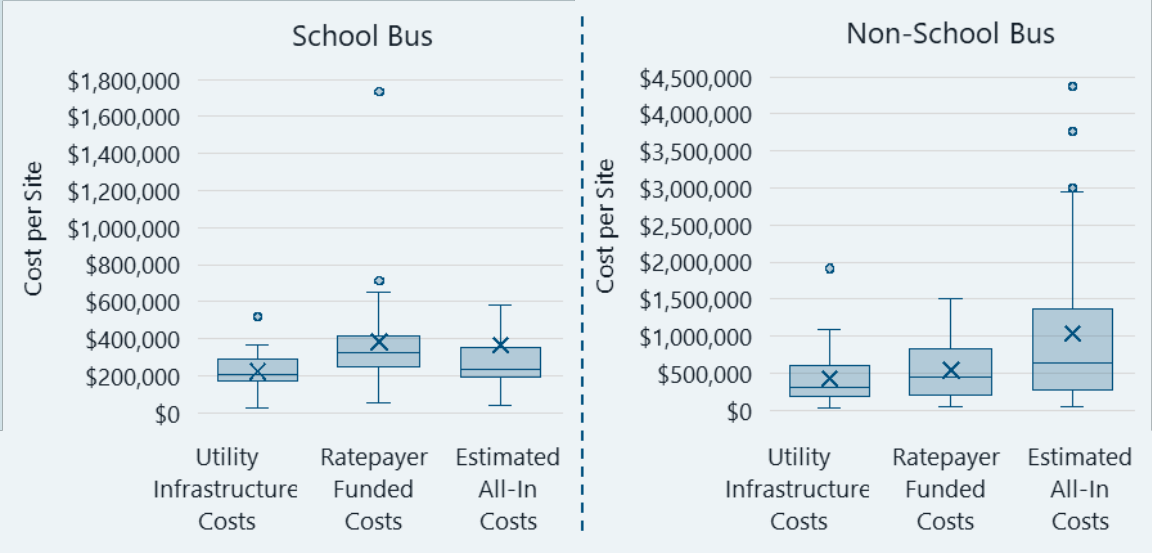
MDHD | Costs Per Site

Costs Organized by Three Perspectives Across Closed-Out PTD Sites

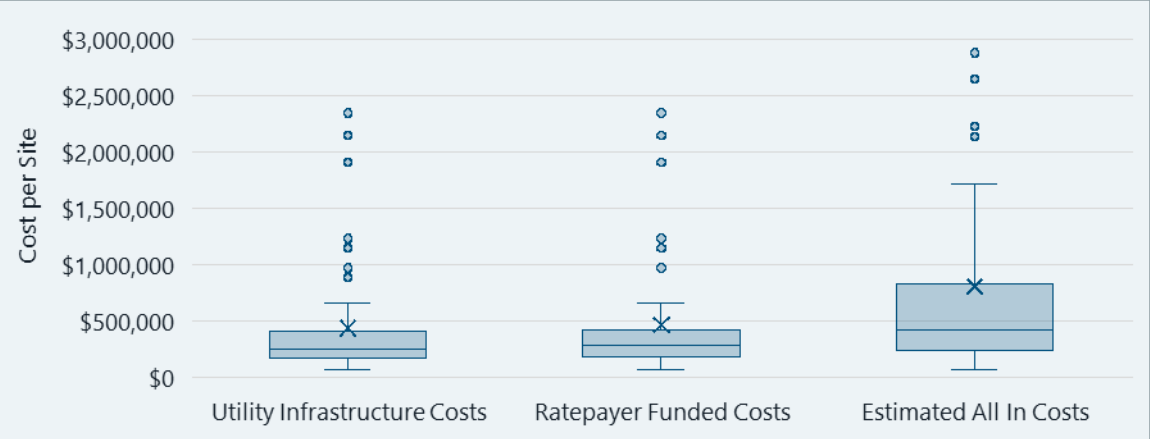
Distribution of site-level costs for all sites

- **Utility Infrastructure Costs.** Actual site costs paid by the Utility for TTM and BTM infrastructure/rebates, including capital and labor costs.
- **Ratepayer-Funded Costs.** Actual site costs paid for by the Utility for TTM, BTM (or BTM incentive if infrastructure is customer owned), and EVSE rebates.
- **Estimated All-in Costs.** Estimated costs of installing the site borne by the Utility and the customer including capital and labor costs. The value is calculated by summing TTM, BTM, and EVSE costs.

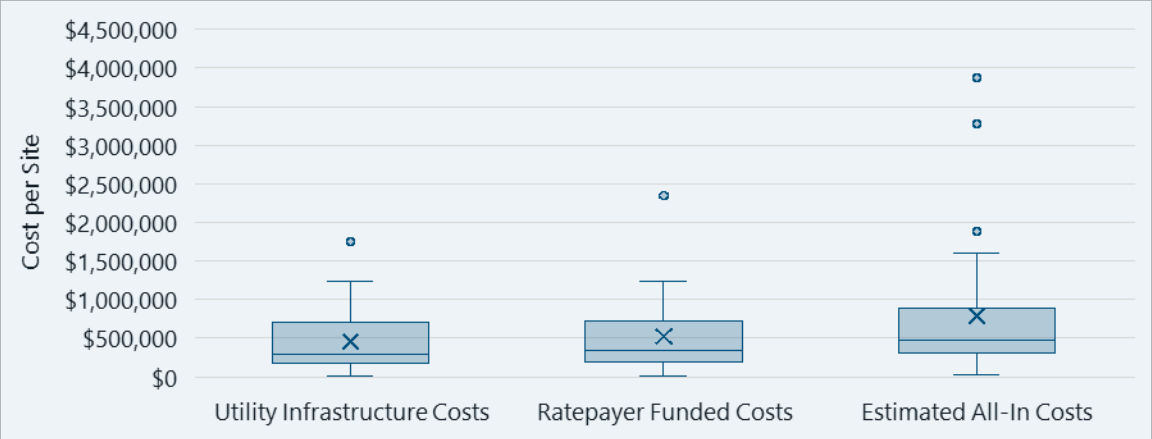
PG&E EV Fleet (75 sites)



SCE Charge Ready Transport (55 sites)



SDG&E Power Your Drive for Fleets (23 sites)

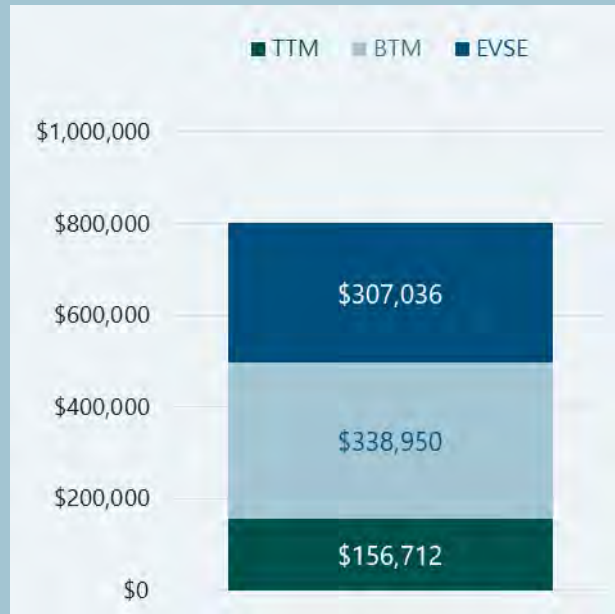


MDHD | Average Estimated All-In Costs across Closed-Out PTD Sites

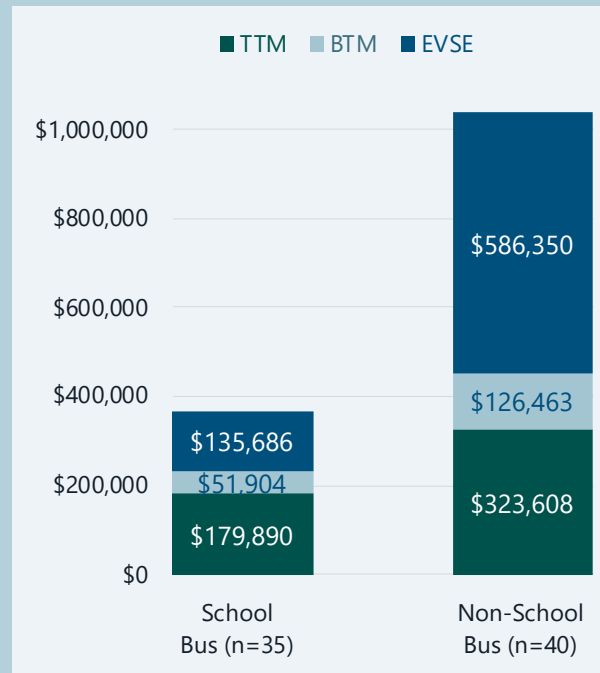
These figures show the distribution of site-level costs for the all sites.

- **EVSE is the largest estimated cost** for PG&E non-school bus and SDG&E sites
- **BTM is the largest estimated cost** across SCE sites, followed closely by estimated EVSE, then TTM

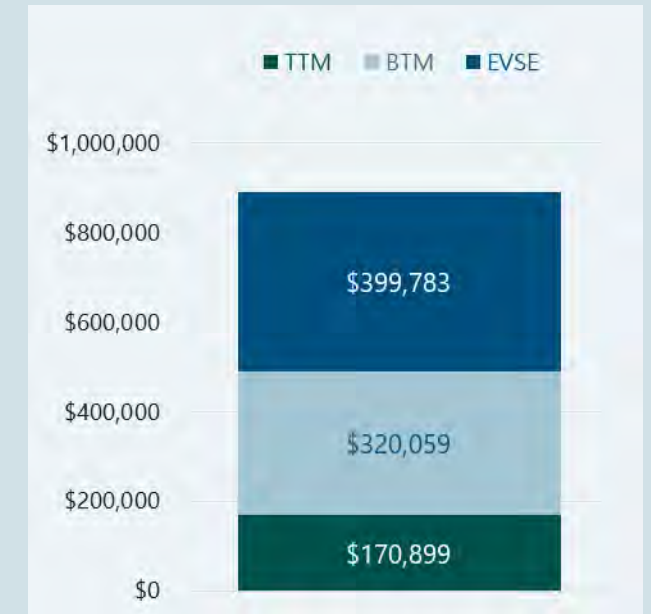
SCE Charge Ready Transport (55 sites)



PG&E EV Fleet (75 sites)



SDG&E Power Your Drive For Fleets (23 sites)



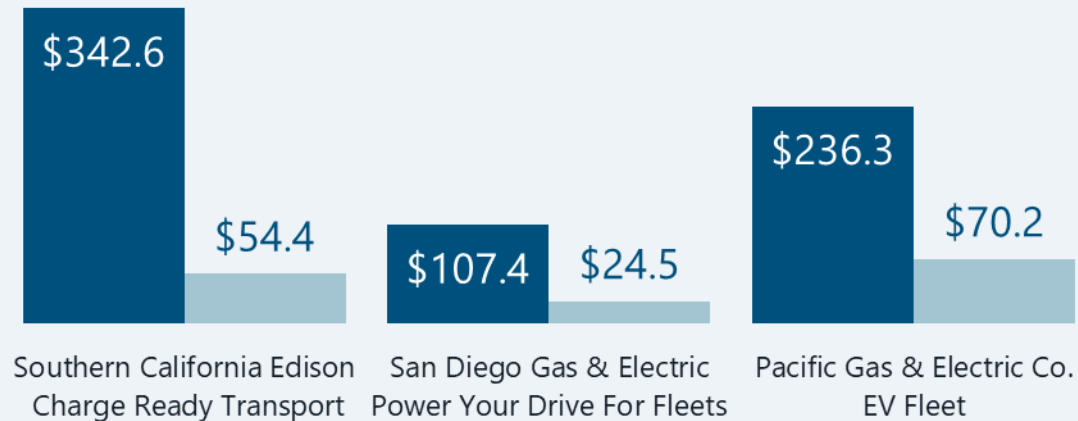


MDHD | Lessons Learned

PG&E reported that outside of the dedicated budget to the transit bus market sector, the EV Fleet program expects to be fully subscribed by the end of 2025.

Total Spending (Millions)

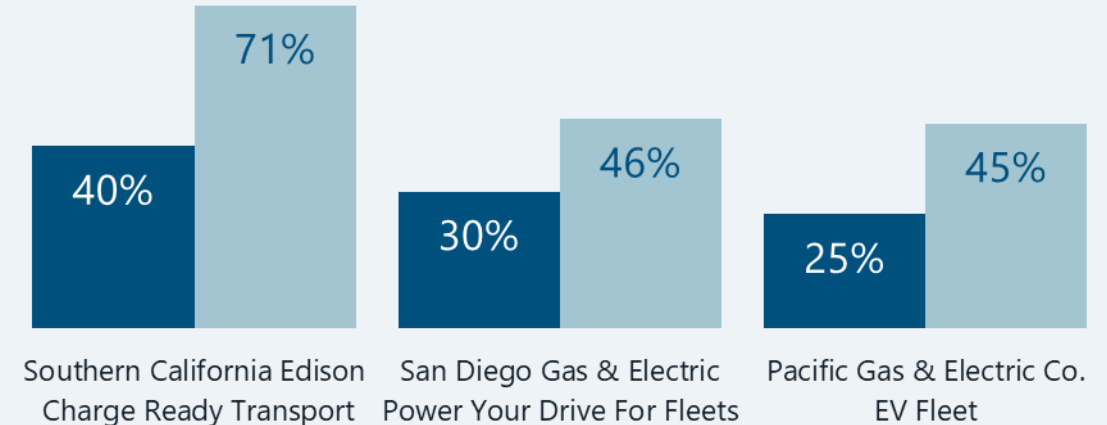
■ Target ■ Program to Date



Utility spending in disadvantaged communities exceeds targets across all programs; however, overall spending in MDHD programs remains low, and only one of three Utilities is currently on pace to meet its site and vehicle goals.

Percentage Spending in Disadvantaged Communities

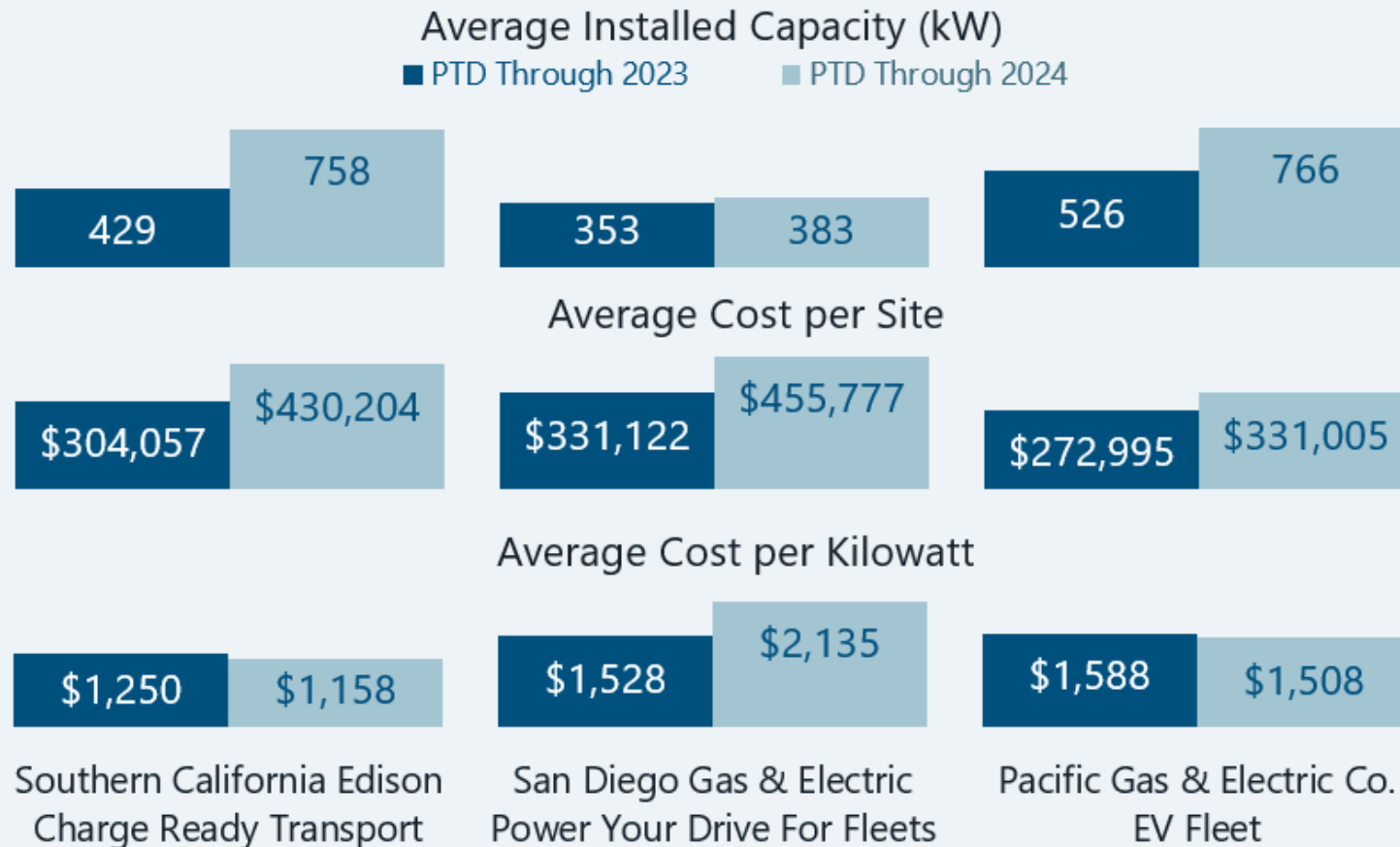
■ Target ■ Program to Date





MDHD | Lessons Learned

The average installed capacity per site for the three MDHD programs increased for PTD sites through 2024, resulting in an increase in the average cost per site and a decrease in the average cost per kilowatt.



There is a strong relationship between installed capacity and cost per kilowatt, with **larger sites in general having a lower cost per kilowatt than smaller sites.**

Based on additional EY2024 analysis of **weighted average** cost compared to **simple average** cost:

- When weighting by the installed capacity of sites, the weighted average cost is higher and the weighted average cost per kilowatt is lower



MDHD | Lessons Learned

Per Delphi panels conducted for EY2024, market share is projected to increase by 2035 to:

- **54%** for transit buses
- **52%** for electric transportation refrigeration units
- **48%** for delivery vehicles*

However, the panels forecasted that both transit bus and delivery vehicle market share will fall short of CARBs Innovative Clean Transit (ICT) and ACT sales requirements.

*Delivery vehicles are a subsector of Medium-Duty Vehicles

Transit Buses

- **Supply chain challenges around manufacturing and reliability** cited as reasons for not meeting requirements

Electric Transportation Refrigeration Units

Several major factors influenced panelists' projections of impacts to early adoption:

- Unclear status of California regulations and federal policy
- High capital costs
- Technology immaturity

Delivery Vehicles

- Forecasted to reach a lower market share than previously estimated and fall short of ACT sales requirements
- Uncertainty around **policy and funding** anticipated to slow adoption in near term
- Yet, improving economics expected to accelerate growth in 2030s, leading to **infrastructure** as primary constraint

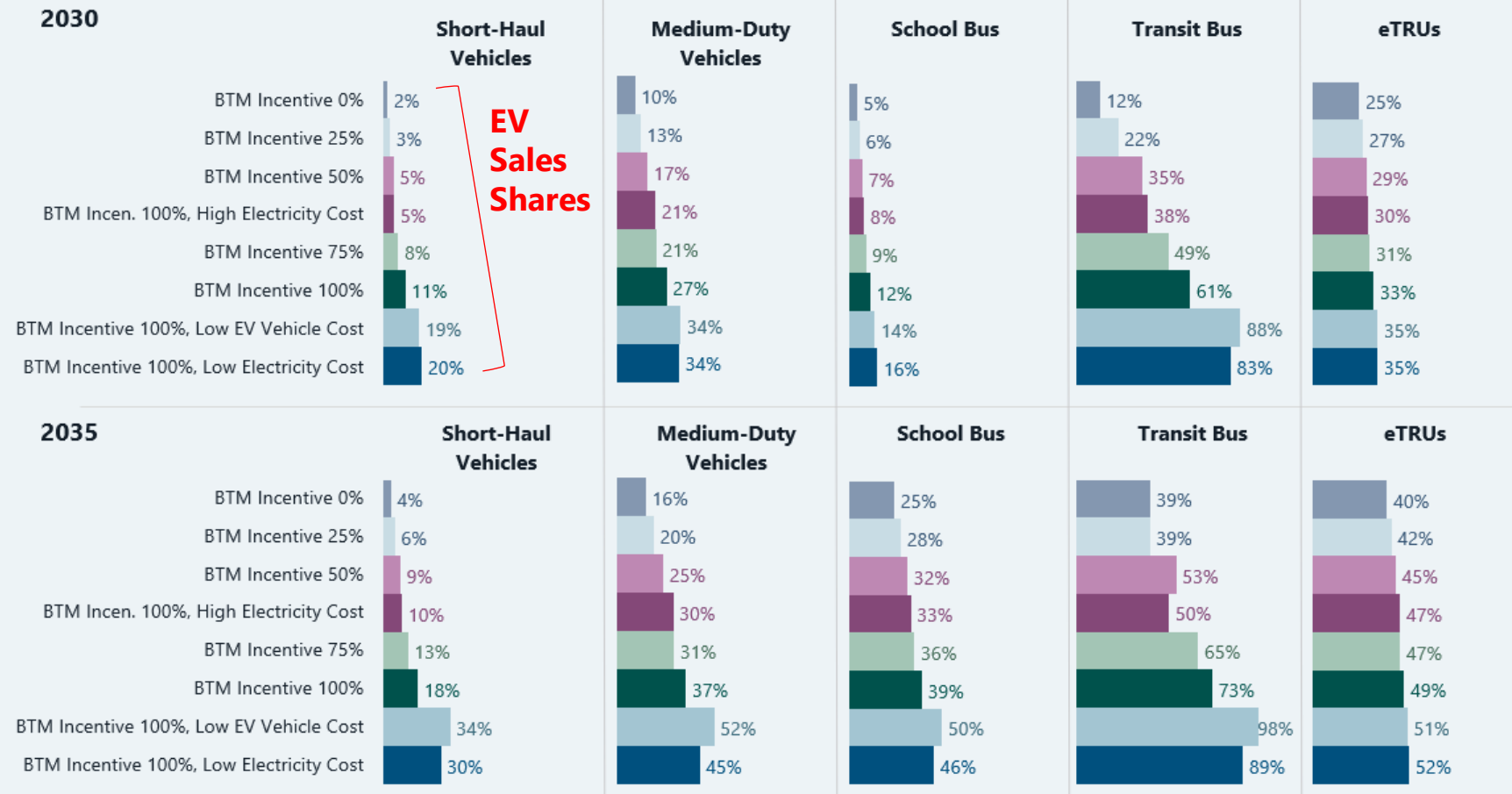
MDHD | Truck Choice Model

New EV Sales Share in Five Market Sectors Statewide

Highlights

Figure shows EV sales shares across scenarios of BTM incentive, electricity cost, and vehicle cost

- **100% BTM** leads to a **two to three times higher** share of EV sales compared with the no incentive scenario
- 2035 is higher across all scenarios because of assumed reductions in vehicle costs and in risk





Public Charging

Schools, Parks and Beaches,
and PG&E EV Fast Charge

Public Charging | Program Overview – Actuals and Targets (slide 1 of 2)

Liberty		PG&E		
Program Targets				
Schools	Parks and Beaches	Schools	Parks and Beaches	EV Fast Charge
<ul style="list-style-type: none">• 17 schools• 56 L2 and 2 DCFC ports	<ul style="list-style-type: none">• 3 sites• 5 dual-pedestal ports	<ul style="list-style-type: none">• 40% DAC• 22 K–12 schools• 4 or 6 L2 ports per location	<ul style="list-style-type: none">• 25% DAC• 15 state parks and beaches• 40 L2 and 3 DCFC ports	<ul style="list-style-type: none">• 25% DAC• 30 to 40 sites• 234 DCFC ports
Actual PTD				
<ul style="list-style-type: none">• 1 site• 8 ports	<ul style="list-style-type: none">• 0 sites• 0 ports	<ul style="list-style-type: none">• 12 sites• 72 L2 ports	<ul style="list-style-type: none">• 0 sites• 0 ports	<ul style="list-style-type: none">• 29 sites• 152 DCFC ports

Public Charging | Program Overview - Actuals and Targets (slide 2 of 2)

SCE		SDG&E	
Program Targets			
Schools	Parks and Beaches	Schools	Parks and Beaches
<ul style="list-style-type: none">• 40% DAC• 40 K-12 schools• 250 L2 ports	<ul style="list-style-type: none">• 25% DAC• 21 state parks and beaches• 120 L2, 10 DCFC, and 15 mobile ports	<ul style="list-style-type: none">• 40% DAC• 30 schools• 184 L2 and 12 DCFC ports	<ul style="list-style-type: none">• 50% DAC• 74 charging ports at 12 state parks and beaches• 66 ports at 10 city and county parks (100% DAC)
Actual PTD			
<ul style="list-style-type: none">• 22 sites• 172 L2 ports	<ul style="list-style-type: none">• 0 sites• 0 ports	<ul style="list-style-type: none">• 19 sites• 167 L2 and 7 DCFC ports	<ul style="list-style-type: none">• 11 sites• 82 L2 and 8 DCFC ports

Public Charging | 2024 Findings



Population of Activated Sites in EY2024 (#)

20



Ports Installed in Analyzed Sites (#)

145



Electric Energy Consumption (MWh)

3,826



Petroleum Displacement (diesel gallons equivalent)

259,628



GHG Emission Reduction (metric ton [MT] GHG)

2,222

GHGs include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) multiplied by their respective Global Warming Potentials (GWP) as defined by the Intergovernmental Panel on Climate Change (IPCC) published fifth assessment (AR5; see the Methodology section for more details).

Local Emissions	Reduction (kg)
Particulate Matter (PM ₁₀)	12
Particulate Matter (PM _{2.5})	11
Reactive Organic Gases (ROG)	263
Carbon Monoxide (CO)	5,691

Public Charging | 2024 Findings by Pilot/Program Type

 Population of Activated Sites in EY2024 (#)

Schools Pilot	7
Parks Pilot	2
EV Fast Charge	11

 Ports Installed in Analyzed Sites (#)

Schools Pilot	52
Parks Pilot	25
EV Fast Charge	68

 Electric Energy Consumption (MWh)

Schools Pilot	40
Parks Pilot	83
EV Fast Charge	3,703

 Petroleum Displacement (diesel gallons equivalent)

Schools Pilot	2,699
Parks Pilot	5,614
EV Fast Charge	251,315



GHG Emission Reduction (metric ton [MT] GHG)

Schools Pilot	24
Parks Pilot	49
EV Fast Charge	2,149

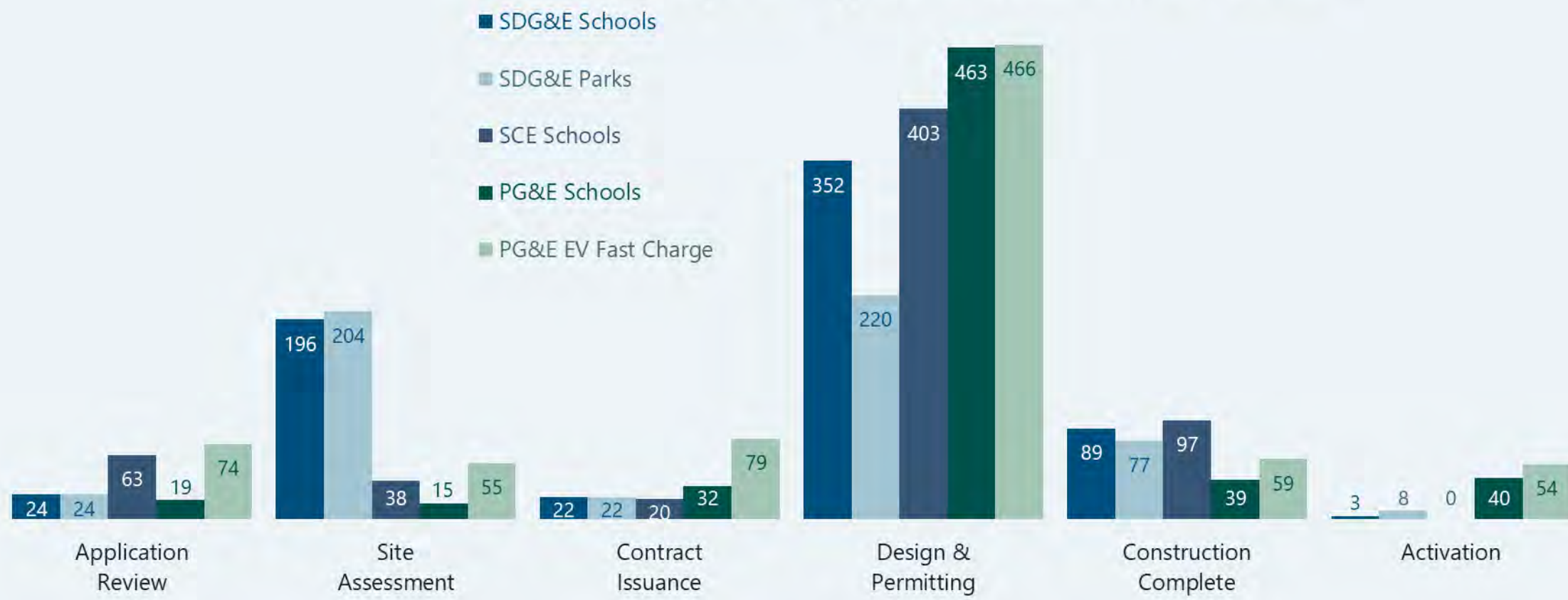
GHGs include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) multiplied by their respective Global Warming Potentials (GWP) as defined by the Intergovernmental Panel on Climate Change (IPCC) published fifth assessment (AR5; see the Methodology section for more details).

Local Emissions	Schools Pilot	Parks Pilot	EV Fast Charge
Particulate Matter (PM ₁₀)	0.1	0.3	11.6
Particulate Matter (PM _{2.5})	0.1	0.2	10.7
Reactive Organic Gases (ROG)	2	3	147
Carbon Monoxide (CO)	59	123	5,509

Public Charging | Site Timelines

Phase with longest duration across all programs is Design & Permitting

Median Calendar Days from Application to Activation for PTD Sites

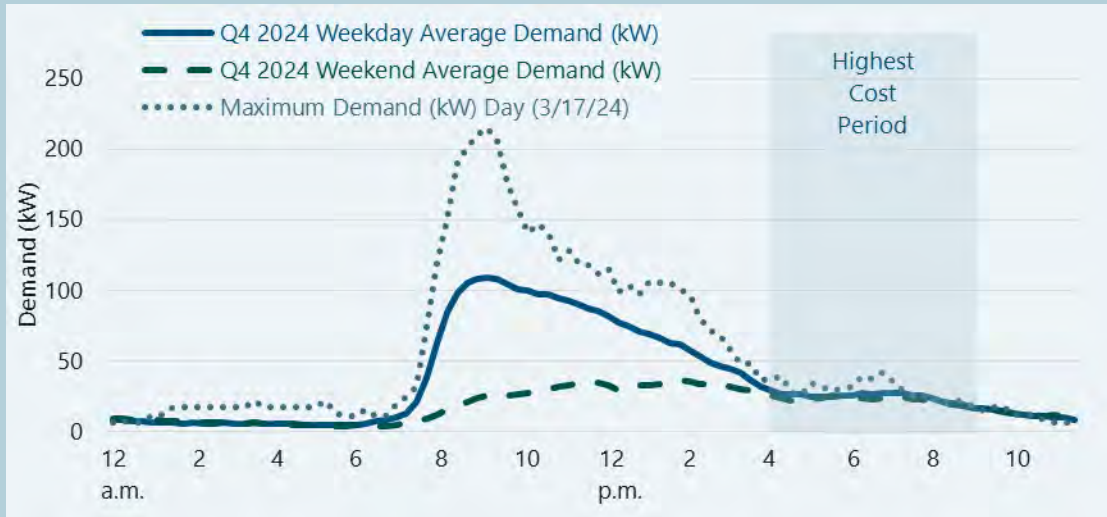


Public Charging | Average Demand

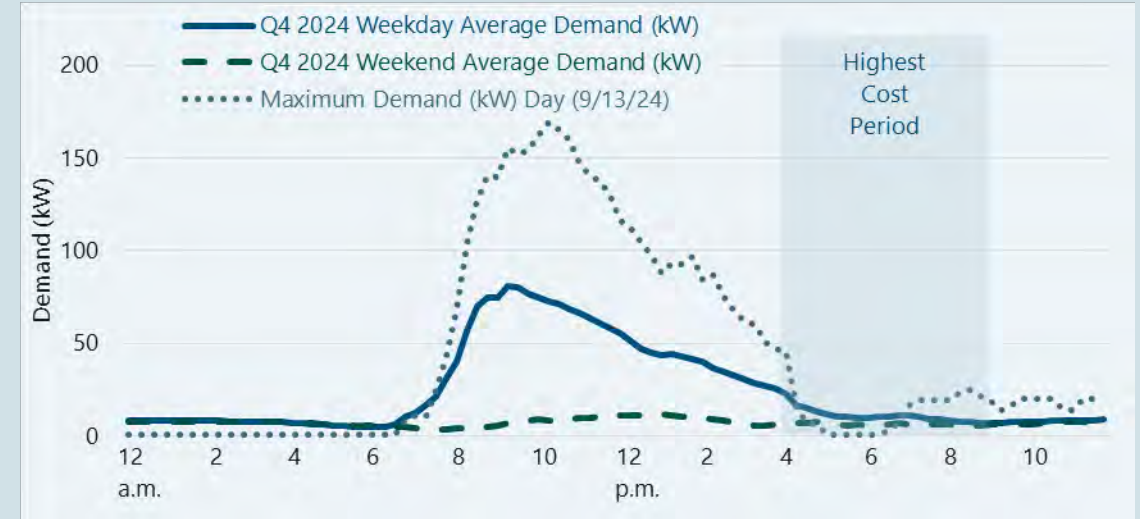
AB 1082 Schools

- **School district charging** is typical of workplace; ramping up quickly as EV drivers arrive to work and tapering off thereafter to end the business day.
- A few individual school sites show significantly higher weekend and overnight charging compared to the average **likely highlighting local communities benefiting** from these projects.
- **High Utilization** days exemplify what the portfolios could become as they continue to mature.

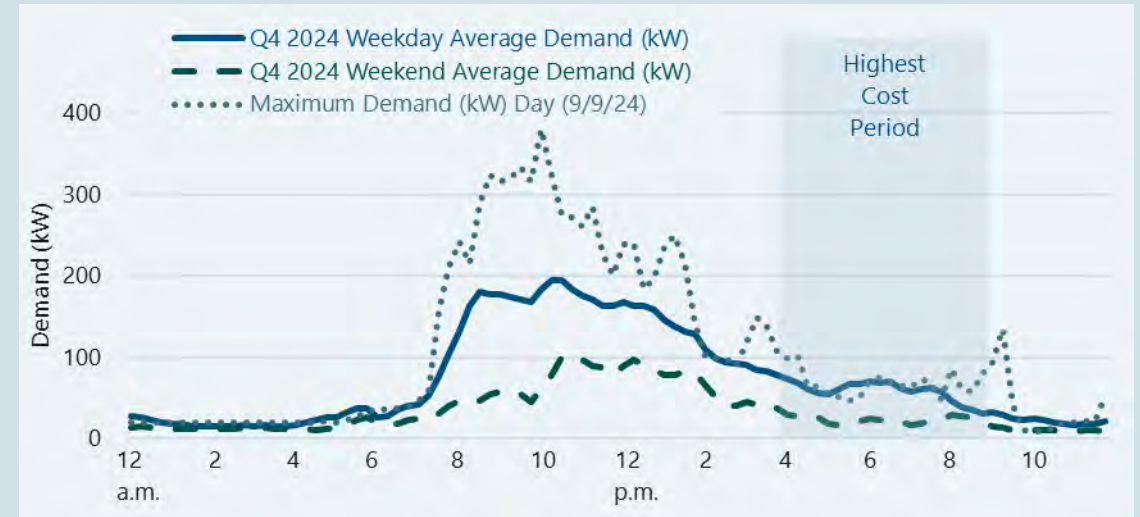
SCE Schools Pilot



PG&E Schools Pilot



SDG&E Schools Pilot

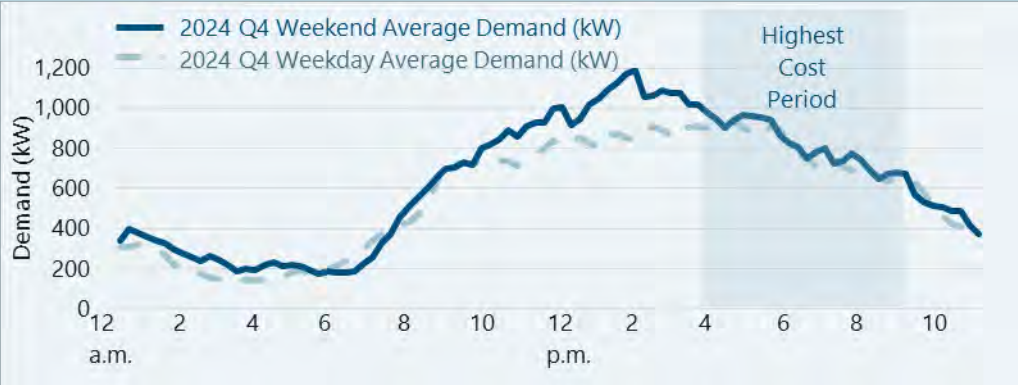
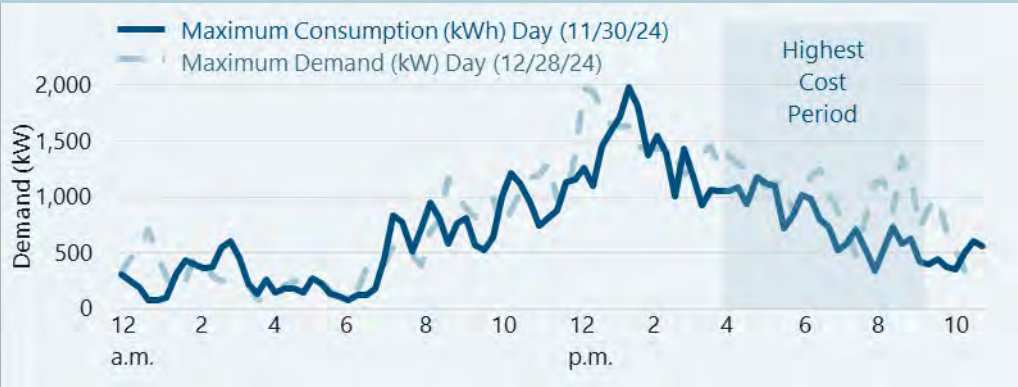


Public Charging | Energy Trends

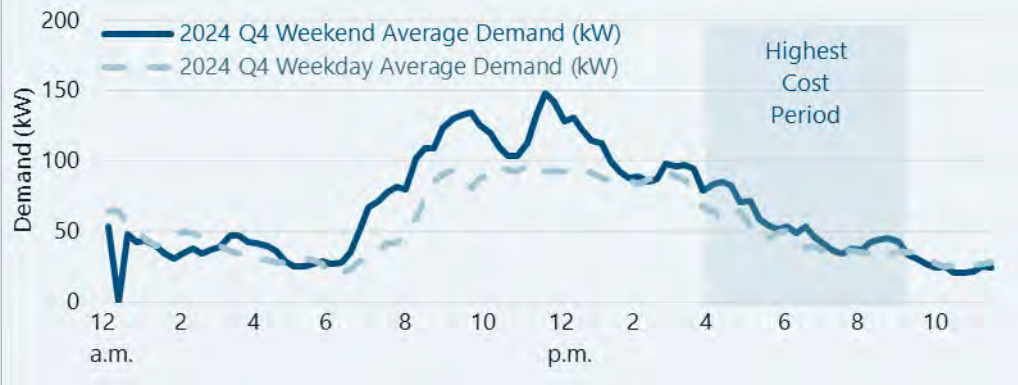
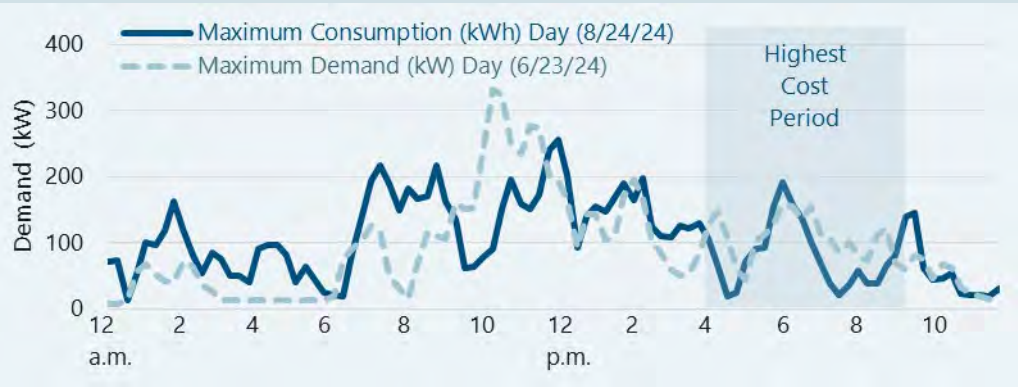
EV Fast Charge and AB1083 Parks

- **Public oriented sites** have higher demand and consumption on weekends than on weekdays.
- Overnight charging is not as heavily utilized but provides value to the community.

PG&E EV Fast Charge



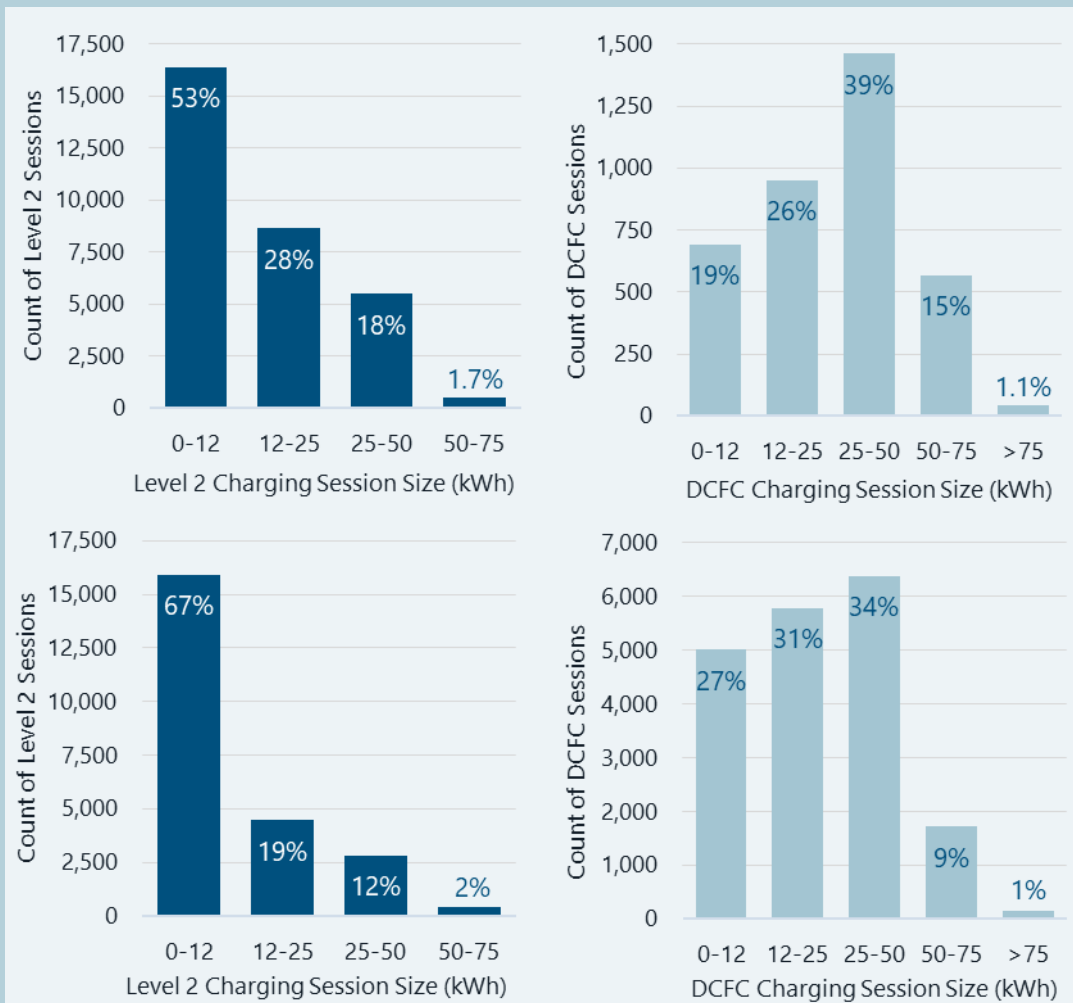
SDG&E Parks Pilot



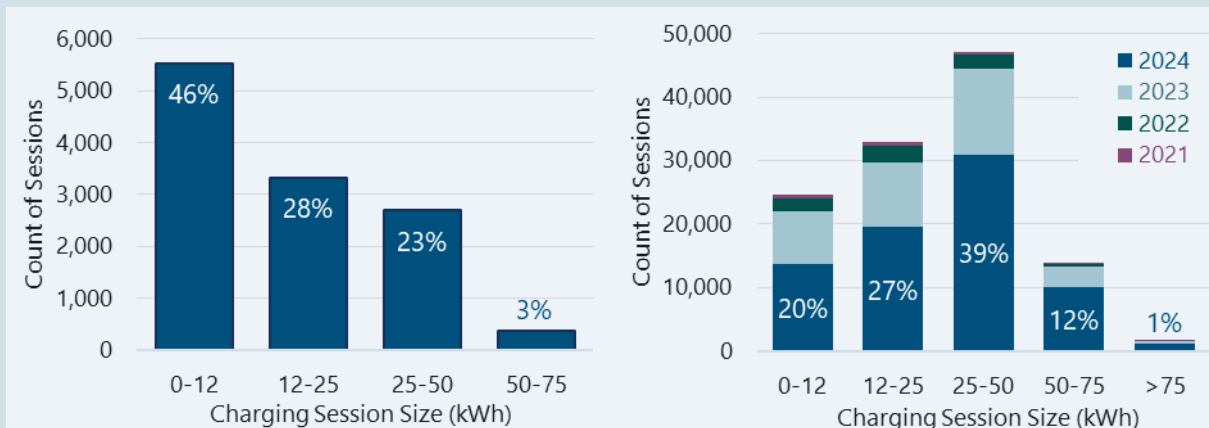
Public Charging | Charging Sessions

Charging Session Count by Consumption Size (kWh) for PTD Sites

SDG&E Schools Pilot (Top) and Parks Pilot (Bottom)

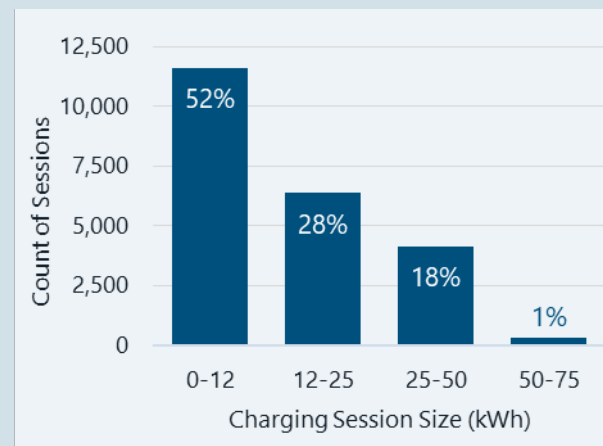


PG&E Schools Pilot (Left) and EV Fast Charge (Right)



- **Charging Session utilization** varies by charger type, with DCFC charging often consuming much more energy.
- **PG&E DCFC** program shows charging sessions have gotten larger, potentially related to availability of larger battery EVs.
- **Level 2 charging** is predominantly under 25 kWh.

SCE Schools Pilot



Public Charging | Site Maturation

- **Utilization and energy consumption** varies significantly by site over their lifetimes.
- Sites with higher overall utilization are also utilized more quickly, highlighting driver adoption of these sites.
- Utilization may reflect the level of EV adoption in the region or nearby charging sites with lower energy pricing.
- Commissioning delays seen at multiple sites (mostly a single NSP) of 6-15 months (considered months before Zero) are not depicted but had a material impact on utilization and benefits.

PG&E EV Fast Charge



SCE Schools Pilot



SDG&E Parks Pilot



- **Pricing** may influence the utilization rates of a given **public charging** site and the perception of driving an EV.
- Many public sites are not communicating Time-of-Use rates to EV drivers, but doing so could improve electricity emissions and benefits.
- Most public pricing is close to \$0.50/kWh and is less competitive with fuel-efficient gas cars.

Miles per Gallon	Cost per Gallon		
	\$4	\$5	\$6
	Cost per mile		
50	\$0.08	\$0.10	\$0.12
25	\$0.16	\$0.20	\$0.25

3 Miles per kWh	Cost per kWh		
	\$0.25	\$0.50	\$0.75
	Cost per mile		
	\$0.083	\$0.167	\$0.25

Public Charging | Retail Pricing to EV Drivers

SCE Schools

TOU rates (10 sites)

- Costs ranged from \$0.12/kWh to \$0.75/kWh.
- On-Peak compared to Super-Off-Peak ranged from 125% to 330% higher (\$0.05 to \$0.35/kWh higher).

Flat rates (11 sites)

- Costs ranged from \$0.30/kWh to \$0.53/kWh.
- Idle fees ranged from \$3/hour to \$20/hour to encourage people to vacate charging stations.

PG&E Schools

12 sites

- One had free charging for a period.
- One charged \$0.60/kWh with \$0.50/hour idle fees.
- Three used **TOU rates**.

25 sites

- 75% use flat rates with idle fees from \$2 to \$60/hour. Six sites also charge \$1/session.
- Sites using **TOU rates** increased On-Peak pricing by 10% to 200%.
- Pricing is typically \$0.42/kWh to \$0.69/kWh, with some as low as \$0.25/kWh.

PG&E EVFC

SDG&E Parks and Schools

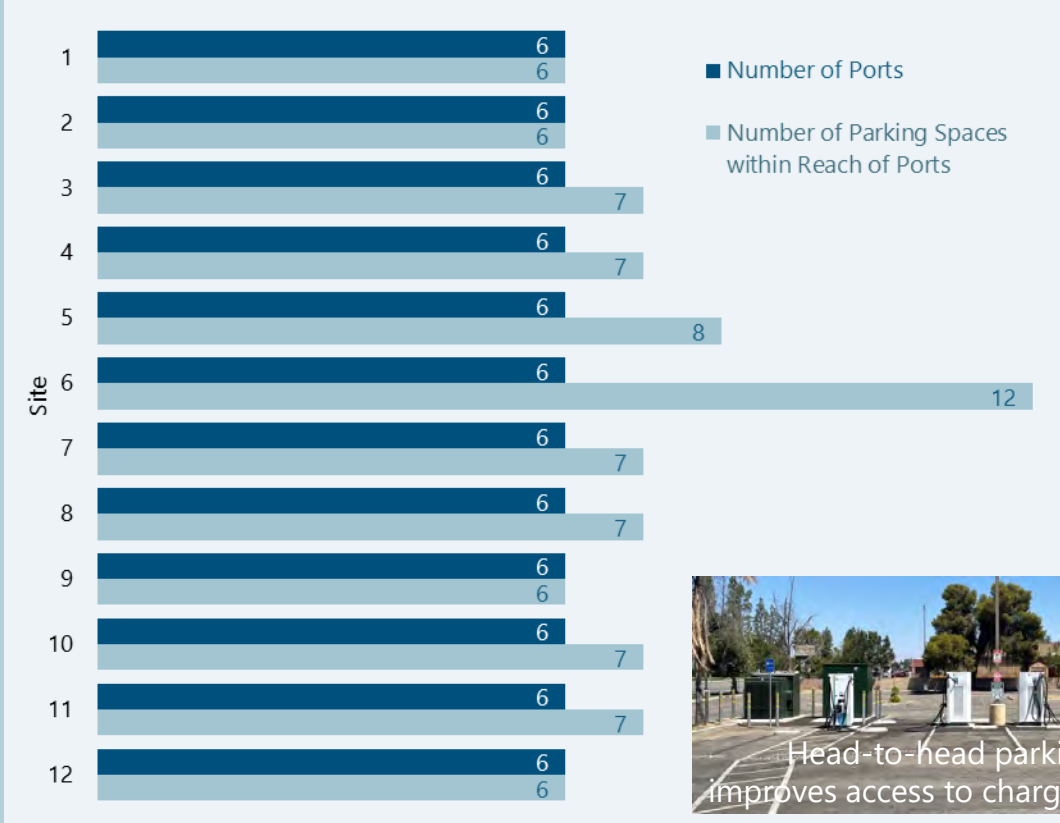
TOU rates (30 sites)

- \$0.25/kWh, \$0.50/kWh, and \$0.75/kWh per time period.
- An increase of 200% and 300% compared to Super-Off-Peak.

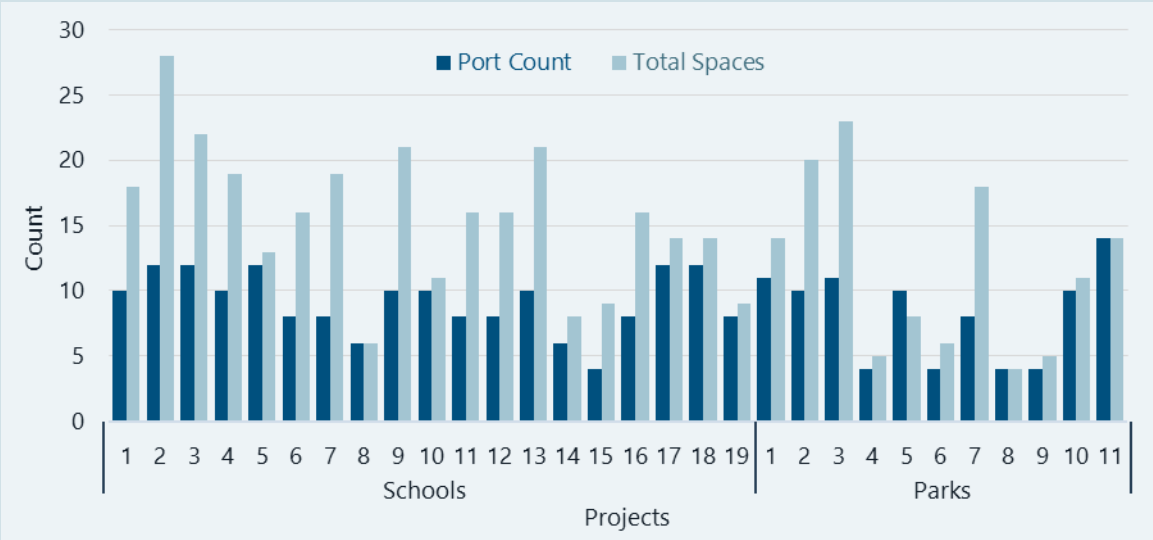
Public Charging | Parking Layout Trends

Some sites have higher access in terms of parking spaces per port. Though not a design goal, this facilitates turnover of charging ports in congested parking lots and increases resiliency in the event that a charging station is out of order or inaccessible.

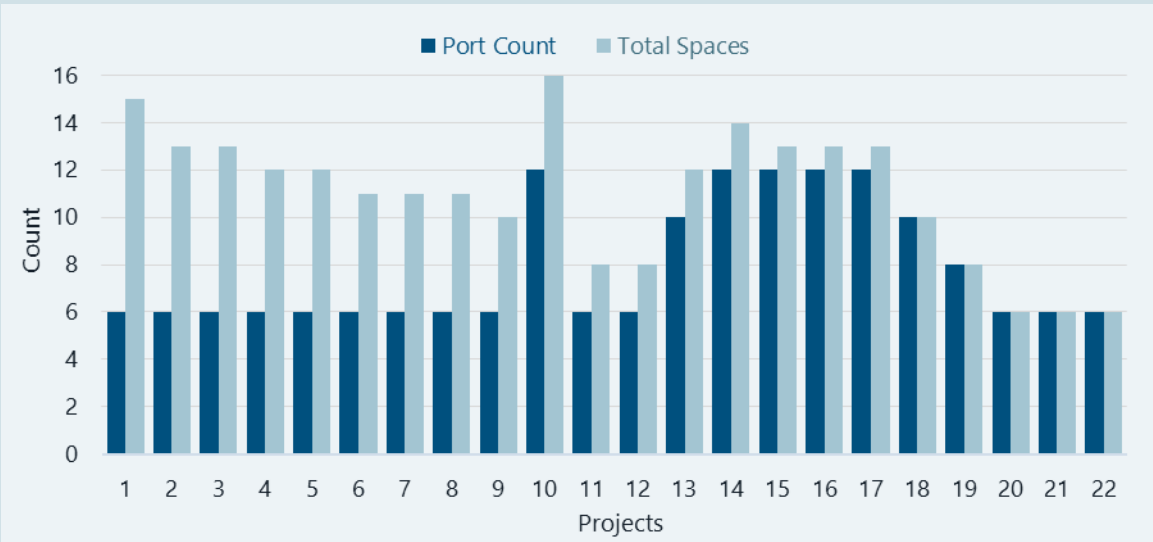
PG&E Schools Pilot



SDG&E Schools and Parks Pilots



SCE Schools Pilot

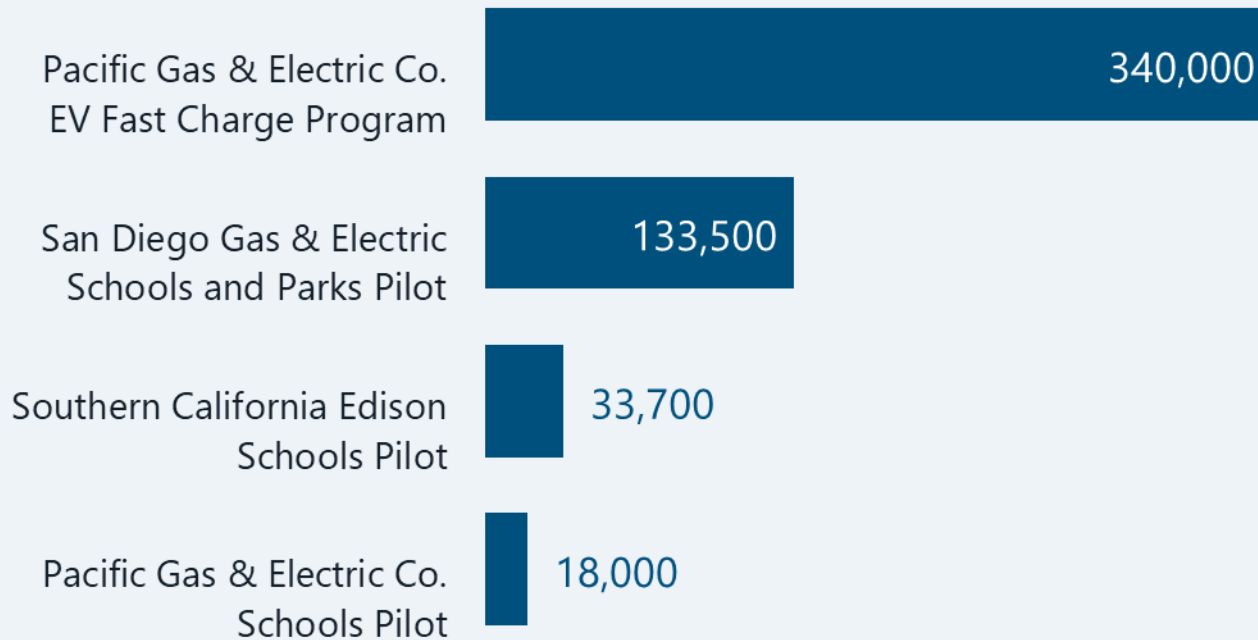
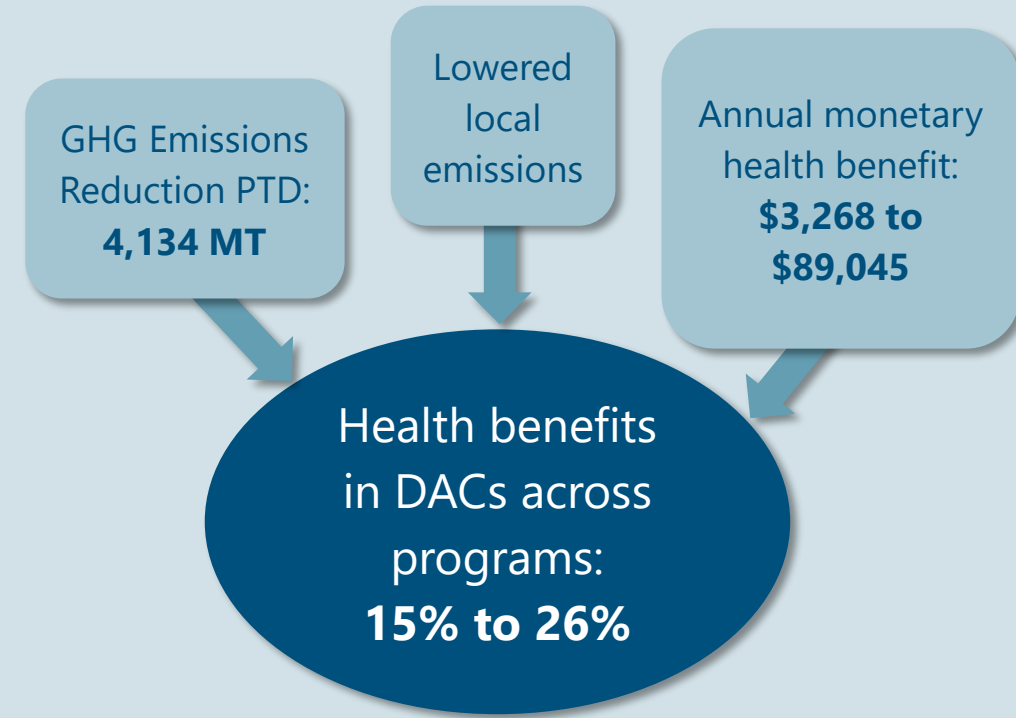




Public Charging | Lessons Learned

The Schools and Parks Pilots sites and the EV Fast Charge program sites continue to displace petroleum, reduce GHG and local emissions, and achieve health impacts overall and within disadvantaged communities.

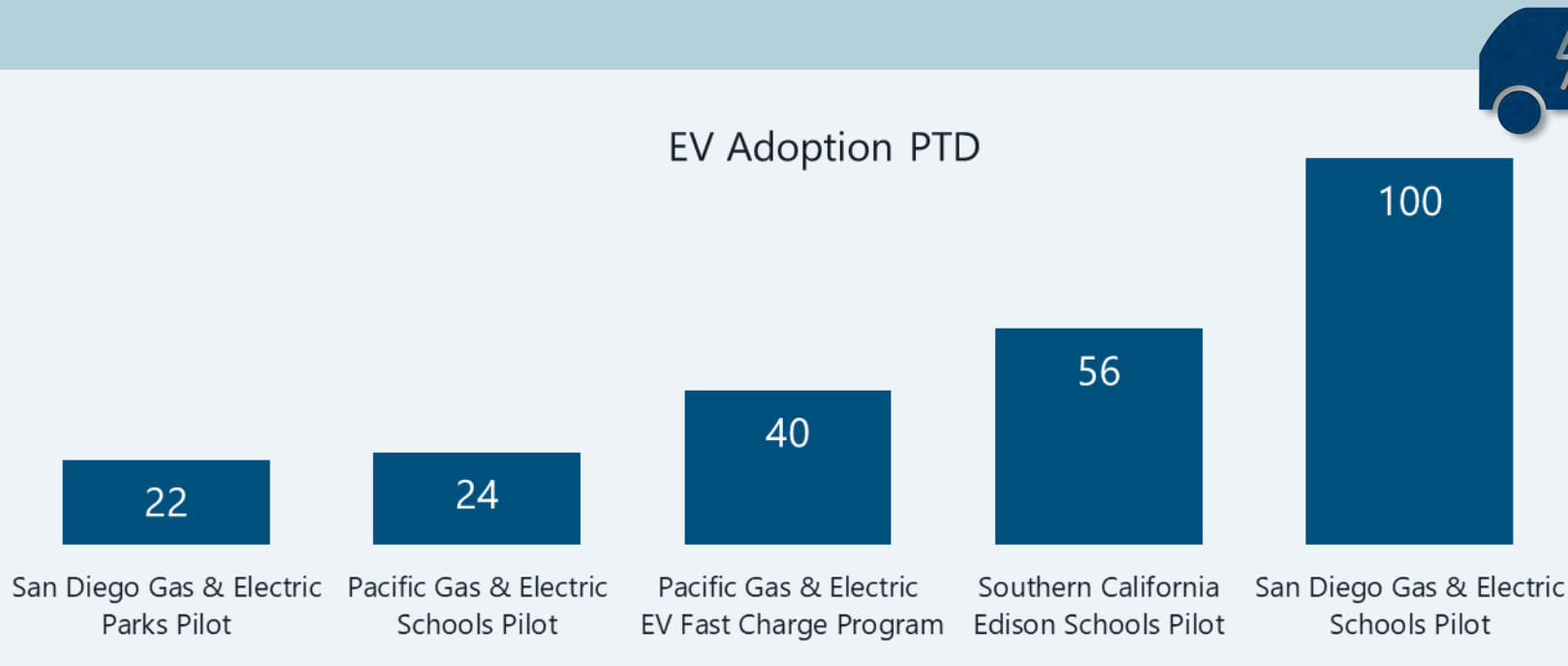
Pilot-to-Date Displaced Petroleum (gallons)





Public Charging | Lessons Learned

The Schools and Parks Pilots' sites and the EV Fast Charge program sites continue to modestly promote EV adoption in surrounding neighborhoods.



The pilots and program contribute to EV adoption in households neighboring the charging infrastructure.

To date the Utility investments have had an economically meaningful impact on EV adoption, contributing to adoption of nearly 250 EVs collectively.



Any questions?

Thank You

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MDHD | Time-of-Use Rates

Hourly TOU Electricity Rates and Average Carbon Intensity

TOU On-Peak Energy Costs

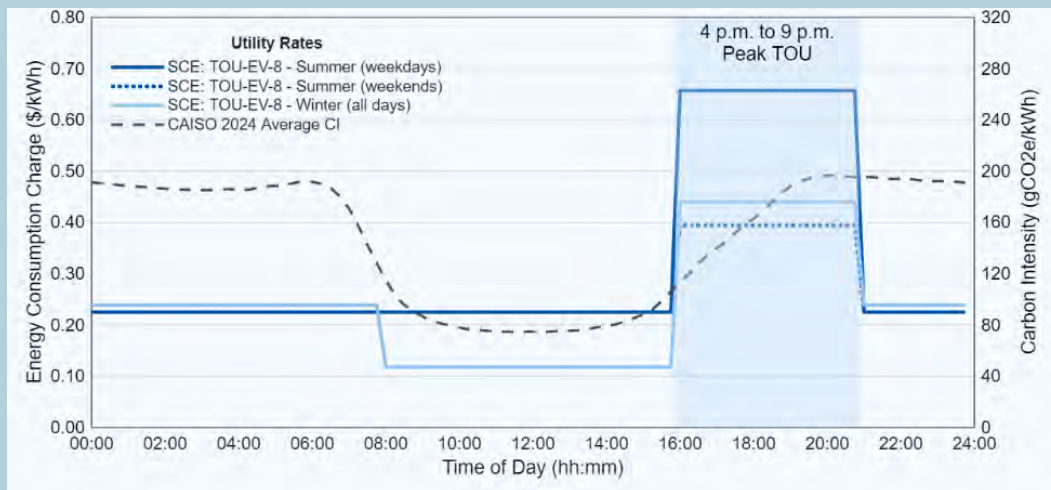
- SCE: \$0.11/kWh–\$0.66/kWh (depending on time of year and day)
- PG&E: ~\$0.40/kWh
- SDG&E: ~\$0.25/kWh (depending on time of year)

TOU Off-Peak and Super-Off Peak Energy Costs

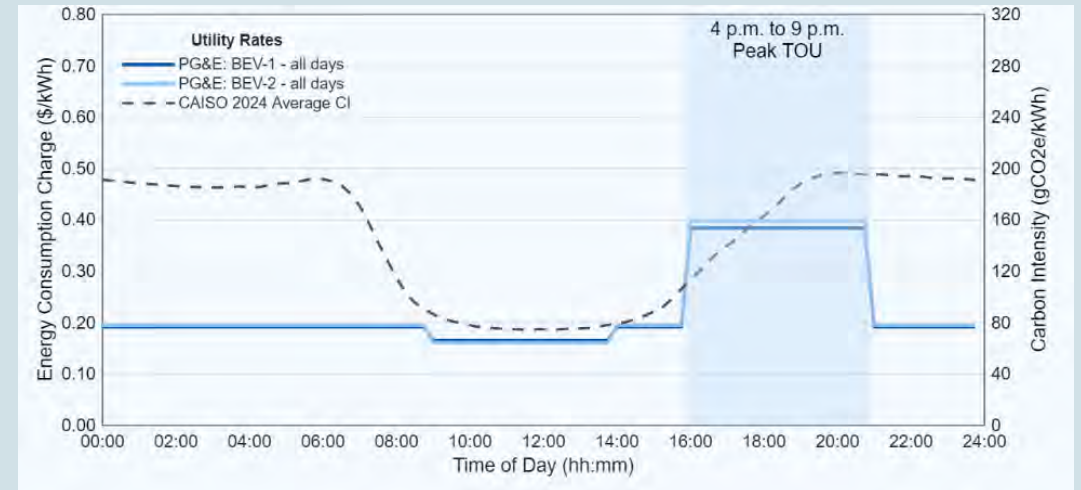
- PG&E: \$0.20/kWh
- SDG&E: \$0.12/kWh–\$0.13/kWh

In many cases, lower-cost TOU periods correlate with **lower carbon intensity of the grid**

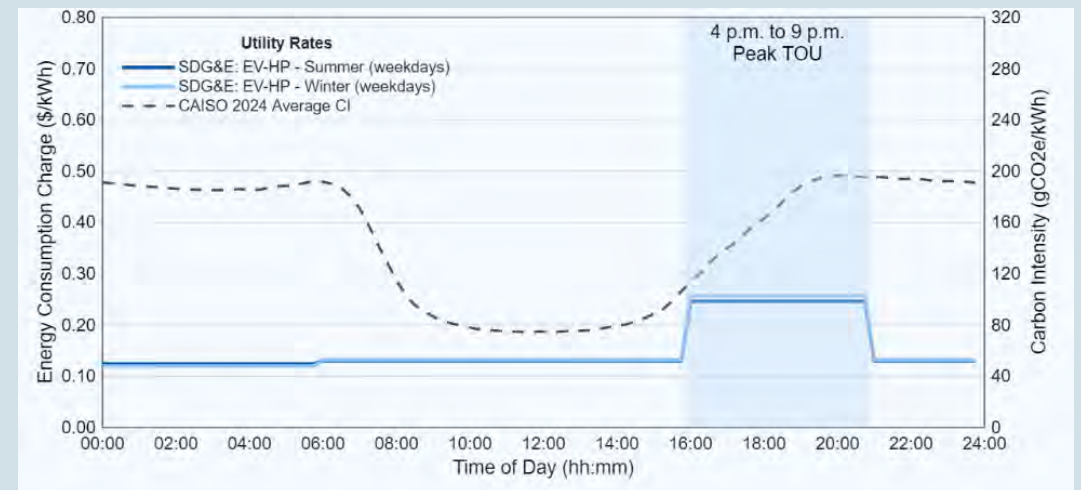
SCE Charge Ready Transport



PG&E EV Fleet



SDG&E Power Your Drive for Fleets



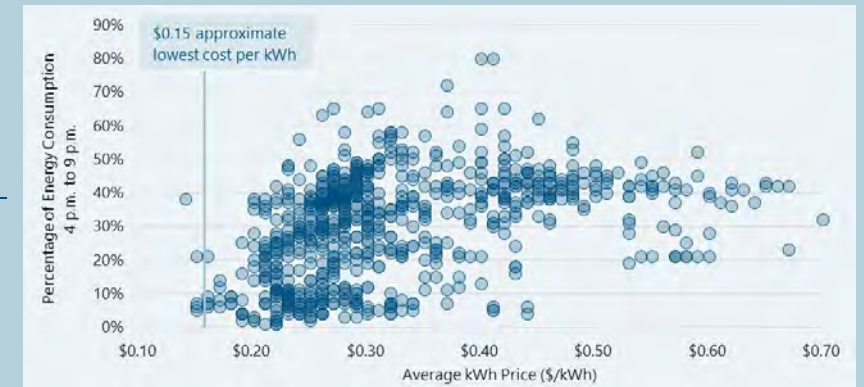
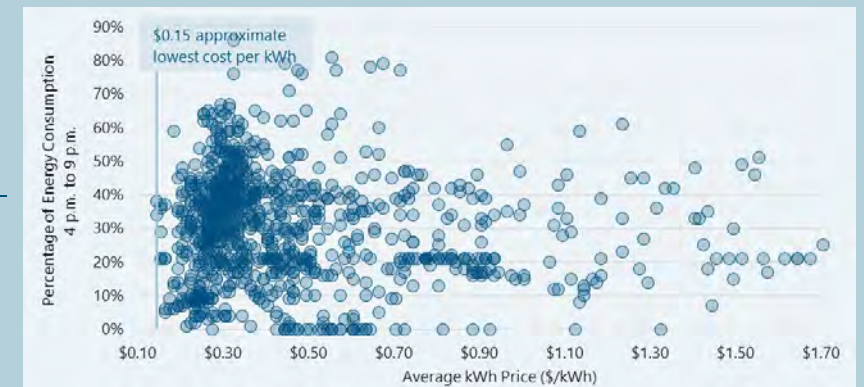
MDHD | Grid Impacts – Billing

These figures show PG&E EV Fleet percentage of monthly energy consumed from 4 p.m. to 9 p.m. versus the average energy price for consumption billing months for PTD sites.

High consumption billing months (>20 MWh) highlight the potential financial opportunity to use load management to reduce costs.

Medium consumption billing months (5 MWh to 20 MWh) show a higher proportion above \$0.40 than in the largest billing months.

Low consumption billing months (<5 MWh) show a correlation between average energy price and consumption from 4 p.m. to 9 p.m. Sites with the **lowest monthly energy consumption** often have less opportunity for the lowest costs but **can leverage load management to mitigate bills based on TOU periods**.



MDHD | Grid Impacts – Billing

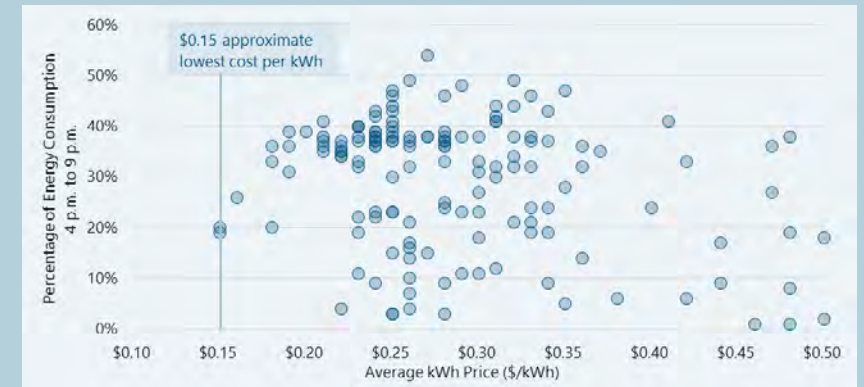
These figures show SDG&E Power Your Drive For Fleets percentage of monthly energy consumed from 4 p.m. to 9 p.m. versus the average energy price of consumption billing months for PTD sites.

SDG&E uses **capacity subscriptions**, billing demand using increments of 10 kW or 25 kW and including overage fees instead of a per-kilowatt fee.

High consumption billing months (>15 MWh) show a trend of higher average cost per kilowatt-hour accompany increased proportion of charging between 4 p.m. and 9 p.m.



Medium consumption billing months (5 MWh to 15 MWh) hovering around \$0.35/kWh. Fewer data points make correlating to 4 p.m. to 9 p.m. for challenging than other utilities.



Low consumption billing months (<5 MWh) often have less opportunity for the lowest costs but **can still influence their bills based on TOU periods (via load management)**.



MDHD | EY2024 Recommendations



Recommendation 1.1: To continue advancing MDHD electrification, the Evaluation Team recommends that the State of California **maintain and/or strengthen** the set of incentives currently offered for MDHD fleets.



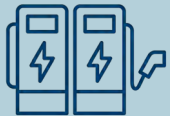
Recommendation 2.1: **Extend the existing programs in the absence of FC1-BTM support** if programs are not yet fully subscribed and funding remains by the scheduled program end date.



Recommendation 2.2: **Share committed spending for projects that are not yet fully closed out**, even if these are estimates, as Utility-reported spending is still relatively low compared to approved program budgets.



Recommendation 2.3: PG&E should undertake a similar process as SCE and SDG&E to **proactively track activated sites' progress toward fulfilling their VAPs** to ensure that program participants are meeting their obligations as a response to the EY2023 recommendation.



Recommendation 4.1: Consider **mandating that all new EVSE technology included in the approved product list be capable of performing basic load management services**, such as rules-based charging. Utilities should also consider **requiring all NSPs to offer load management capabilities** to allow fleet operators to implement more cost-effective charging behavior.



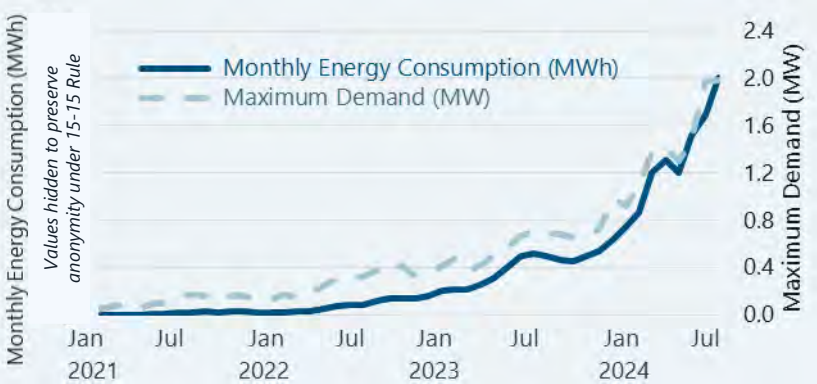
Recommendation 4.2: Be proactive about **holding annual technical assistance sessions with fleet managers who have charging flexibility and potential to achieve substantial energy savings**. These technical assistance sessions—ideally held in person—could help connect the fleet manager with the office that pays the electricity bills to give fleet managers a better understanding of the impacts of TOU rates on operational costs.

Public Charging | Energy Trends

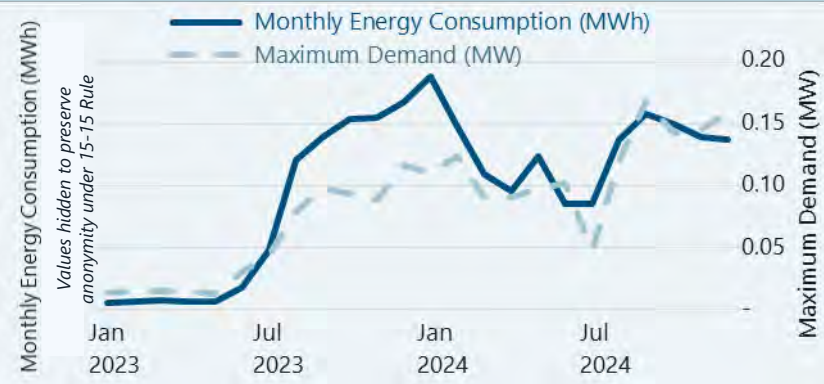
Monthly Energy Consumption and Maximum Demand

PG&E

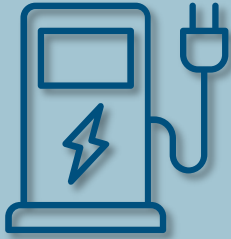
EV Fast Charge



Schools Pilot

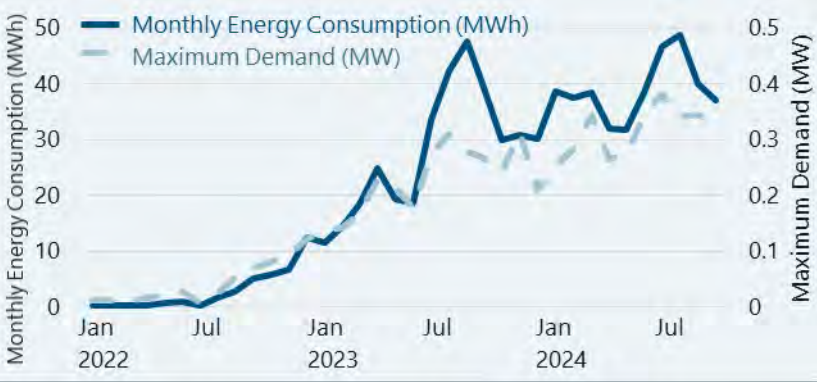


Monthly consumption and demand
continue to grow as sites are
completed and mature in utilization

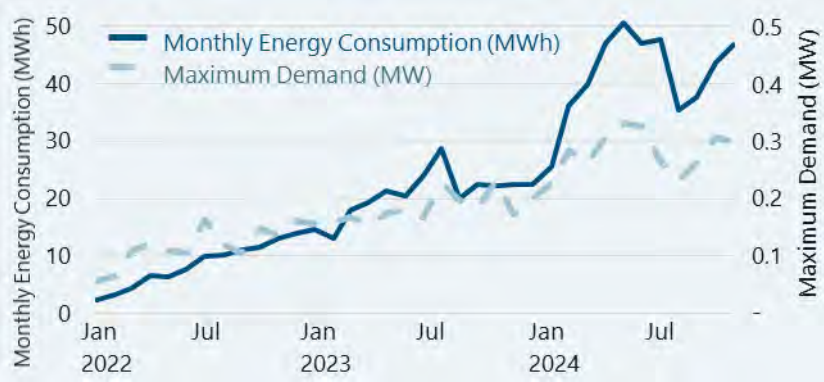


SDG&E

Schools Pilot

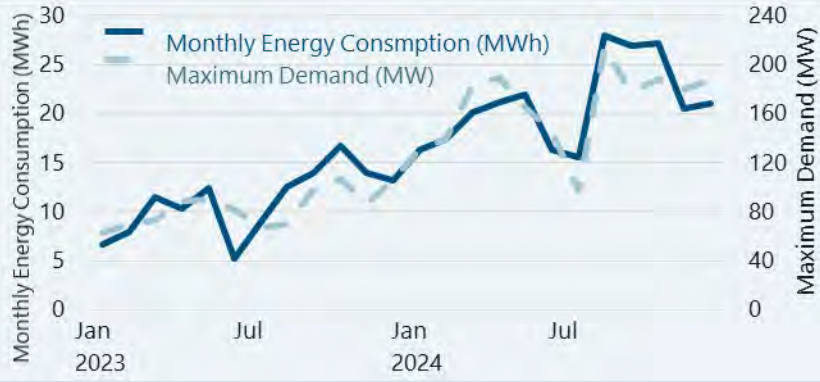


Parks Pilot



SCE

Schools Pilot





Public Charging | Lessons Learned

Although higher-than-expected site costs and delays continue to be a challenge for the Schools and Parks Pilots and the EV Fast Charge program, committed staff have worked diligently to mitigate these costs.

2024 Budgetary Reviews

- SCE program staff used actual site cost data to **improve forecasts** for all Standard Review Projects (SRP) programs.
- PG&E EV Fast Charge staff determined in 2023 through a budget exploration that about **five more sites could be built**, which were secured in 2024.
- In 2024, PG&E Schools Pilot staff continued to **identify several key strategies** as effective for keeping **school site costs low**:
 - Pre-desktop reviews
 - Regular reviews of actual costs
 - Open communication during construction

Staff have continued to adjust the program design and processes and to conduct ongoing budgetary reviews.

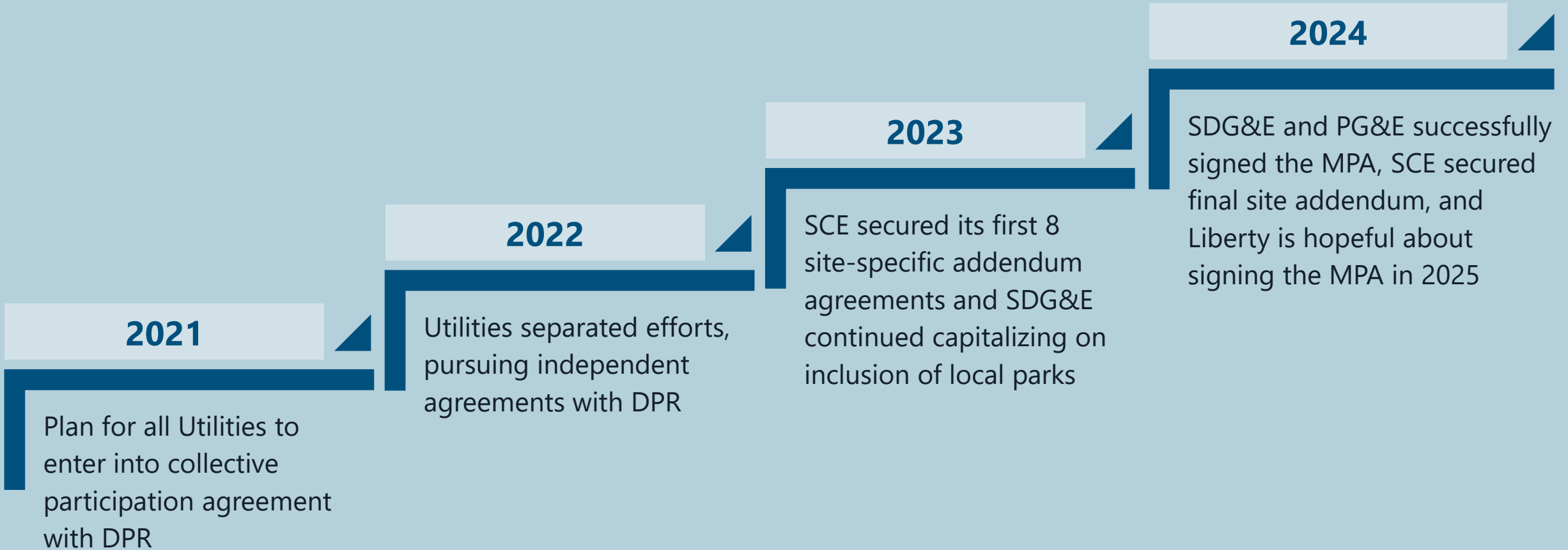
2024 Program Processes

SCE Schools Pilot staff focused on improving communication with the schools and EVSE providers as more schools transitioned to maintenance for their operational sites.



Public Charging | Lessons Learned

Although cross-jurisdiction coordination was a significant challenge in previous years, the deep commitment all Utility staff have maintained for the Parks Pilot is beginning to show positive results.



DOCKETED	
Docket Number:	21-IEPR-03
Project Title:	Electricity and Natural Gas Demand Forecast
TN #:	240934
Document Title:	Presentation - Transportation Energy Demand Forecast
Description:	**** THIS DOCUMENT SUPERSEDES TN 240755 **** - Presentation 3A. Aniss Bahreinian.V4
Filer:	Raquel Kravitz
Organization:	California Energy Commission
Submitter Role:	Commission Staff
Submission Date:	12/14/2021 3:21:38 PM
Docketed Date:	12/14/2021

Transportation Energy Demand Forecast

2021 IEPR Workshop on Electricity & Natural Gas Demand Forecast

December 2, 2021



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Transportation Energy Forecasting Unit

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Transportation Energy Demand Cases

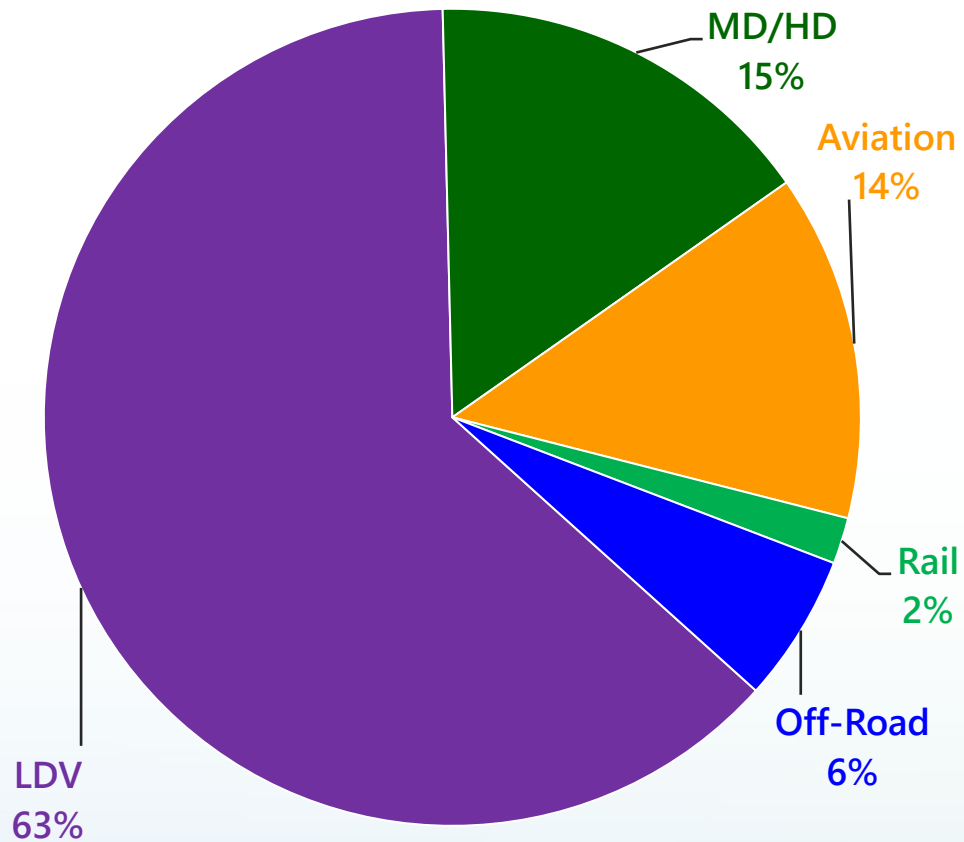
Demand cases represent different levels of transportation electricity demand

Demand Case	Population	Income	Petroleum Fuel Prices	Electricity, Natural Gas, and Hydrogen Prices
High Demand	High	High	High	Low
Mid	Mid	Mid	Mid	Mid
Low Demand	Low	Low	Low	High

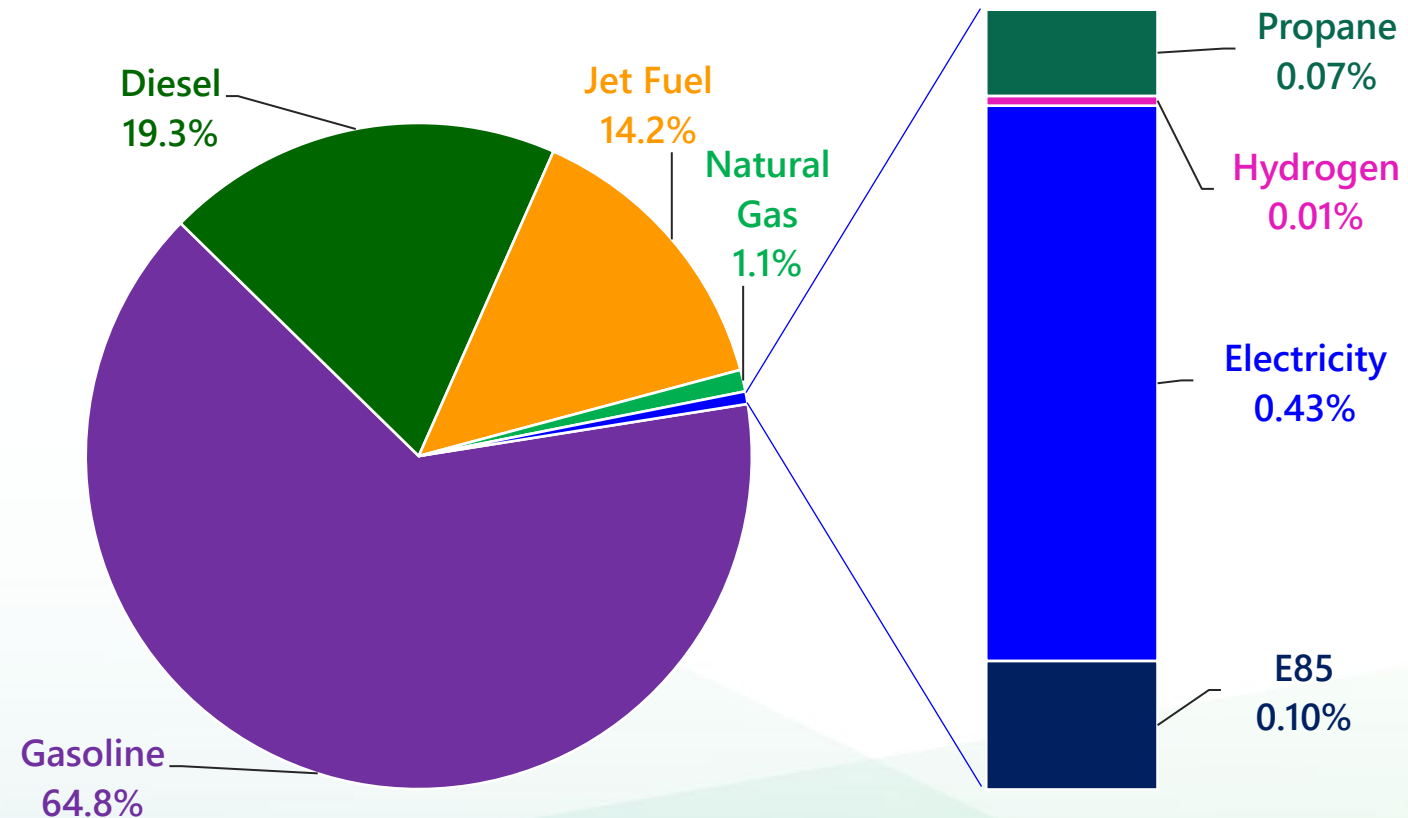


2020 Distribution of Transportation Energy (GGE) 65% Light-Duty Vehicles (LDV), 65% Gasoline

2020 Distribution by Sector



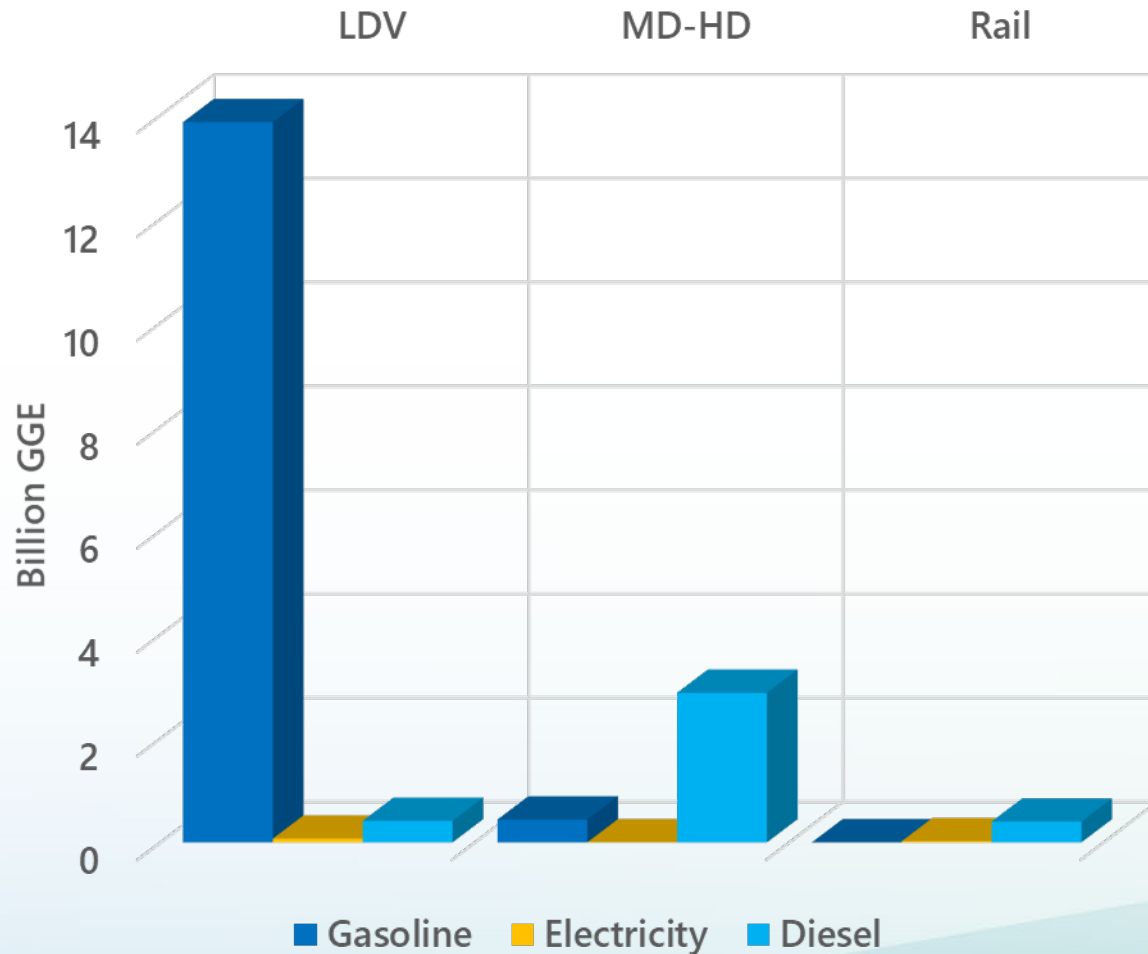
Distribution by Fuel Type



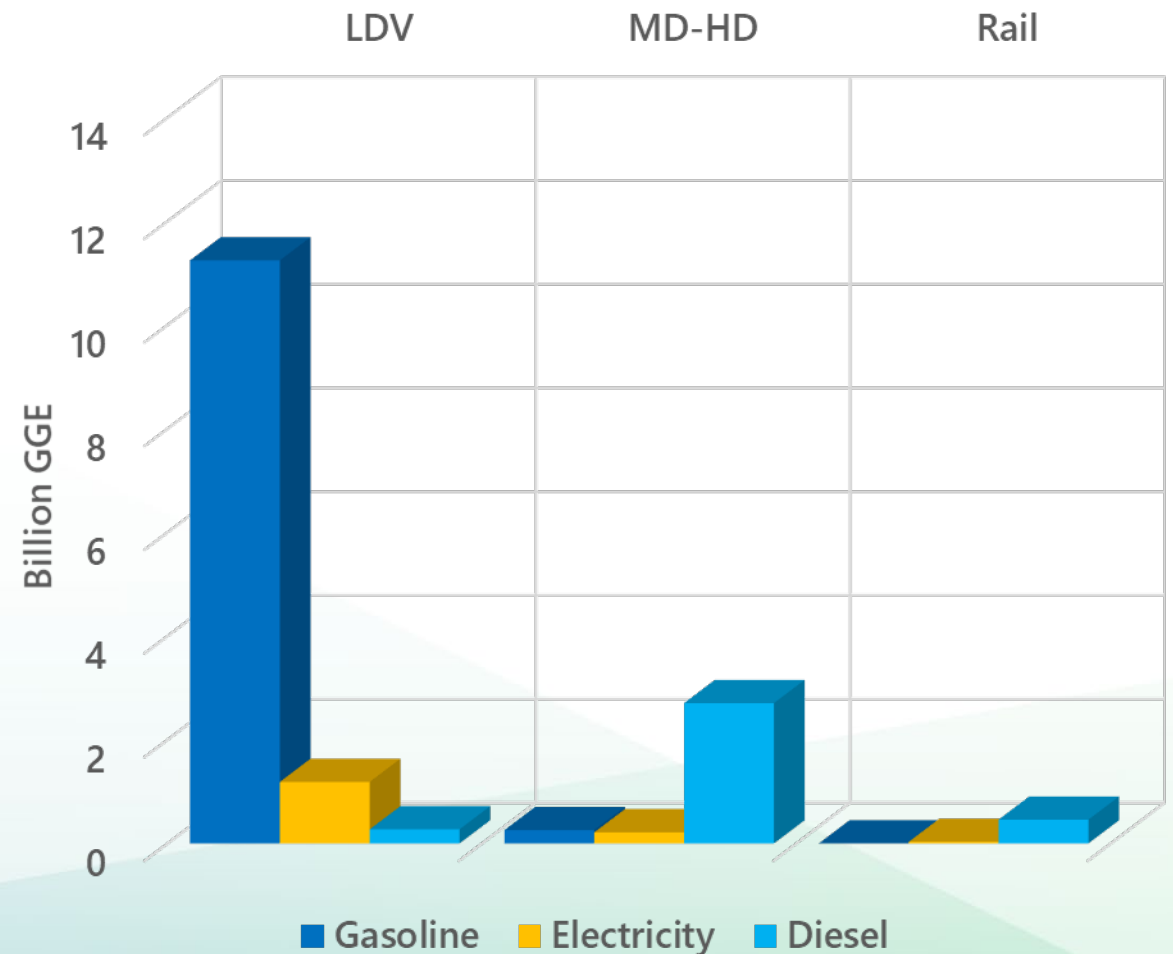


Diesel Dominates Medium- and Heavy-Duty (MD-HD) & Electricity Makes Inroads with Light-Duty Vehicles (LDV)

2020 Fuel Consumption, Billion Gasoline Gallon Equivalents



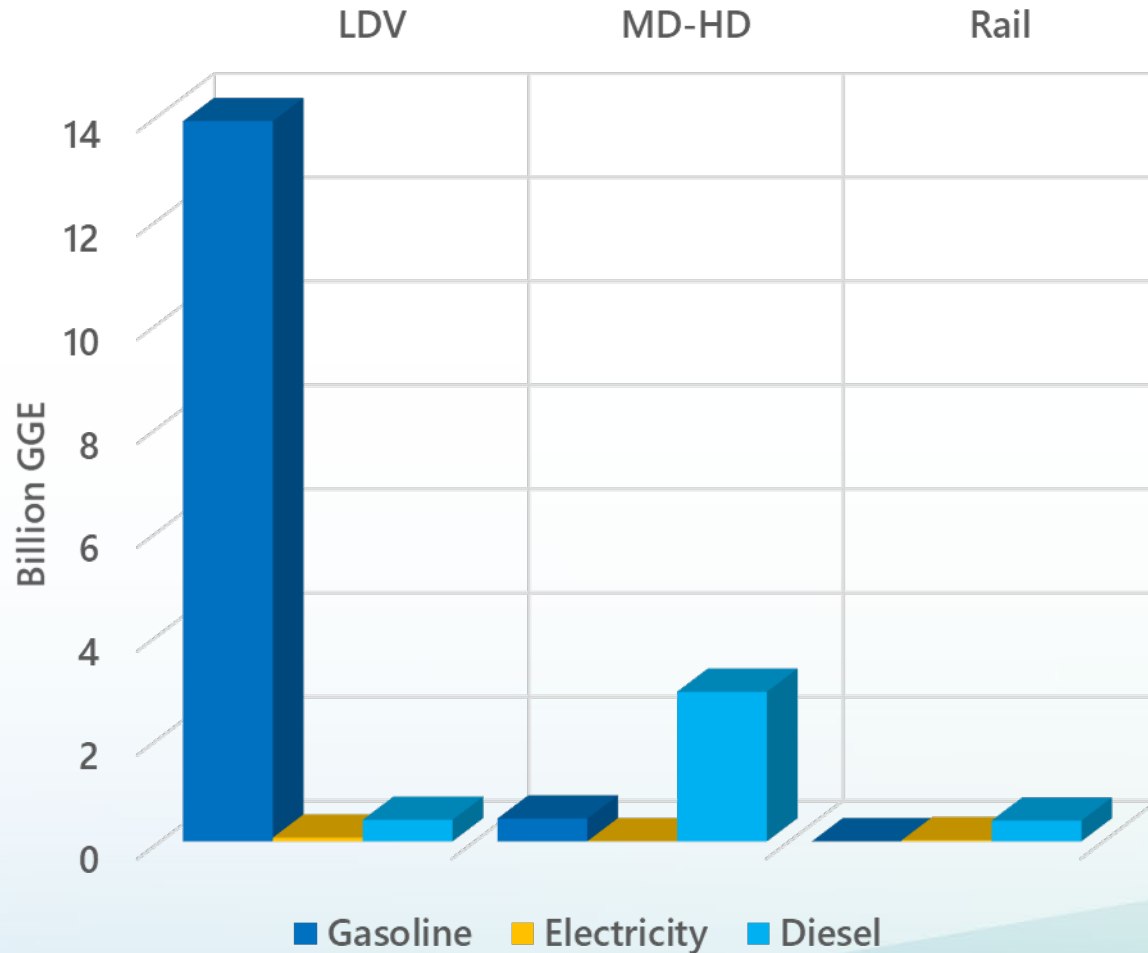
2035 Forecast High Case Fuel Consumption, Billion Gasoline Gallon Equivalents



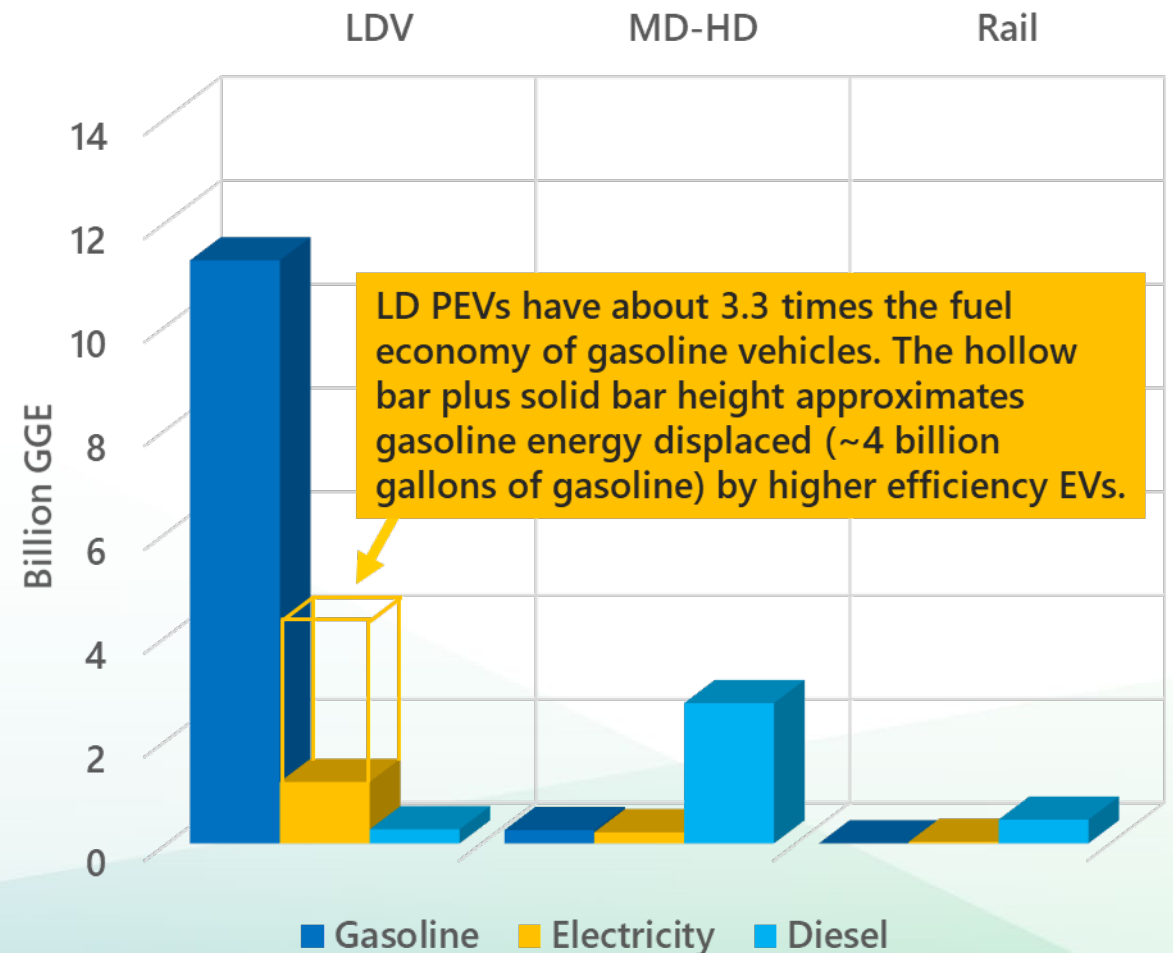


Light-Duty Electric Vehicle Efficiency Displaces More Gasoline Energy per Energy Unit Used

2020 Fuel Consumption, Billion Gasoline Gallon Equivalents



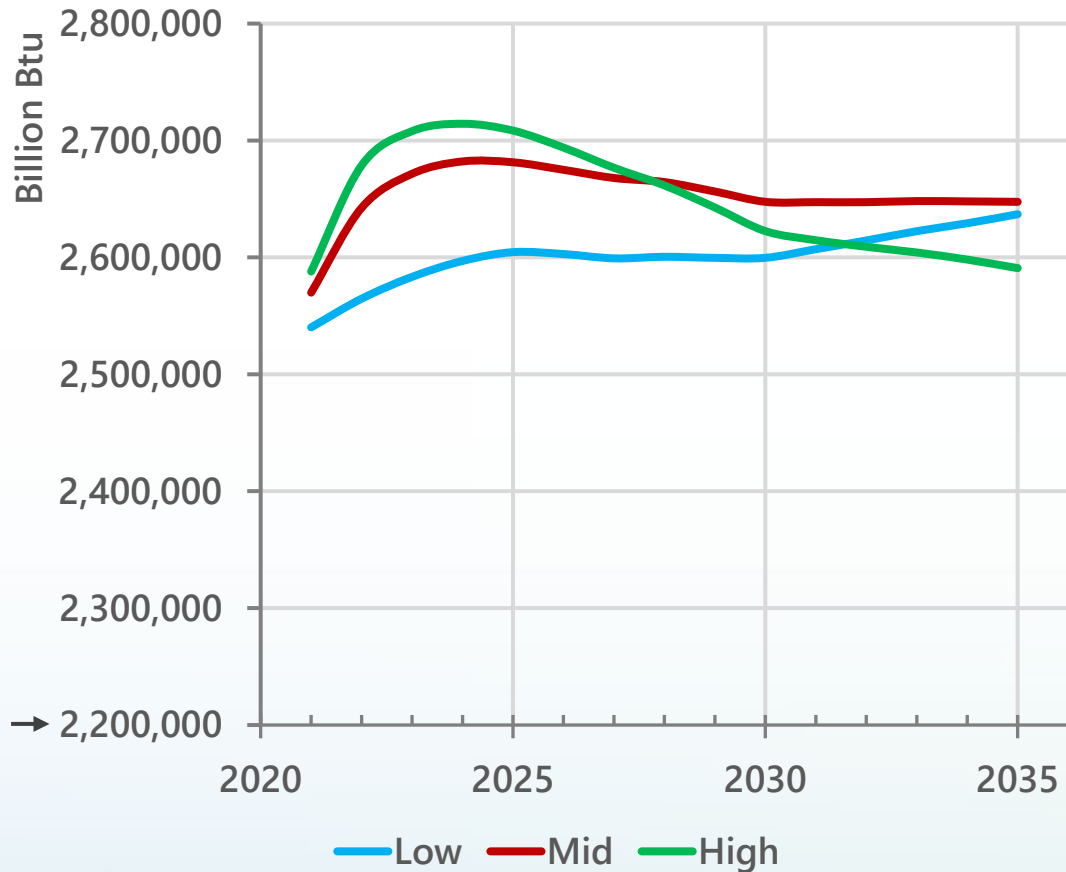
2035 Forecast High Case Fuel Consumption, Billion Gasoline Gallon Equivalents



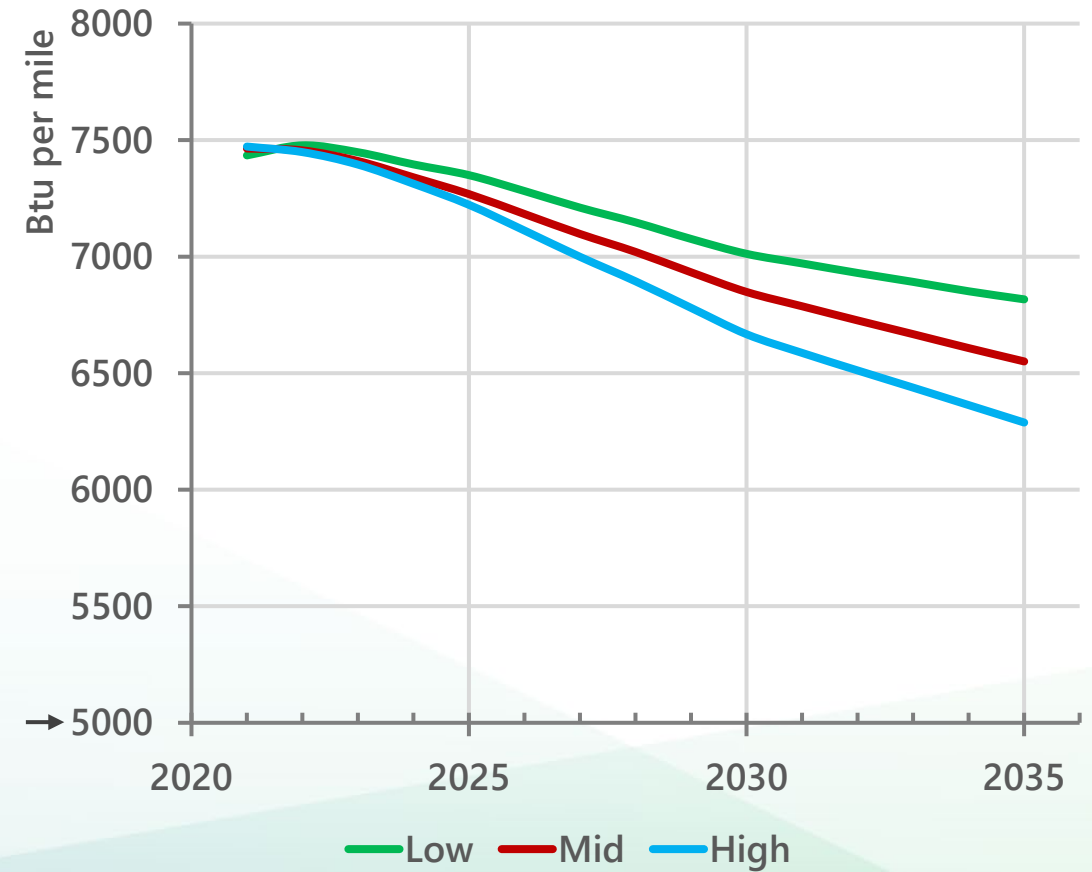


Higher Electrification and Improved Fuel Economy Lowers Energy Intensity

Transportation Energy Demand (Btu)

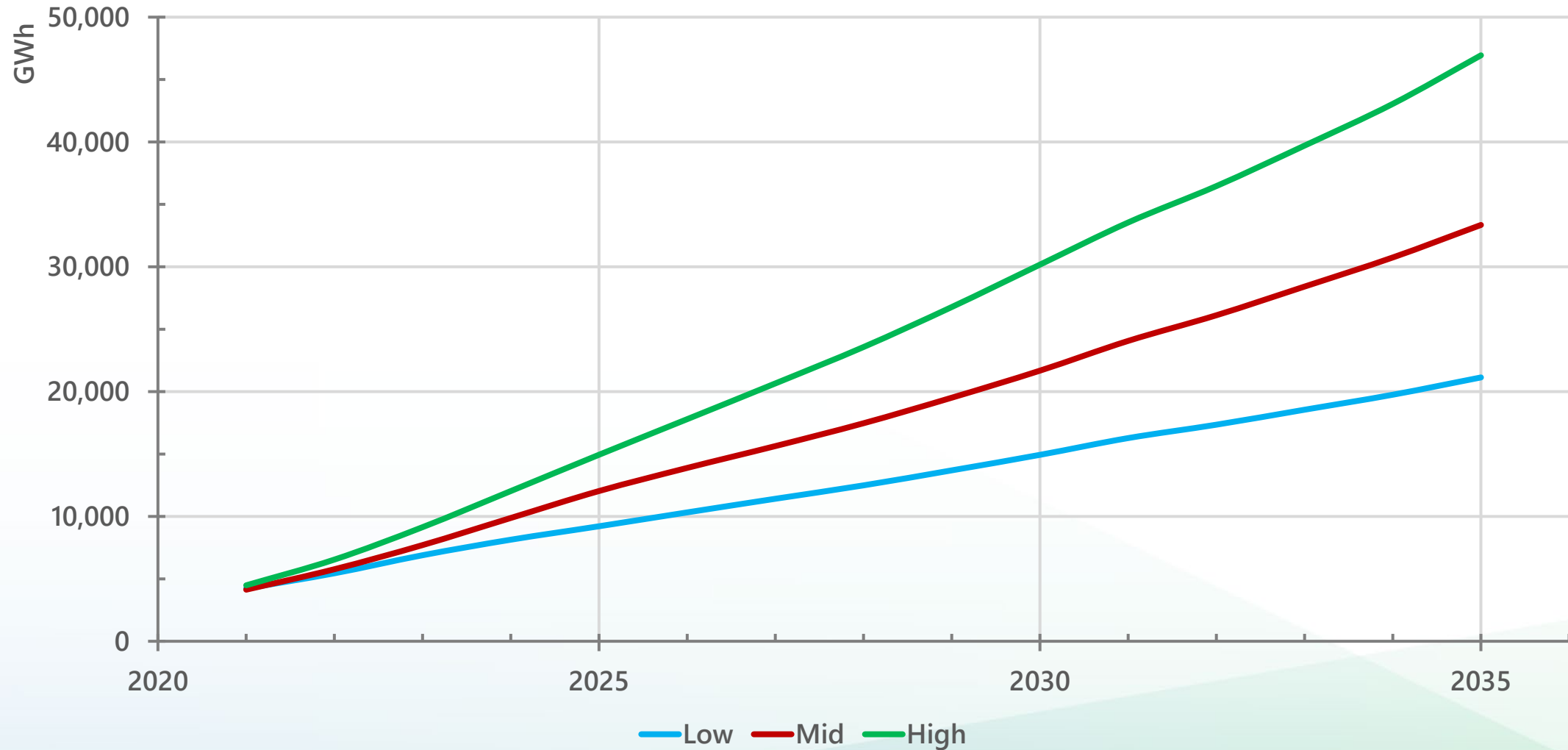


Transportation Energy (Btu) Per Mile



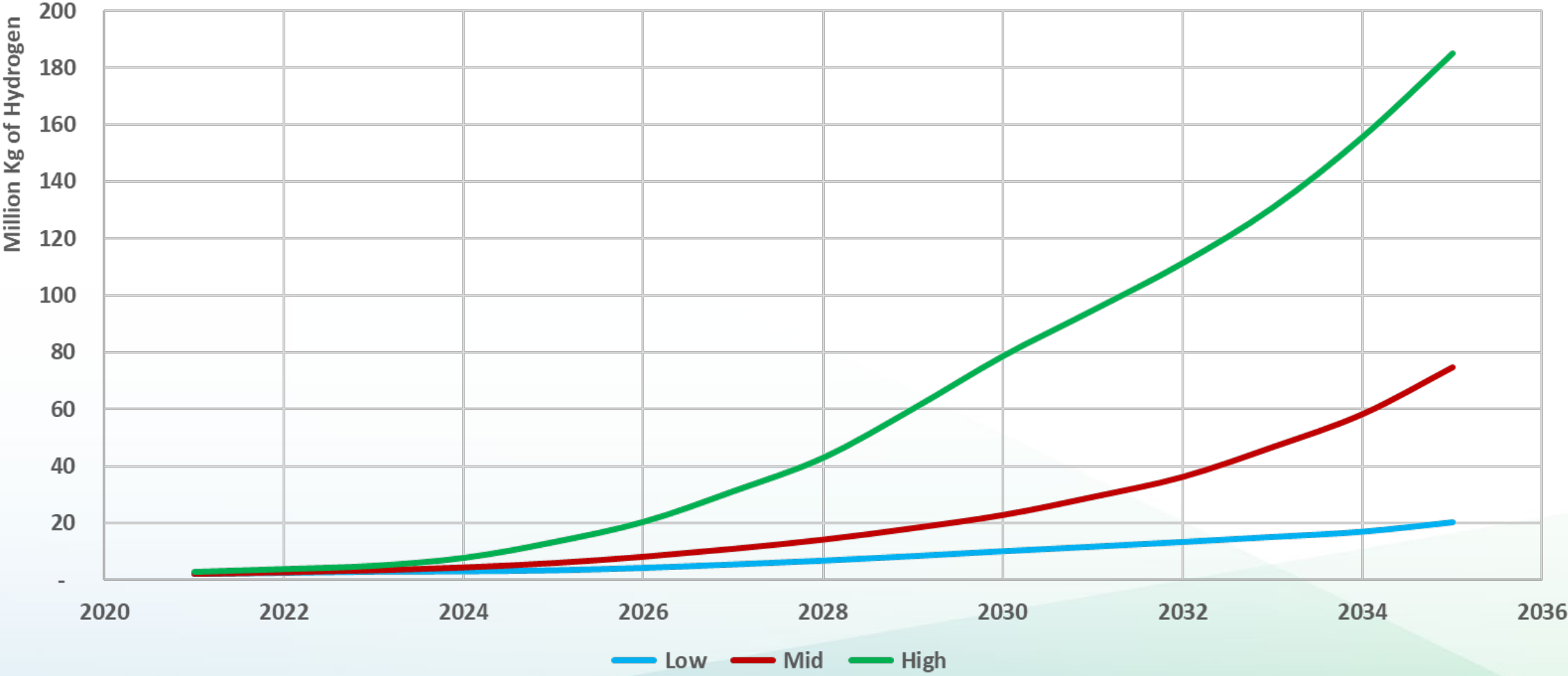


Transportation Electricity Demand Forecast



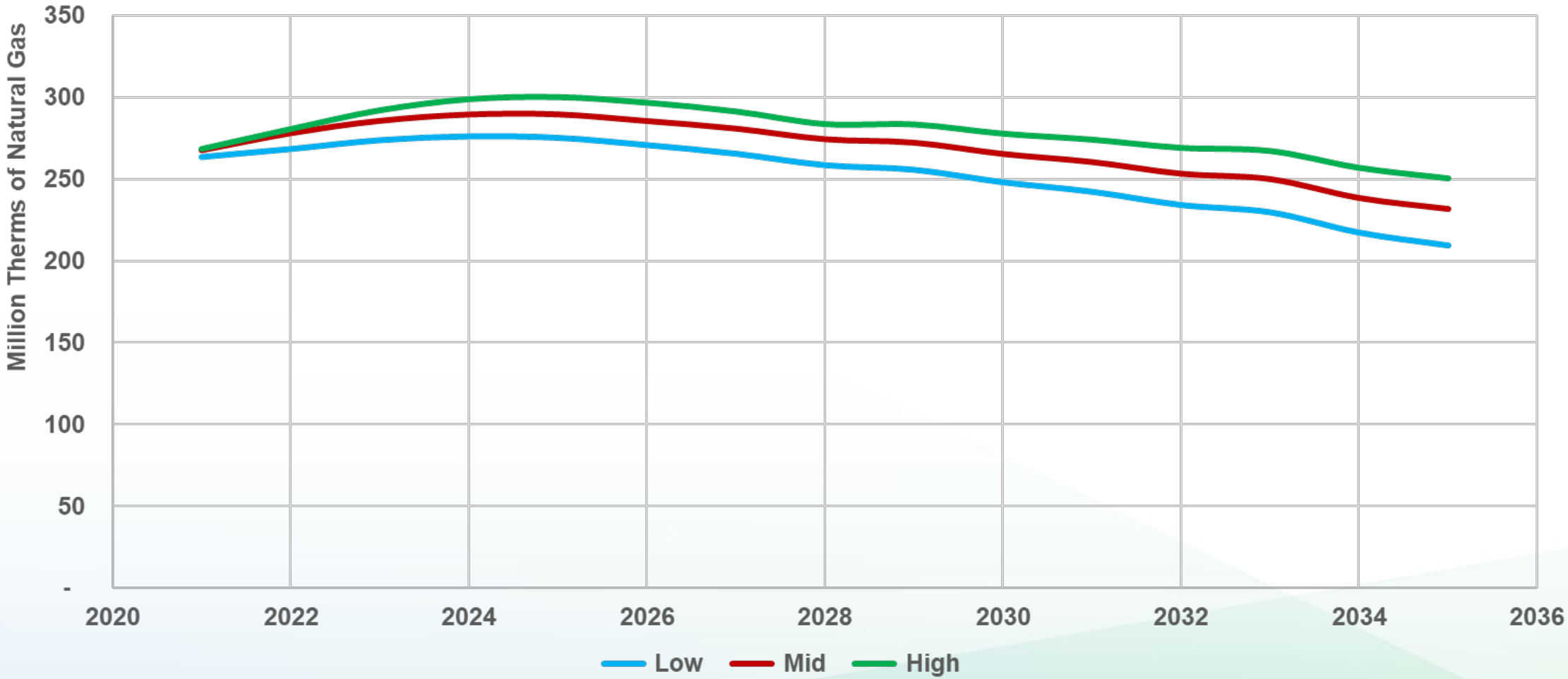


Transportation Hydrogen Demand Forecast





Transportation Natural Gas Demand Forecast



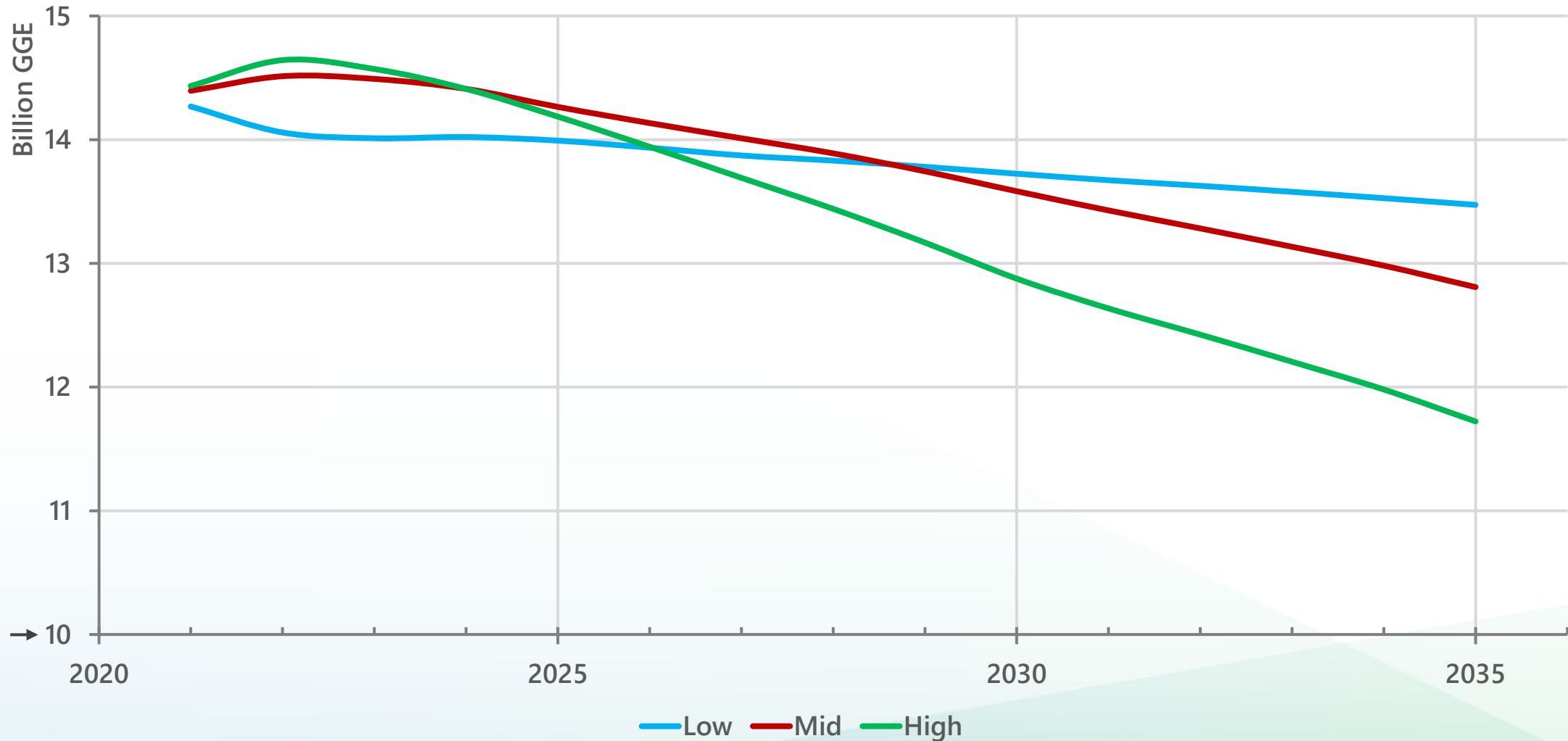
*Includes biomethane
Source: Energy Commission Staff



Appendix

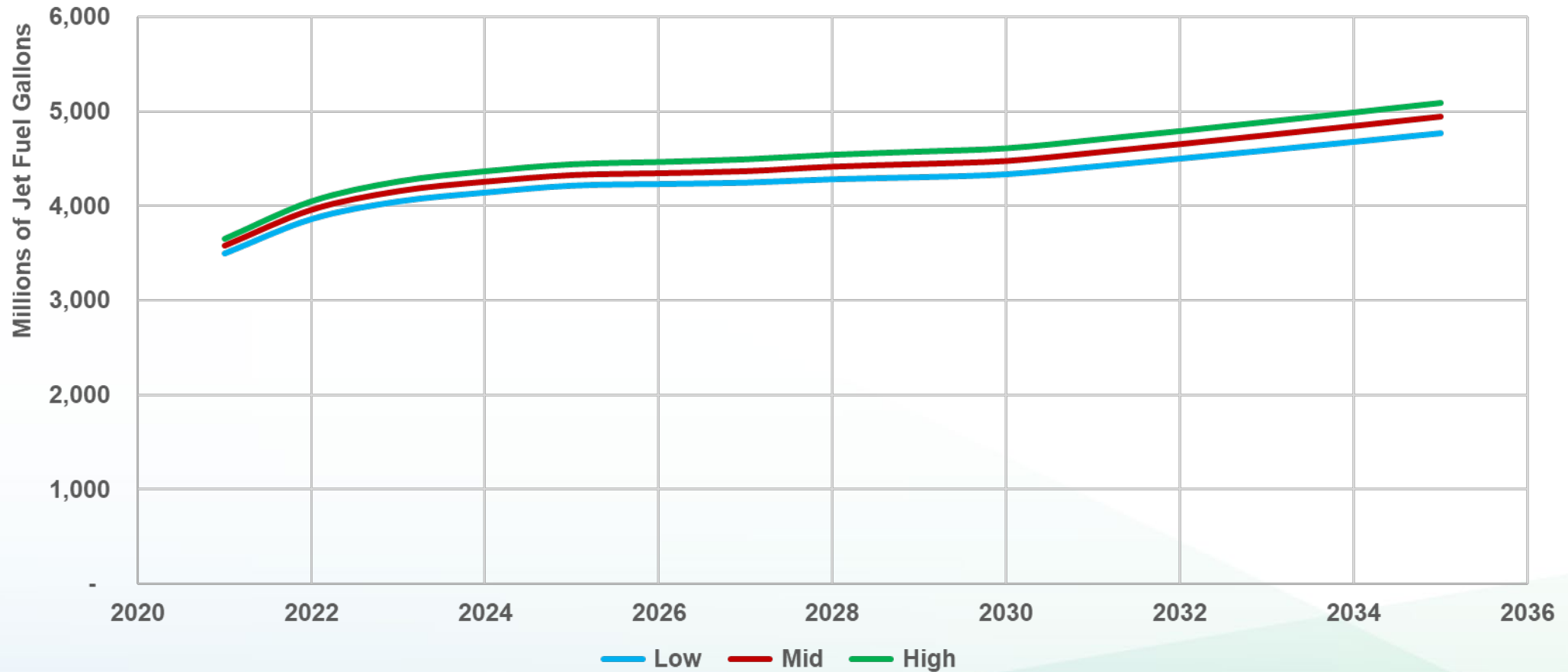


Gasoline Demand Forecast



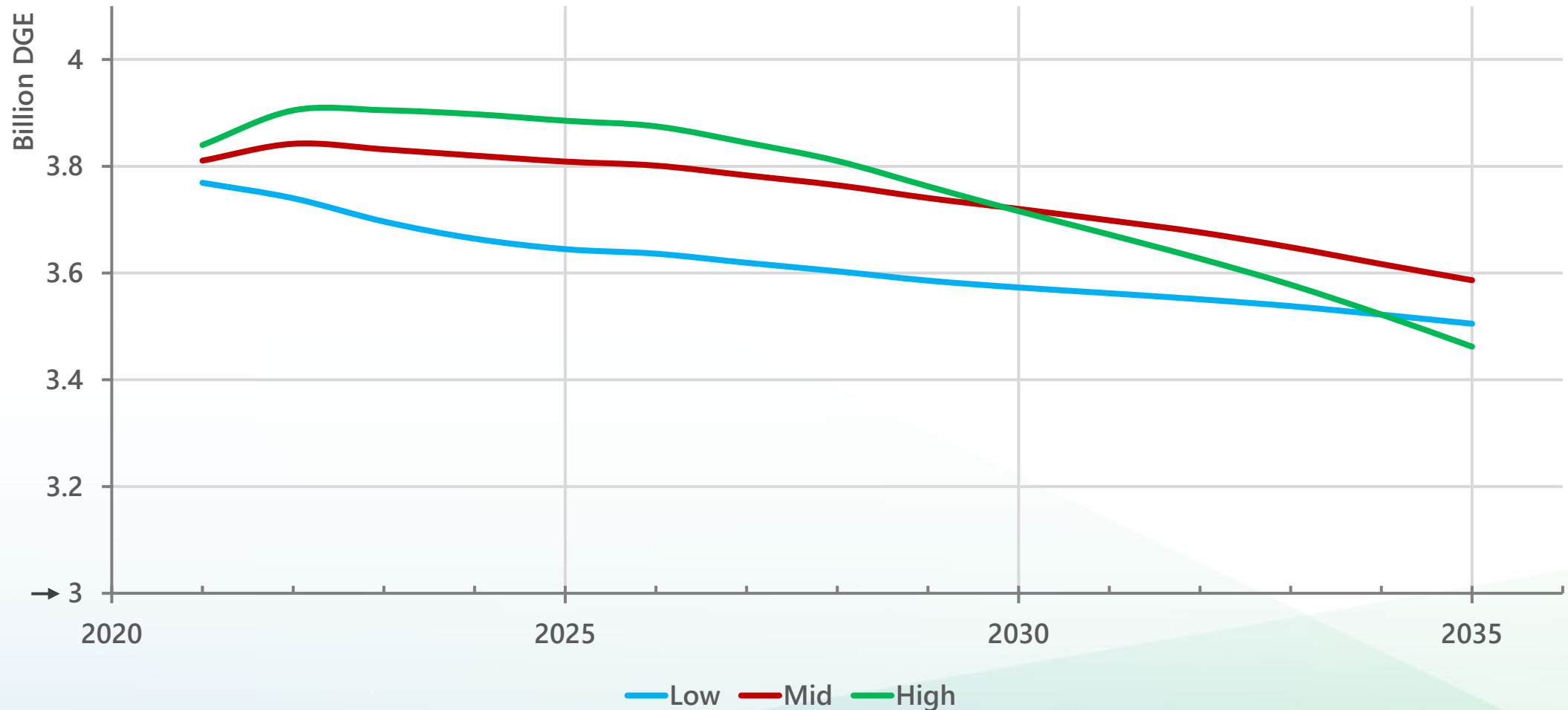


Jet Fuel Demand Forecast





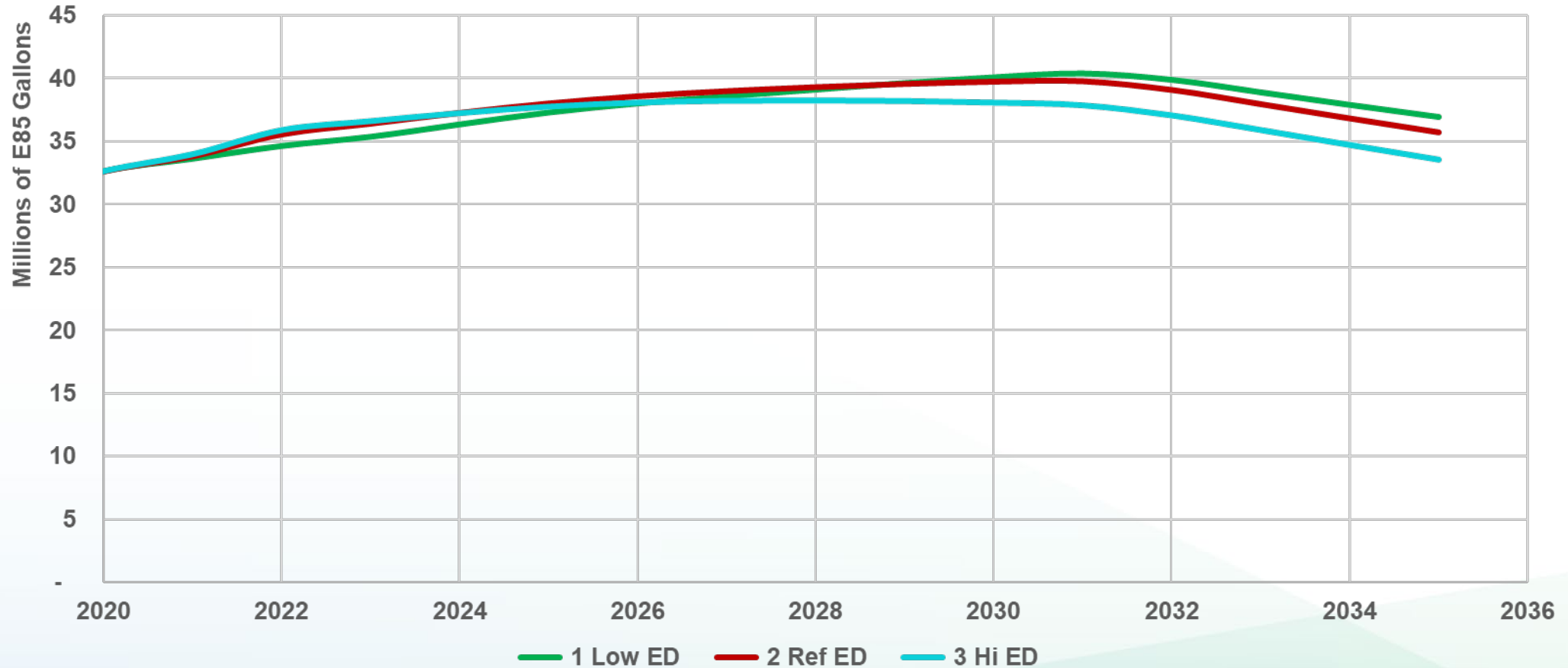
Diesel Demand Forecast



*Includes renewable diesel and biodiesel
Source: Energy Commission Staff

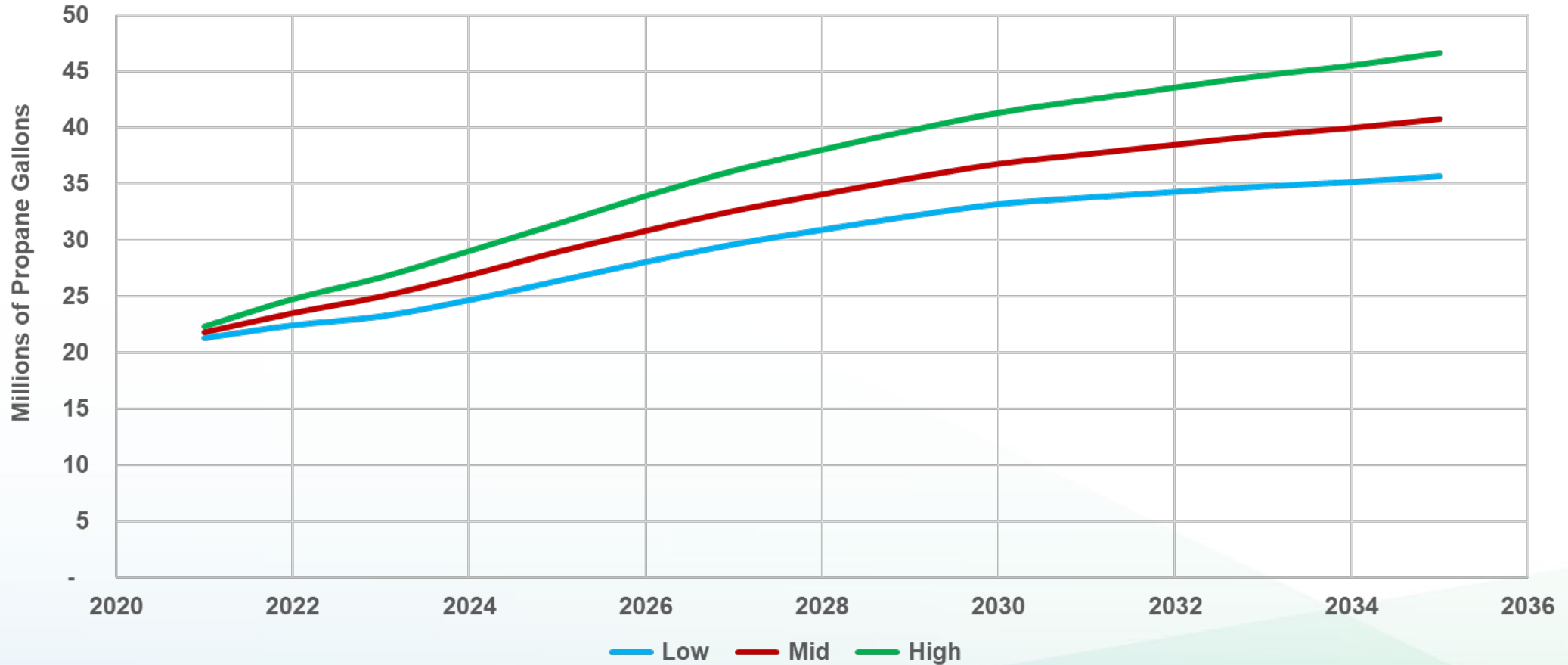


Ethanol E85 Demand Forecast





Propane Demand Forecast





Transportation Energy Price Forecasts



Gasoline and Diesel Price Forecasts

Gasoline, \$/GGE

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	3.66	3.66	3.66
2019	3.72	3.72	3.72
2020	3.13	3.13	3.13
2021	3.86	3.86	3.86
2022	3.86	4.07	3.78
2023	3.86	4.29	3.70
2024	3.86	4.41	3.62
2025	3.90	4.50	3.61
2026	3.92	4.58	3.60
2027	3.96	4.66	3.59
2028	4.00	4.78	3.58
2029	4.04	4.85	3.57
2030	4.11	4.94	3.56
2031	4.18	5.02	3.55
2032	4.25	5.10	3.54
2033	4.28	5.17	3.53
2034	4.31	5.24	3.52
2035	4.34	5.31	3.51

Diesel, \$/DGE

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	3.99	3.99	3.99
2019	3.97	3.97	3.97
2020	3.38	3.38	3.38
2021	3.91	3.91	3.91
2022	3.87	4.20	3.64
2023	4.00	4.52	3.70
2024	4.07	4.69	3.72
2025	4.12	4.81	3.73
2026	4.15	4.87	3.73
2027	4.18	4.97	3.72
2028	4.20	5.04	3.69
2029	4.21	5.11	3.67
2030	4.28	5.19	3.69
2031	4.30	5.19	3.68
2032	4.31	5.26	3.69
2033	4.31	5.31	3.67
2034	4.31	5.34	3.65
2035	4.31	5.38	3.64



Natural Gas and Hydrogen Price Forecasts

Natural Gas (\$/DGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	2.91	2.91	2.91
2019	3.15	3.15	3.15
2020	2.77	2.77	2.77
2021	2.60	2.60	2.60
2022	2.65	2.40	2.92
2023	2.72	2.45	3.01
2024	2.78	2.51	3.09
2025	2.85	2.57	3.19
2026	2.92	2.63	3.27
2027	2.99	2.70	3.36
2028	3.08	2.78	3.45
2029	3.16	2.85	3.56
2030	3.23	2.91	3.65
2031	3.29	2.96	3.72
2032	3.36	3.03	3.81
2033	3.43	3.09	3.90
2034	3.50	3.15	3.99
2035	3.57	3.22	4.08

Hydrogen (\$/GGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	16.73	16.73	16.73
2019	16.75	16.75	16.75
2020	16.52	16.52	16.52
2021	16.50	15.30	16.60
2022	16.40	14.60	16.50
2023	16.20	13.80	16.50
2024	16.10	12.70	16.40
2025	15.80	11.50	16.40
2026	15.50	10.30	16.30
2027	15.00	9.20	16.20
2028	14.30	8.40	16.10
2029	13.50	7.80	16.00
2030	12.60	7.40	15.80
2031	11.70	7.10	15.60
2032	11.00	7.00	15.20
2033	10.30	6.90	14.80
2034	9.90	6.80	14.30
2035	9.60	6.80	13.70



Electricity Price Forecasts

Commercial Electricity (\$/GGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	\$5.56	\$5.56	\$5.56
2019	\$5.61	\$5.61	\$5.61
2020	\$6.04	\$6.04	\$6.04
2021	\$6.19	\$6.18	\$6.20
2022	\$6.23	\$6.17	\$6.26
2023	\$6.35	\$6.29	\$6.46
2024	\$6.45	\$6.37	\$6.58
2025	\$6.62	\$6.52	\$6.80
2026	\$6.71	\$6.56	\$6.93
2027	\$6.76	\$6.57	\$7.04
2028	\$6.88	\$6.63	\$7.19
2029	\$7.00	\$6.67	\$7.35
2030	\$7.08	\$6.63	\$7.43
2031	\$7.14	\$6.67	\$7.53
2032	\$7.21	\$6.71	\$7.65
2033	\$7.29	\$6.76	\$7.76
2034	\$7.36	\$6.80	\$7.88
2035	\$7.43	\$6.84	\$7.99

Residential Electricity (\$/GGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	\$6.29	\$6.29	\$6.29
2019	\$6.32	\$6.31	\$6.32
2020	\$6.64	\$6.64	\$6.64
2021	\$7.36	\$7.35	\$7.36
2022	\$7.44	\$7.38	\$7.49
2023	\$7.62	\$7.52	\$7.80
2024	\$7.72	\$7.56	\$7.96
2025	\$7.93	\$7.69	\$8.26
2026	\$8.06	\$7.73	\$8.48
2027	\$8.10	\$7.72	\$8.66
2028	\$8.25	\$7.78	\$8.83
2029	\$8.38	\$7.80	\$9.03
2030	\$8.49	\$7.73	\$9.16
2031	\$8.57	\$7.76	\$9.31
2032	\$8.67	\$7.81	\$9.48
2033	\$8.76	\$7.85	\$9.66
2034	\$8.85	\$7.89	\$9.83
2035	\$8.94	\$7.92	\$9.99



Transportation Propane and Ethanol E85 Price Forecasts

Propane (\$/GGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	2.04	2.04	2.04
2019	1.85	1.85	1.85
2020	1.32	1.32	1.32
2021	1.66	1.66	1.66
2022	1.74	1.85	1.69
2023	1.76	1.97	1.71
2024	1.81	2.05	1.72
2025	1.85	2.12	1.73
2026	1.88	2.17	1.74
2027	1.90	2.22	1.76
2028	1.95	2.27	1.77
2029	1.97	2.32	1.77
2030	2.04	2.40	1.84
2031	2.06	2.42	1.85
2032	2.10	2.45	1.88
2033	2.12	2.47	1.89
2034	2.13	2.49	1.90
2035	2.14	2.51	1.91

E85 (\$/GGE)

Year	Mid Demand	High Electricity Demand	Low Electricity Demand
2018	3.66	3.66	3.66
2019	3.72	3.72	3.72
2020	3.13	3.13	3.13
2021	3.86	3.86	3.86
2022	3.86	4.07	3.78
2023	3.86	4.29	3.70
2024	3.86	4.41	3.62
2025	3.90	4.50	3.61
2026	3.92	4.58	3.60
2027	3.96	4.66	3.59
2028	4.00	4.78	3.58
2029	4.04	4.85	3.57
2030	4.11	4.94	3.56
2031	4.18	5.02	3.55
2032	4.25	5.10	3.54
2033	4.28	5.17	3.53
2034	4.31	5.24	3.52
2035	4.34	5.31	3.51



TEFU Team: Quentin Gee (Unit Supervisor)

Aniss Bahreinian

Jesse Gage

Alex Lonsdale

Bob McBride

Mark Palmere

Elizabeth Pham

Ysbrand van der Werf

ZEVI cost: Comparison of passenger car retail prices

Verified on 6 June 2025

Top selling ICE passenger car price comparison with equivalent EV passenger cars with or without incentives in select markets

10 ▾ entries per page

Search:

Market ▴▾	Year ▴▾	Top selling ICE passenger car model ▴▾	ICE Price ▴▾	Equivalent EV passenger car model ▴▾
Germany	2024	VW Golf Life 2 I TSI	\$ 32,545	VW ID.3 Pro 150 kW
United Kingdom	2024	Opel Vauxhall Corsa Design 1.2 Turbo Petrol	\$ 30,141	Opel Vauxall Corsa Electric 100kW
France	2024	Peugeot 208 Like Essence 74 kW	\$ 20,070	Peugeot 208 Like Electrique 100 kW
United States	2024	Ford F-150 XL 2.7L V6	\$ 36,965	Ford F-150 Lightning XLT
Canada	2024	Toyota RAV4 LE AWD	\$ 26,786	VW ID.4 Pro AWD
Japan	2024	Toyota Yaris Cross X 2WD	\$ 12,052	Nissan Leaf Leaf X (2WD); 40 kWh
India	2024	Maruti Swift VXI AMT	\$ 9,300	Tata Tigor XE

Notes regarding exclusion and inclusion of taxes and other fees in prices before incentives:

- Germany: Excluding delivery and registration costs, including VAT. Purchase incentives for BEVs no longer offered.
- United Kingdom: Including VAT and first vehicle registration fee for ICE vehicles. Purchase incentives for BEVs no longer offered.
- France: Excluding registration, including VAT. Includes Bonus écologique and Prime à la conversion incentives.
- United States: Including destination charges, delivery, processing and handling fees. Includes Federal Tax Credit.
- Canada: Excluding sales and registration tax, including dealer fees and delivery charges. Includes federal iZEV rebate.
- Japan: Excluding tax, insurance premium, compulsory liability insurance, recycling costs, registration fee. Including consumption tax and national purchase subsidy.
- India: Excluding registration, insurance and road tax, including dealer's profit margin and GST. Includes FAME II incentives.

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2024 Fueling Cost Comparison: Mid-Priced ICE Cars Less Expensive to Fuel than EVs; Luxury EVs Have Cost Advantage

October 8, 2024October 7, 2024 [AEG Press Releases](#)

California's high energy prices mean mid-priced EVs make more sense there than in Michigan or New York

Anderson Economic Group has released fueling cost estimates for comparable internal combustion engine (ICE) vehicles and electric vehicles (EV) for the first and second quarters of 2024. These estimates indicate the real-world costs that American households face when choosing between a gasoline powered vehicle and a battery electric vehicle.

The quarterly AEG cost comparisons, which have been prepared since 2021 and calculate costs from 2019 forward, follow a rigorous methodology that counts the same categories of fueling costs for both types of vehicles, including energy, state excise taxes, and the pump or charger. AEG calculates costs for entry-level, mid-priced, and luxury cars (including crossovers), as well as pickup trucks, all assumed to drive 12,000 miles per year. For electric vehicles, we calculate costs for drivers that mostly charge at home and those that mostly charge at commercial charging stations. As state taxes, costs of electricity and gasoline all vary among states, we include calculations for the benchmark state of Michigan as well as New York and California.

Included in this release:

- Summary results for the first half of 2024
- Commentary from AEG experts
- Detailed results for Michigan, California, and New York

- Graphics illustrating the results
- A methodological summary

Summary results in the first half of 2024

The AEG calculations for the first half of 2024 show that:

- Drivers of vehicles in the most popular segments, mid-priced cars and crossovers, and pickup trucks, typically save money driving a traditional gasoline-powered ICE vehicle compared to a battery-electric vehicle (BEV),
- BEV drivers who rely primarily on commercial charging pay substantially more than their counterparts in any other category.
- Drivers of luxury vehicles, which tend to have more weight and more powerful engines, typically save money driving an EV compared to an ICE vehicle, if they can charge primarily at home. As many drivers of luxury vehicles also own their own homes, a luxury EV for them can often be relatively affordable compared to a luxury ICE car.
- Higher energy prices in California, which include both electricity and gasoline, make the EV cost differential disappear for mid-priced drivers who can mostly charge at home. As with Michigan and New York, luxury EV drivers charging at home have a cost advantage.
- In all three states, drivers of pickup trucks face significantly higher costs if they rely on an EV. That is primarily because of the cost of commercial charging for these relatively thirsty vehicles.
- Drivers in New York face relative costs that are similar to those in our benchmark state of Michigan. As in Michigan, entry- and mid-priced cars and crossovers typically cost less to operate if they were ICE vehicles than if they were electric vehicles. And, as Michigan and California, EVs were relatively less expensive for luxury car buyers who could rely on home charging,.

Commentary from AEG Experts

“Consumers are strongly influenced by the cost of ownership,” says Patrick Anderson, principal at Anderson Economic Group, “It’s no coincidence that the state with the highest percentage of EV adoption is also the state where consumers often pay less to drive them.”

“California drivers pay some of the highest electrical and gasoline prices in the country, but they also have a better charging infrastructure than most states. That works out to relatively affordable EV operating costs in that state, at least for drivers that can rely on home charging most of the time.”

“The 2024 results confirm what we saw in 2023: for most consumers, who are interested in affordable cars, crossovers and pick-up trucks, electric vehicles cost more to operate across three states analyzed. Luxury cars charged primarily at home are an exception. These cost data explain a lot of the consumer reluctance to buy EVs outside of the luxury class of vehicles. “

Detailed Findings: Michigan

AEG has used Michigan as the benchmark state to calculate fueling costs since 2021. Michigan’s state taxes, electricity and gasoline costs are all well within the range of other states, the state is the home to automakers and suppliers, and it has big cities like Detroit as well as rural areas.

Entry-priced cars and crossovers, Michigan: In the entry-priced segment, gas-powered cars like the VW Jetta and Hyundai Elantra remained more economical to fuel at around \$10.25 per 100 purposeful miles. That's up slightly from the end of 2023, but still significantly more affordable than entry priced EVs like the Nissan Leaf or Chevy Bolt charged mostly at home (\$12.92). These operating costs represented a dramatic savings over an EV charged mostly at commercial charging stations (\$16.12).

Mid-priced cars and crossovers, Michigan: Mid-priced ICE vehicles that include the Chevy Malibu and Nissan Altima were also more cost-effective at approximately \$11.61 per 100 miles. That's lower than EVs in this segment (e.g., Tesla Models 3 and Y, Kia EV6) that utilized primarily home charging (\$12.99) or mostly commercial charging (\$16.25).

Luxury-priced cars and crossovers, Michigan: In the luxury segment, electric vehicles like the Porsche Taycan or the Tesla Model X charged mostly at home continue to be the most economical to fuel. These drivers paid around \$13.90 per 100 miles, as opposed to \$18.56 to fuel a comparable ICE car like the BMW 5 series or the Cadillac CTS. Luxury EV drivers charging mostly commercially also experienced some savings over a comparable ICE vehicle at \$17.95 per 100 miles.

Pickup trucks, Michigan: At around \$18.42 per 100 miles, ICE-powered trucks like the Ford F Series or GMC Sierra were slightly more expensive to fuel than their mostly home-charged electric counterparts in Michigan at \$18.26. Drivers of electric pickups like the Ford F-150 Lightning who needed to charge commercially most of the time found themselves paying about \$26.38—exceeding their ICE counterparts by nearly \$8.

Detailed Findings: California & New York

Here are the comparable results from California and New York using energy prices and state taxes in those states:

Entry-priced cars and crossovers: In the entry-priced segment, gas-powered cars were cheaper to fuel than their EV counterparts in both New York and California. For New York drivers, gasoline offered a cost advantage between \$2.27 and \$5.54, depending on the driver's home or commercial charging habits. In California, the difference ranged from \$1.90 to \$2.72.

Mid-priced cars and crossovers: Mid-priced ICE vehicles were also more cost-effective to fuel in New York at \$12.07 per 100 miles. That's lower than EVs in this segment at \$13.01 for mostly home charging or \$16.34 for mostly commercial charging. Even in California, ICE powered cars were very slightly cheaper to fuel at \$16.88 as compared to an EV charged mostly at home for \$16.92 or charged mostly commercially at \$17.78.

Luxury-priced cars and crossovers: In the luxury segment, electric vehicles charged mostly at home are less expensive to fuel in both states. New York drivers paid around \$14.07 per 100 miles, as opposed to the \$18.83 needed to fuel an ICE counterpart. California's Luxury EV drivers experienced even more of a discount, paying \$18.30 for mostly home charging versus the \$23.19 it would have cost them to fuel a Luxury ICE vehicle. Even those charging mostly commercially had an advantage in California, paying just \$1.33 more than those charging mostly at home – still considerably less than the ICE fueling cost.

Pickup trucks: Pickup truck drivers in New York paid about the same to drive an EV mostly charged at home (\$19.14) as they would have for an ICE vehicle (\$19.16) per 100 miles. In California, ICE-powered trucks were nearly \$2 more expensive to fuel at \$26.80 than their mostly home-charged

electric counterparts at \$24.89. California's electric pickup drivers charging commercially most of the time paid about \$28.67, exceeding ICE pickup fueling costs by \$1.87.

Methodology

The quarterly AEG cost comparisons, which have been prepared since 2021 and calculate costs from 2019 forward, follow a rigorous methodology and include three categories of fueling costs for both types of vehicles: the cost of underlying energy (gas, diesel, electric); state excise taxes; and the cost to operate the pump or charger. The AEG fueling cost studies calculate costs for entry-level, mid-priced, and luxury cars (including crossovers), as well as pickup trucks. All vehicles are assumed to drive 12,000 miles per year. For electric vehicles, we calculate costs for drivers that mostly charge at home and those that mostly charge at commercial charging stations.

As state taxes, costs of electricity and gasoline all vary among states, we include calculations for the benchmark state of Michigan as well as New York and California in our 2024 comparisons.

The general methodology and data sources are described in Real World Costs of Fueling EVs and ICE Vehicles, Second Edition, Anderson Economic Group, 2022 (see AndersonEconomicGroup.com/second-edition-real-world-cost-of-fueling-evs-and-ice-vehicles).

Recent updates to methodology and data include:

- AEG used the State of Michigan as the benchmark for calculating costs beginning in 2019. Starting with 2024, calculations include the states of California and New York.
- Costs of electricity and gasoline are updated every quarter. Gasoline prices are calculated on a regional basis for Michigan and state basis for California and New York. Each year, state electric vehicle taxes are updated.
- In 2023, AEG updated segments, models, and fuel consumption. With the introduction of sufficient electric vehicles in the entry-priced and pickup truck segments, we included these in the calculations as well.
- In 2024, AEG improved the methodology for calculating deadhead miles and commercial charger prices. Deadhead miles were adjusted for each state by calculating drivetimes to the nearest DC fast charger for each state and comparing to a US average. Data on DC fast charger locations came from the EIA Alternative Fuels Data Center.
- For 2019 through 2023, prices for commercial chargers were based on small-sample surveys done by AEG of commercial charging locations in various states. Beginning in 2024, prices were calculated using data from the EIA AFDC and corroborated using a separate survey. For both methods, substantial professional judgement was required to account for dynamic pricing schemes, missing data, and reliability of DC fast chargers.

About Anderson Economic Group

Anderson Economic Group is one of the most recognized boutique consulting firms in the United States. The company has offices in East Lansing, Michigan and Chicago, Illinois. AEG's clients include universities, state governments, nonprofits, manufacturers, suppliers, trade associations, and automobile dealers.

The automobile industry has been an area of specialization for AEG since our founding in 1996. AEG clients in the automotive industry include OEMs, tier I and tier II suppliers, automobile dealers and

dealer trade groups, and states and economic development associations representing automotive producing regions in the US and Canada. Nearly all AEG automotive industry clients build or sell both ICE and electric vehicles.

Detailed Data Available by Subscription

AEG publishes summary results for four segments and three use cases (representing 12 different combinations) for selected states each quarter. These results are available free of charge from the AEG website, at the time and in the format AEG publishes these results.

Detailed data, including intermediate calculations for individual cost categories, and additional segment-use cases such as diesel trucks and hybrid gas-electric vehicles, are available by subscription. Please contact the AEG office if you are interested.

Related Reports of Interest

- AEG's *Automotive Dashboard* tracks the auto industry (including electric vehicles) along with related economic metrics: AndersonEconomicGroup.com/auto-dashboard.
- *Infrastructure Funding: The Impact of EVs on Michigan Roads* looks at funding disparities based on state and federal taxes for road maintenance that differ for EVs and ICE vehicles. See AndersonEconomicGroup.com/infrastructure-funding-the-impact-of-evs-on-michigan-roads/ or micountyroads.org.

You may also be interested in:

[Michigan EV charging stations infrastructure strengthened in 2023, but access still limited](#)

[Automotive Dashboard](#)

[Real World Cost of Fueling EVs and ICE Vehicles \(2nd Edition\)](#)

[First Edition \(2021\): Real World Cost of Fueling EVs and ICE Vehicles](#)

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Federal Tax Credits for New Plug-in Electric and Fuel Cell Electric Vehicles Acquired from January 1, 2023, through September 30, 2025

Federal Tax Credit Up To \$7,500!

All-electric, plug-in hybrid, and fuel cell electric vehicles acquired new from January 1, 2023, through September 30, 2025 may be eligible for a federal income tax credit of up to \$7,500.

The availability of the credit will depend on several factors, including the vehicle's MSRP, its final assembly location, battery component and/or critical minerals sourcing, and your modified adjusted gross income (AGI).

Important! A vehicle is *acquired* as of the date a written binding contract is entered into and a payment has been made. A *payment* includes a nominal downpayment or a vehicle trade-in. The credit cannot be claimed until the vehicle is *placed in service* (i.e., the taxpayer takes possession). However, as long as the vehicle is acquired by September 30, 2025, the taxpayer can claim the credit upon possession of the vehicle, even if that occurs after September 30, 2025.

Learn more about additional requirements. ►

Qualified vehicles purchased before 2023 may be eligible for a similar tax credit of up to \$7,500.

Pre-owned vehicles acquired from January 1, 2023, through September 30, 2025, are eligible for a tax credit of up to \$4,000.

Time-of-Sale Requirement!

In accordance with IRS regulations, beginning January 1, 2024, Clean Vehicle Tax Credits must be initiated and approved at the time of sale.

Buyers are advised to obtain a copy of the IRS’s confirmation that a “time-of-sale” report was submitted successfully by the dealer.

Go to IRS publication 5900 to learn more!

State and/or local tax incentives may also apply.

The information on this page applies to the Clean Vehicle Credit available to individuals and businesses. For details about the credit available to businesses and non-profit organizations, see Commercial Clean Vehicle Credit (IRS).

Note: Some qualified manufacturers have yet to submit information on eligible vehicles that meet the current requirements. Please check back for updated information.

Search for Eligible Vehicles

Vehicle eligibility for some makes and models depends on the date you take delivery of the vehicle—this is sometimes called the placed-in-service date.

Select date you plan to take delivery (required)

Delivery date

▼

Requirements

Claiming the Credit

Additional Information

DISCLAIMER

The information on this page should not be viewed as an official or legally binding document. Other requirements or exceptions may apply. For more detailed information, please consult an IRS tax representative and/or official IRS publications.

ALSO IN THIS SECTION...

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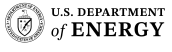
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PRESIDENTIAL ACTIONS

ADJUSTING IMPORTS OF AUTOMOBILES AND AUTOMOBILE
PARTS INTO THE UNITED STATES

Proclamations

March 26, 2025

BY THE PRESIDENT OF THE UNITED STATES OF AMERICA

A PROCLAMATION

1. On February 17, 2019, the Secretary of Commerce (Secretary) transmitted to me a report on his investigation into the effects of imports of passenger vehicles (sedans, sport utility vehicles, crossover utility vehicles, minivans, and cargo vans) and light trucks (collectively, automobiles) and certain automobile parts (engines and engine parts, transmissions and powertrain parts, and electrical components) (collectively, automobile parts) on the national security of the United States under section 232 of the Trade Expansion Act of 1962, as amended (19 U.S.C. 1862) (section 232). Based on the facts considered in that investigation, the Secretary found and advised me of his opinion that automobiles and certain automobile parts are being imported into the United States in such quantities and under such circumstances as to threaten to impair the national security of the United States.
2. In Proclamation 9888 of May 17, 2019 (Adjusting Imports of Automobiles and Automobile Parts Into the United States), I concurred with the Secretary's finding in the February 17, 2019, report that automobiles and certain automobile parts are being imported into the United States in such quantities and under such circumstances as to threaten to impair the national security of the United States. I also directed the United

States Trade Representative (Trade Representative), in consultation with other executive branch officials, to pursue negotiation of agreements to address the threatened impairment of the national security of the United States with respect to imported automobiles and certain automobile parts from the European Union, Japan, and any other country the Trade Representative deems appropriate.

3. The Trade Representative's negotiations did not lead to any agreements of the type contemplated by section 232.

4. In Proclamation 9888, I also directed the Secretary to monitor imports of automobiles and certain automobile parts and inform me of any circumstances that, in the Secretary's opinion, might indicate the need for further action under section 232 with respect to such imports.

5. The Secretary has informed me that, since the February 17, 2019, report, the national security concerns remain and have escalated. The COVID-19 pandemic exposed critical vulnerabilities and choke points in global supply chains, undermining our ability to maintain a resilient domestic industrial base. In recent years, American-owned automotive manufacturers have experienced numerous supply chain challenges, including material and parts input shortages, labor shortages and strikes, and electrical-component shortages. Meanwhile, foreign automotive industries, propelled by unfair subsidies and aggressive industrial policies, have grown substantially. Today, only about half of the vehicles sold in the United States are manufactured domestically, a decline that jeopardizes our domestic industrial base and national security, and the United States' share of worldwide automobile production has remained stagnant since the February 17, 2019, report. The number of employees in the domestic automotive industry has also not improved since the February 17, 2019, report.

6. I am also advised that agreements entered into before the issuance of Proclamation 9888, such as the revisions to the United States-Korea Free Trade Agreement and the United States-Mexico-Canada Agreement (USMCA), have not yielded sufficient positive outcomes. The threat to national security posed by imports of automobiles and certain automobile parts remains and has increased. Investments resulting from other efforts, such as legislation, have also not yielded sufficient positive outcomes to eliminate the threat to national security from such imports.

7. After considering the current information newly provided by the Secretary, among other things, I find that imports of automobiles and certain automobile parts continue to threaten to impair the national security of the United States and deem it necessary

and appropriate to impose tariffs, as defined below, to adjust imports of automobiles and certain automobile parts so that such imports will not threaten to impair national security.

8. To ensure that the imposition of tariffs on automobiles and certain automobile parts in this proclamation are not circumvented and that the purpose of this action to eliminate the threat to the national security of the United States by imports of automobiles and certain automobile parts is not undermined, I also deem it necessary and appropriate to establish processes to identify and impose tariffs on additional automobile parts, as further described below.

9. Section 232 provides that, in this situation, the President shall take such other actions as the President deems necessary to adjust the imports of the relevant article so that such imports will not threaten to impair national security.

10. Section 604 of the Trade Act of 1974, as amended (19 U.S.C. 2483), authorizes the President to embody in the Harmonized Tariff Schedule of the United States (HTSUS) the substance of statutes affecting import treatment, and actions thereunder, including the removal, modification, continuance, or imposition of any rate of duty or other import restriction.

NOW, THEREFORE, I, DONALD J. TRUMP, President of the United States of America, by the authority vested in me by the Constitution and the laws of the United States of America, including section 301 of title 3, United States Code; section 604 of the Trade Act of 1974, as amended; and section 232 of the Trade Expansion Act of 1962, as amended, do hereby proclaim as follows:

(1) Except as otherwise provided in this proclamation, all imports of articles specified in Annex I to this proclamation or in any subsequent annex to this proclamation, as set out in a subsequent notice in the *Federal Register*, shall be subject to a 25 percent tariff with respect to goods entered for consumption or withdrawn from warehouse for consumption, on or after 12:01 a.m. eastern daylight time on April 3, 2025, for automobiles, and on the date specified in the *Federal Register* for automobile parts, but no later than May 3, 2025, and shall continue in effect, unless such actions are expressly reduced, modified, or terminated. The above ad valorem tariff is in addition to any other duties, fees, exactions, and charges applicable to such imported automobiles and certain automobile parts articles.

(2) For automobiles that qualify for preferential tariff treatment under the USMCA, importers of such automobiles may submit documentation to the Secretary identifying

the amount of U.S. content in each model imported into the United States. “U.S. content” refers to the value of the automobile attributable to parts wholly obtained, produced entirely, or substantially transformed in the United States. Thereafter, the Secretary may approve imports of such automobiles to be eligible to apply the ad valorem tariff of 25 percent in clause (1) of this proclamation exclusively to the value of the non-U.S. content of the automobile. The non-U.S. content of the automobile shall be calculated by subtracting the value of the U.S. content in an automobile from the total value of the automobile.

(3) If U.S. Customs and Border Protection (CBP) determines that the declared value of non-U.S. content of an automobile, as described in clause (2) of this proclamation, is inaccurate due to an overstatement of U.S. content, the 25 percent tariff shall apply to the full value of the automobile, regardless of the actual U.S. content of the automobile. In addition, the 25 percent tariff shall be applied retroactively (from April 3, 2025, to the date of the inaccurate overstatement) and prospectively (from the date of the inaccurate overstatement to the date the importer corrects the overstatement, as verified by CBP) to the full value of all automobiles of the same model imported by the same importer. This clause does not apply to or otherwise affect any other applicable fees or penalties.

(4) The ad valorem tariff of 25 percent described in clause (1) of this proclamation shall not apply to automobile parts that qualify for preferential treatment under the USMCA until such time that the Secretary, in consultation with CBP, establishes a process to apply the tariff exclusively to the value of the non-U.S. content of such automobile parts and publishes notice in the *Federal Register*.

(5) For avoidance of doubt, clause (4) of this proclamation does not apply to automobile knock-down kits or parts compilations. Clause (4) of this proclamation applies only to individual automobile parts as defined by Annex I to this proclamation that otherwise meet the requirements of clause (4) of this proclamation.

(6) The Secretary, in consultation with the United States International Trade Commission and CBP, shall determine the modifications necessary to the HTSUS to effectuate this proclamation and shall make such modifications to the HTSUS through notice in the *Federal Register*.

(7) Within 90 days of the date of this proclamation, the Secretary shall establish a process for including additional automobile parts articles within the scope of the tariffs described in clause (1) of this proclamation. In addition to inclusions made by the

Secretary, this process shall provide for including additional automobile parts articles at the request of a domestic producer of an automobile or automobile parts article, or an industry association representing one or more such producers, where the request establishes that imports of additional automobile parts articles have increased in a manner that threatens to impair the national security or otherwise undermines the objectives set forth in any proclamation issued on the basis of the Secretary's February 17, 2019, report or any additional information submitted to the President under clause (3) of Proclamation 9888 or clause (9) of this proclamation. When the Secretary receives such a request from a domestic producer or industry association, the Secretary, after consultation with the United States International Trade Commission and CBP, shall issue a determination regarding whether to include the articles within 60 days of receiving the request. Any additional automobile parts articles that the Secretary has determined to be included within the scope of the tariffs described in clause (1) of this proclamation shall be so included on or after 12:01 a.m. eastern daylight time the day after a notice in the *Federal Register* describing the determination of the Secretary. The notice in the *Federal Register* shall be made as soon as practicable but no later than 14 days after the Secretary's determination.

(8) Any automobile or automobile part, except those eligible for admission under "domestic status" as defined in 19 CFR 146.43, that is subject to the duty imposed by this proclamation and that is admitted into a United States foreign trade zone on or after the effective date of this proclamation, in accordance with clause (1) of this proclamation, must be admitted as "privileged foreign status" as defined in 19 CFR 146.41, and will be subject upon entry for consumption to any ad valorem rates of duty related to the classification under the applicable HTSUS subheading.

(9) The Secretary shall continue to monitor imports of automobiles and automobile parts. The Secretary also shall, from time to time, in consultation with any senior executive branch officials the Secretary deems appropriate, review the status of such imports with respect to national security. The Secretary shall inform the President of any circumstances that, in the Secretary's opinion, might indicate the need for further action by the President under section 232. The Secretary shall also inform the President of any circumstance that, in the Secretary's opinion, might indicate that the increase in duty rate provided for in this proclamation is no longer necessary.

(10) No drawback shall be available with respect to the duties imposed pursuant to this proclamation.

(11) The Secretary may issue regulations and guidance consistent with this proclamation, including to address operational necessity.

(12) CBP may take any necessary or appropriate measures to administer the tariffs imposed by this proclamation.

(13) Any provision of previous proclamations and Executive Orders that is inconsistent with the actions taken in this proclamation is superseded to the extent of such inconsistency.

IN WITNESS WHEREOF, I have hereunto set my hand this twenty-sixth day of March, in the year of our Lord two thousand twenty-five, and of the Independence of the United States of America the two hundred and forty-ninth.



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PRESIDENTIAL ACTIONS

AMENDMENTS TO ADJUSTING IMPORTS OF AUTOMOBILES AND AUTOMOBILE PARTS INTO THE
UNITED STATES

Proclamations

April 29, 2025

BY THE PRESIDENT OF THE UNITED STATES OF AMERICA

A PROCLAMATION

1. On February 17, 2019, the Secretary of Commerce (Secretary) transmitted to me a report on his investigation into the effects of imports of passenger vehicles (sedans, sport utility vehicles, crossover utility vehicles, minivans, and cargo vans) and light trucks (collectively, automobiles) and certain automobile parts (engines and engine parts, transmissions and powertrain parts, and electrical components) (collectively, automobile parts) on the national security of the United States under section 232 of the Trade Expansion Act of 1962, as amended (19 U.S.C. 1862) (section 232). Based on the facts considered in that investigation, the Secretary found and advised me of his opinion that automobiles and certain automobile parts are being imported into the United States in such quantities and under such circumstances as to threaten to impair the national security of the United States.
2. In Proclamation 9888 of May 17, 2019 (Adjusting Imports of Automobiles and Automobile Parts Into the United States), I concurred with the Secretary's finding in the February 17, 2019, report that automobiles and certain automobile parts are being imported into the United States in such quantities and under such circumstances as to

threaten to impair the national security of the United States. I directed the United States Trade Representative (Trade Representative), in consultation with other executive branch officials, to pursue negotiation of agreements to address the threatened impairment of the national security of the United States with respect to imported automobiles and certain automobile parts from certain countries. The Trade Representative's negotiations did not lead to any agreements of the type contemplated by section 232. I also directed the Secretary to monitor imports of automobiles and certain automobile parts and inform me of any circumstances that, in the Secretary's opinion, might indicate the need for further action under section 232 with respect to such imports.

3. In Proclamation 10908 of March 26, 2025 (Adjusting Imports of Automobiles and Automobile Parts Into the United States), I found, based on information newly provided by the Secretary, that imports of automobiles and certain automobile parts continued to threaten to impair the national security of the United States and deemed it necessary and appropriate to impose a tariff system to adjust imports of automobiles and certain automobile parts so that such imports will not threaten to impair national security. The tariffs on automobiles have been in effect since 12:01 a.m. eastern daylight time on April 3, 2025; the tariffs on automobile parts are set to go into effect on or after 12:01 a.m. eastern daylight time on May 3, 2025.

4. In Proclamation 10908, I also deemed it necessary and appropriate to establish processes to identify and impose tariffs on additional automobile parts to ensure that the tariffs on automobiles and certain automobile parts are not circumvented and that the purpose of this action to eliminate the threat to the national security of the United States by imports of automobiles and certain automobile parts is not undermined. I directed the Secretary to set up such a process within 90 days of the date of Proclamation 10908.

5. In Proclamation 10908, I also directed the Secretary to continue to monitor imports of automobiles and automobile parts, to review the status of such imports with respect to national security, and to inform me of any circumstances that, in the Secretary's opinion, might indicate the need for further action by the President under section 232. The Secretary has advised me that additional action is warranted in the interest of meeting the national security objectives outlined in Proclamation 10908.

6. In my judgment, it is necessary and appropriate to modify the system of monetary fees and related measures imposed to adjust imports of automobiles and certain

automobile parts pursuant to Proclamation 10908 to more effectively eliminate the threat imports of automobiles and certain automobile parts pose on the national security of the United States.

7. I determine that the modified system, by linking the ultimate monetary fee imposed on imports of automobile parts to the imports' use in assembly of automobiles within the United States, in the way and on the timeline described below, will adjust imports of automobiles and automobile parts and more effectively eliminate such imports' threat to impair national security. I find that the modified system will more effectively eliminate the national security threat because it will more quickly reduce reliance on foreign manufacturing and importation of automobiles and automobile parts; strengthen United States vehicle assembly operations by encouraging companies to expand domestic production capacity, which is critical to a strong domestic defense industrial base; shift manufacturing activity into the United States; increase domestic automotive research and development so that American-owned producers can produce cutting-edge technologies that are essential to the United States defense industrial base and our military superiority; create jobs in the automotive industry that increase the number of employees in the domestic automotive industry; and ensure that other benefits of production are concentrated in the United States.

8. Section 232 authorizes the President to adjust the imports of an article and its derivatives that are being imported into the United States in such quantities or under such circumstances as to threaten to impair the national security of the United States so that such imports will not threaten to impair national security.

9. Section 604 of the Trade Act of 1974, as amended (19 U.S.C. 2483), authorizes the President to embody in the Harmonized Tariff Schedule of the United States (HTSUS) the substance of statutes affecting import treatment, and actions thereunder, including the removal, modification, continuance, or imposition of any rate of duty or other import restriction.

NOW, THEREFORE, I, DONALD J. TRUMP, President of the United States of America, by the authority vested in me by the Constitution and the laws of the United States of America, including section 301 of title 3, United States Code; section 604 of the Trade Act of 1974, as amended; and section 232 of the Trade Expansion Act of 1962, as amended, do hereby proclaim as follows:

(1) To more effectively eliminate the threat to impair national security posed by imports of automobiles and automobile parts, I find that it is necessary to modify the system

imposed in Proclamation 10908 by reducing duties assessed on automobile parts accounting for 15 percent of the value of an automobile assembled in the United States for 1 year and equivalent to 10 percent of that value for an additional year as follows:

(a) For automobiles assembled in the United States, automobile manufacturers shall be eligible to receive an import adjustment offset amount applicable to section 232 duties on automobile parts based on the following schedule:

(i) The automobile manufacturer may apply for an import adjustment offset amount equal to 3.75 percent of the aggregate Manufacturer's Suggested Retail Price (MSRP) value of all automobiles assembled in the United States from April 3, 2025, through April 30, 2026.

(ii) The automobile manufacturer may apply for an import adjustment offset amount equal to 2.5 percent of the aggregate MSRP value of all automobiles assembled in the United States from May 1, 2026, through April 30, 2027.

(b) The percentage rate provided in subsection (i) reflects the total duty that would be owed when a 25 percent duty is applied to parts accounting for 15 percent of an automobile's MSRP value. The percentage rate provided in subsection (ii) reflects the total duty that would be owed when a 25 percent duty is applied to parts accounting for 10 percent of an automobile's MSRP value.

(c) Only automobiles that undergo final assembly in the United States are eligible to be included in this calculation. The manufacturer's import adjustment offset amount may only be used by importers of record authorized by that manufacturer, and the amount may only be used to offset tariff liability related to that manufacturer's automobile parts tariff liability under Proclamation 10908. Should a manufacturer's import adjustment offset amount exceed the total amount attributable to that manufacturer's automobile parts tariff liability under Proclamation 10908, the relief is capped at the total amount of that manufacturer's automobile parts tariff liability under Proclamation 10908, and the manufacturer may not use the additional amount above that cap to offset any other tariff liability. A manufacturer with an approved import adjustment offset amount may determine the importers of record eligible to decrement against that manufacturer's import adjustment offset amount, and that list of importers of record may include suppliers in that manufacturer's supply chain for automobiles assembled in the United States if the manufacturer so chooses.

(2) (a) Within 30 days of the date of this order, the Secretary shall establish a process by which manufacturers seeking an import adjustment offset amount shall submit to

the Secretary:

- (i) documentation certifying the number of automobiles the manufacturer projects it will assemble in the United States, as well as a list of all plant locations where the projected automobiles will undergo final production;
- (ii) documentation certifying the manufacturer's projected cost of tariffs due to imported automobile parts subject to Proclamation 10908, broken down by tariff costs the manufacturer will incur directly and tariff costs the manufacturer will incur from its suppliers;
- (iii) documentation detailing the total import adjustment offset amount requested within the schedule determined by the Secretary in accordance with this proclamation;
- (iv) documentation identifying the importer(s) of record, including importer of record numbers, eligible to use that manufacturer's import adjustment offset amount, as well as the amount of the manufacturer's offset amount allotted to each importer of record; and
- (v) a certification, signed by a senior officer of the manufacturer, attesting under penalty of perjury that the information submitted under subsections (i) through (iv) is true, complete, and accurate to the best of the manufacturer's knowledge, and that the manufacturer has conducted reasonable due diligence to verify the accuracy of the assertions and facts contained in its submissions.

(b) Upon verification of the completeness and accuracy of a manufacturer's submission and the manufacturer's eligibility, the Secretary shall approve the application and notify U.S. Customs and Border Protection (CBP) with the information necessary for CBP to administer and implement the manufacturer's import adjustment offset amount, including importer of record number(s) for the importer(s) eligible to use each offset amount and the approved import adjustment offset amount. CBP shall confer the approved offset amount to the approved importer(s) of record using processes and mechanisms consistent with CBP's operational framework and tariff administration procedures, including offset against current tariff obligations due at the time of entry, or other lawful methods.

(3) The Secretary, in consultation with the Secretary of the Treasury and the Commissioner of CBP, shall issue such regulations, guidance, and procedures as necessary to carry out the provisions of this proclamation and Proclamation 10908, and may establish standards for determining United States content and for validating manufacturer certifications.

(4) The Secretary, in consultation with the United States International Trade

Commission and CBP, shall determine whether modifications to the HTSUS are necessary to effectuate this proclamation and may make such modifications through notice in the *Federal Register* if needed.

(5) CBP shall begin providing approved importers with an import adjustment offset amount as soon as practicable and may request information from importers of record as necessary to implement a particular manufacturer's import adjustment offset amount.

(6) Should an importer claim and receive any import adjustment offset amount from CBP in excess of the amount approved by the Secretary, CBP may assess monetary penalties in the maximum amount permitted by law.

(7) The Secretary shall continue to monitor imports of automobiles and automobile parts. The Secretary also shall, from time to time, in consultation with any senior executive branch officials the Secretary deems appropriate, review the status of such imports with respect to national security. The Secretary shall inform the President of any circumstances that, in the Secretary's opinion, might indicate the need for further action by the President under section 232. The Secretary shall also inform the President of any circumstance that, in the Secretary's opinion, might indicate that the duty rate provided for in Proclamation 10908, or any proclamation issued pursuant thereto, is no longer necessary.

(8) Any provision of previous proclamations and Executive Orders that is inconsistent with the actions taken in this proclamation is superseded to the extent of such inconsistency. This proclamation shall apply in accordance with the Executive Order of April 29, 2025 (Addressing Certain Tariffs on Imported Articles).

IN WITNESS WHEREOF, I have hereunto set my hand this
twenty-ninth day of April, in the year of our Lord two thousand twenty-five, and of the Independence of the United States of America the two hundred and forty-ninth.

DONALD J. TRUMP

PRESIDENTIAL ACTIONS

ADJUSTING IMPORTS OF MEDIUM- AND HEAVY-DUTY VEHICLES, MEDIUM-
AND HEAVY-DUTY VEHICLE PARTS, AND BUSES INTO THE UNITED STATES

Proclamations

October 17, 2025

BY THE PRESIDENT OF THE UNITED STATES OF AMERICA
A PROCLAMATION

1. Three weeks ago, the Secretary of Commerce (Secretary) transmitted to me a report on his investigation into the effects of imports of medium- and heavy-duty vehicles (MHDVs) (such as trucks), medium- and heavy-duty vehicle parts (MHDVPs), and buses on the national security of the United States under section 232 of the Trade Expansion Act of 1962, as amended, 19 U.S.C. 1862 (section 232). Based on the facts considered in that investigation, the Secretary found and advised me of his opinion that MHDVs, certain MHDVPs, and buses are being imported into the United States in such quantities and under such circumstances as to threaten to impair the national security of the United States and provided recommendations for action under section 232 to adjust the imports of MHDVs, certain MHDVPs, and buses so that such imports will not threaten to impair the national security of the United States.
2. The Secretary found that MHDVs are essential to United States national security. MHDVs and MHDVPs play a vital role in sustaining national security by enabling the Department of War to maintain military readiness. They do so by enabling the transport of personnel, weapons systems, ground defense vehicles, and critical supplies. In addition to aiding critical ground mobility, combat support, and logistics operations throughout all branches of the military, MHDVs and MHDVPs support emergency

response across medical, law enforcement, and disaster relief efforts by providing mobile coordination, evacuation, and field-operations capabilities. Beyond crisis scenarios, MHDVs are indispensable to the continuity of American critical infrastructure and economic stability, moving over 70 percent of the Nation's freight by weight, including essential goods like food, fuel, and medical supplies.

3. The Secretary also found that import penetration from foreign assemblers of MHDVs is substantial and growing. From the 1950s through the 1990s, the United States was an undisputed leader in MHDV manufacturing, with iconic American brands like Ford, General Motors, Chrysler, and others producing nearly all MHDVs domestically.

Offshoring of MHDV manufacturing, enabled by foreign industrial practices and other policies, has resulted in an import penetration level of 43 percent of Class 4 through 8 MHDVs sold on the United States market. The United States suffers 50 percent import penetration in Class 8 MHDVs — the heaviest-duty trucks. American companies continue to shift production outside the United States because of favorable dynamics for offshoring.

4. Further, the Secretary found that the United States relies on foreign suppliers for several important categories of MHDVPs. The domestic truck industry is dependent on engines, batteries, transmission shafts, castings, forgings, and other MHDVPs at a level that creates national security vulnerabilities. The supply chain for MHDVPs is much less diversified than for domestic passenger vehicles and light trucks, with significantly fewer United States producers of MHDVPs. Without a secure domestic supply chain for critical MHDVPs, a disruption of imports could strain the ability to execute national defense missions and critical infrastructure requirements, such as transporting personnel, weapons, or essential supplies in a conflict or an emergency.

5. The Secretary also found that there is significant overlap in the components, materials, and manufacturing capacity between the MHDV industry and the bus industry, including because many MHDVPs are used as components in buses. The Secretary noted that buses are vital for United States national security because they directly support, among other things, United States military troop movements, Government disaster response and evacuations, and basic operations in critical infrastructure sectors like energy, healthcare, and emergency services. Yet, as the Secretary found, the bus industry is at risk of becoming overly dependent on foreign supply chains, including MHDVP suppliers, and the United States trade balance in buses

has worsened in recent years. The Secretary determined that this risk of dependency threatens the national security of the United States.

6. In light of these findings, the Secretary recommended a range of actions, including actions to adjust the imports of MHDVs, certain MHDVPs, and buses so that such imports will not threaten to impair the national security. For example, the Secretary recommended that I impose a 25 percent *ad valorem* duty on MHDVs and key MHDVPs and a 10 percent *ad valorem* duty on buses. The Secretary recommended that I conform the previously established section 232 automobile tariff program with any program I establish to adjust the imports of MHDVs and MHDVPs. The Secretary also recommended that the goal of the adjustment of MHDV imports should be a long-term stabilization of United States-produced MHDVs' market share at approximately 80 percent in order to achieve the adjustments' national security objective.

7. After considering the Secretary's report, the factors in section 232(d) (19 U.S.C. 1862(d)), and other relevant factors and information, I concur with the Secretary's finding that imports of MHDVs, certain MHDVPs, and buses threaten to impair the national security of the United States. In my judgment, and in light of the Secretary's report, the factors in section 232(d) (19 U.S.C. 1862(d)), and other relevant factors and information, I also determine that it is necessary and appropriate to impose a tariff system, as described below, to adjust imports of MHDVs, certain MHDVPs, and buses so that such imports will not threaten to impair the national security of the United States.

8. In my judgment, the actions in this proclamation will, among other things, strengthen supply chains; bolster industrial resilience; create high-quality jobs that will expand the skilled workforce in the United States; and increase domestic capacity utilization and United States-produced market share for MHDVs, certain MHDVPs, and buses. These actions will also encourage capital investment and drive innovation in the United States industries for MHDVs, MHDVPs, and buses, and will strengthen the ability of the military and national defense industry to domestically produce key defense systems and products that support critical ground mobility, combat, and logistics operations. Modernization and renewed investment will curb further erosion of the United States truck and bus industries and improve their efficiency, resource utilization, and product yield. These actions will adjust the imports of MHDVs, certain MHDVPs, and buses so that imports of these products do not threaten to impair the national security.

9. To ensure that the imposition of tariffs on MHDVs, certain MHDVPs, and buses in this proclamation is not circumvented or that the purpose of this action to eliminate the

threat to the national security of the United States by imports of MHDVs, certain MHDVPs, and buses is not undermined, I also deem it necessary and appropriate to establish a process to identify and impose tariffs on additional MHDVPs, as further described below.

10. In addition, given the close connections and overlap between part suppliers for the automobile industry and for the medium- and heavy-duty vehicle industry, I determine that it is necessary and appropriate to conform certain aspects of the tariff system imposed in Proclamation 10908 of March 26, 2025 (Adjusting Imports of Automobiles and Automobile Parts Into the United States), as amended, with the tariff system imposed in this proclamation for MHDVs, certain MHDVPs, and buses. In my judgment, conforming the tariff system imposed in Proclamation 10908, as amended, to address the national security threat found in Proclamation 9888 of May 17, 2019 (Adjusting Imports of Automobiles and Automobile Parts Into the United States), as amended, with the tariff system imposed in this proclamation for MHDVs, certain MHDVPs, and buses will more effectively address the national security threat found in Proclamation 9888, as amended, and the national security threat found in this proclamation.

11. Section 232 authorizes the President to adjust the imports of an article and its derivatives that are being imported into the United States in such quantities or under such circumstances as to threaten to impair the national security so that such imports will not threaten to impair the national security.

12. Section 604 of the Trade Act of 1974, as amended (19 U.S.C. 2483) (section 604), authorizes the President to embody in the Harmonized Tariff Schedule of the United States (HTSUS) the substance of statutes affecting import treatment, and actions thereunder, including the removal, modification, continuance, or imposition of any rate of duty or other import restriction.

NOW, THEREFORE, I, DONALD J. TRUMP, President of the United States of America, by the authority vested in me by the Constitution and the laws of the United States of America, including section 232, the International Emergency Economic Powers Act (50 U.S.C. 1701 *et seq.*), section 604, and section 301 of title 3, United States Code, do hereby proclaim as follows:

(1) Except as otherwise provided in this proclamation, all imports of MHDVs and the MHDVPs specified in Annex I to this proclamation, or in any action designed to address the national security threat found in this proclamation, shall be subject to a 25 percent *ad valorem* duty rate, except for buses and other vehicles classified in HTSUS heading

8702, which shall be subject to a 10 percent *ad valorem* duty rate. These tariffs shall apply to goods entered for consumption or withdrawn from warehouse for consumption on or after 12:01 a.m. eastern daylight time on November 1, 2025, and shall continue in effect, unless such actions are expressly reduced, modified, or terminated. The above tariffs are in addition to any other duties, taxes, fees, exactions, and charges applicable to such products, except as otherwise specified herein.

(2) For MHDVs, except for buses and other vehicles classified in HTSUS heading 8702, that qualify for preferential tariff treatment under the United States-Mexico-Canada Agreement (USMCA), importers of such products may submit documentation to the Secretary identifying the amount of United States content in each model imported into the United States. The term “United States content” refers to the value of the MHDV attributable to United States-based activity supporting domestic production, as determined by the Secretary. Thereafter, the Secretary may approve imports of such MHDVs to be eligible to apply the *ad valorem* duty rate of 25 percent in clause (1) of this proclamation exclusively to the value of the non-United States content of the MHDV. The non-United States content of the MHDV shall be calculated by subtracting the value of the United States content in an MHDV from the total value of the MHDV.

(3) Imports of individual MHDVPs within the scope of the tariffs described in clause (1) of this proclamation that qualify for preferential tariff treatment under the USMCA shall not be subject to the additional *ad valorem* duty rate imposed under this proclamation until such time that the Secretary, in consultation with the Commissioner of U.S. Customs and Border Protection (CBP), establishes a process to apply the tariff exclusively to the value of the non-United States content of such MHDVPs and publishes a notice in the *Federal Register*. Imports of MHDV knock-down kits or equivalent parts compilations, as determined by CBP, shall continue to be subject to the additional *ad valorem* duty rate imposed under this proclamation regardless of USMCA preferential treatment qualification.

(4) I find that it is necessary to reduce duties assessed on MHDVPs accounting for 15 percent of the value of an MHDV assembled in the United States from 2025 through 2030. Accordingly:

(a) For MHDVs assembled in the United States, MHDV manufacturers shall be eligible to receive an import adjustment offset. An MHDV manufacturer may apply to the Secretary for an import adjustment offset amount equal to 3.75 percent of the aggregate

value of all MHDVs assembled in the United States by that manufacturer, as determined annually by the Secretary, from November 1, 2025, through October 31, 2030.

(b) The percentage rate provided in subsection (a) of this clause reflects the total duty that would be owed when a 25 percent duty is applied to parts accounting for 15 percent of an MHDV's value.

(c) Only MHDVs that undergo final assembly in the United States are eligible to be included in this calculation. The manufacturer's import adjustment offset amount may be used only by importers of record authorized by that manufacturer.

(d) A manufacturer's import adjustment offset amount may be used only to offset tariff liability related to that manufacturer's MHDVP tariff liability under clauses (1), (7), or (12) of this proclamation.

(e) Consistent with the need to address the national security threat found in this proclamation, the Secretary shall establish a process for MHDV engine manufacturers equivalent to the process described in subsections (a) through (d) of this clause. Import adjustment offsets for these engine manufacturers shall be based on the aggregate value of MHDV engines assembled by that manufacturer in the United States and shall follow the same accrual percentage rate and United States assembly requirement as the import adjustment offsets for MHDV manufacturers specified in subsections (a) through (d) of this clause.

(f) If the Secretary finds that the import adjustment offset program for a particular product is inconsistent with addressing the threat to the national security found in this proclamation, the Secretary may publish in the *Federal Register* a notice that prospectively prohibits MHDV or MHDV engine manufacturers from using offset amounts for imports of those products.

(g) Imports of MHDV knock-down kits or other equivalent parts compilations, as determined by CBP, shall not be eligible for import adjustment offsets of the sort specified in this clause.

(5) The Secretary shall take all necessary steps to implement the import adjustment offset program outlined in clause (4) of this proclamation, including supplying CBP with the information necessary for CBP to administer and implement the import adjustment offset, such as importer of record number(s) for the importer(s) eligible to use each offset amount and the approved import adjustment offset amount. CBP shall confer the approved offset amount to the approved importer(s) of record using processes and mechanisms consistent with CBP's operational framework and tariff administration

procedures, including by applying the offset against current tariff obligations due at the time of entry, or by using other lawful methods.

(6) If CBP determines that the declared value of non-United States content of imports under clause (2) of this proclamation is inaccurate due to an overstatement of United States content, the 25 percent tariff specified in clause (1) of this proclamation shall apply to the full value of the MHDV, regardless of the actual United States content. In addition, the 25 percent tariff specified in clause (1) of this proclamation shall be applied to the full value of all MHDVs of the same model imported by the same importer or responsible party from the date of the inaccurate declaration until compliance is verified by CBP. This clause does not apply to or otherwise affect any other applicable duties, taxes, fees, exactions, or charges.

(7) The Secretary shall establish a process for including additional MHDVPs within the scope of the tariffs established in clause (1) of this proclamation. The Secretary may add MHDVPs within the scope of the tariffs established in clause (1) of this proclamation if — after considering the information from the Secretary’s monitoring of imports of MHDVs, MHDVPs, and buses, as well as any factor the Secretary deems appropriate — the Secretary determines that inclusion of the import will reduce or eliminate the national security threat found in this proclamation. Appropriate factors may include the factors in section 232(d) (19 U.S.C. 1862(d)) and whether the imports of MHDVs, MHDVPs, and buses have increased in a manner that threatens to impair the national security of the United States or otherwise undermines the objectives set forth in this proclamation. The process the Secretary establishes may include provisions for the receipt of information and requests for additions of specific MHDVPs from domestic producers of MHDVPs or other interested entities or individuals.

(8) Any product subject to tariffs pursuant to this proclamation, except those eligible for admission under “domestic status” as defined in 19 C.F.R. 146.43, that is admitted into a United States foreign trade zone on or after the effective date of this proclamation, as set forth in clause (1) of this proclamation, must be admitted in “privileged foreign status” as defined in 19 C.F.R. 146.41, and will be subject upon entry for consumption to any duties related to the classification under the applicable HTSUS subheading.

(9) The application of multiple tariffs (stacking) for imports of MHDVs, MHDVPs, and buses subject to this proclamation shall follow the same rules for stacking for imports subject to Proclamation 10908, as amended. For purposes of Executive Order 14289 of April 29, 2025 (Addressing Certain Tariffs on Imported Articles), as amended, a product

remains “subject to” this proclamation or Proclamation 10908, as amended, even if the tariff imposed by these two proclamations is not owed and payable due to compliance with USMCA rules of origin, use of an offset adjustment, or tariff reductions effected through the implementation of agreements on trade and security.

(10) The tariffs imposed under clauses (1) through (3) of this proclamation shall not apply to MHDVs or buses and other vehicles classified in HTSUS heading 8702 that were manufactured in a year at least 25 years prior to the date of entry of those MHDVs or buses.

(11) Clause (1) of Proclamation 10925 of April 29, 2025 (Amendments to Adjusting Imports of Automobiles and Automobile Parts Into the United States), is revised to read as follows:

“(1) To more effectively eliminate the threat to impair national security posed by imports of automobiles and certain automobile parts, I find that it is necessary to reduce duties assessed on automobile parts accounting for 15 percent of the value of an automobile assembled in the United States from 2025 through 2030. Accordingly:

(a) Automobile manufacturers may apply to the Secretary for an import adjustment offset amount equal to 3.75 percent of the aggregate Manufacturer’s Suggested Retail Price (MSRP) value of all automobiles assembled in the United States by the manufacturer, as determined annually by the Secretary, from April 5, 2025, through April 30, 2030.

(b) The percentage rate provided in subsection (a) of this clause reflects the total duty that would be owed when a 25 percent duty is applied to parts accounting for 15 percent of an automobile’s value.

(c) The Secretary shall establish an import adjustment offset equivalent to that specified in subsections (a) and (b) of this clause for automobile engine manufacturers. Offset accrual for these engine manufacturers shall be based on the aggregate value of automobile engines assembled in the United States by the engine manufacturer and shall follow the same accrual percentage rate and United States assembly restriction as the offset program for automobile manufacturers specified in subsection (a) of this clause.

(d) Only automobiles that undergo final assembly in the United States are eligible to be included in this calculation. The manufacturer’s import adjustment offset amount may be used only by importers of record authorized by that manufacturer.

(e) A manufacturer's import adjustment offset amount may be used only to offset tariff liability related to that manufacturer's automobile parts tariff liability under Proclamation 10908, as amended, or under clause (12) of the Proclamation of October 17, 2025 (Adjusting Imports of Medium- and Heavy-Duty Vehicles, Medium- and Heavy-Duty Vehicle Parts, and Buses Into the United States).

(f) If the Secretary finds that the offset program is not fulfilling the purposes of Proclamation 10908, as amended, for particular products, the Secretary may publish in the *Federal Register* a notice that prospectively prohibits automobile or automobile engine manufacturers from using their offset amount for imports of those products.

(g) Imports of automobile knock-down kits or other equivalent parts compilations, as determined by CBP, shall not be eligible for import adjustment offsets.”.

(12) An importer of record may declare an automobile part or MHDVP as subject to the automobile parts tariff pursuant to Proclamation 10908, as amended, or to the MHDVP tariff pursuant to this proclamation. For an automobile or MHDV part to be eligible for this treatment, the part must meet the following conditions:

(a) the part cannot be presently subject to the tariffs imposed pursuant to Proclamation 10908, as amended, or this proclamation;

(b) the part cannot be classifiable in Chapters 72, 73, or 76 of the HTSUS; and

(c) the part must be used for automobile- or MHDV-related production or repair activity in the United States, as attested to by certification from the importer of record.

(13) To more effectively address the national security threats found in Proclamation 9704 of March 8, 2018 (Adjusting Imports of Aluminum Into the United States), as amended; Proclamation 9705 of March 8, 2018 (Adjusting Imports of Steel Into the United States); Proclamation 9888, as amended; and this proclamation, I deem it necessary and appropriate to allow modification of tariffs imposed under Proclamation 9704, as amended, and Proclamation 9705, as amended, based on certain increased commitments of certain steel or aluminum products that support United States production capacity of key products, including United States automobiles and MHDVs. Accordingly, the Secretary is authorized to reduce tariffs owed under Proclamation 9704, as amended, and Proclamation 9705, as amended, by up to half the applicable rate for aluminum or steel producers that operate production facilities in Canada or Mexico and supply United States automobile or MHDV manufacturers. Such adjustments shall be limited to quantities of aluminum or steel equal to newly committed United States production capacity, as determined by the Secretary. In no cases shall the adjusted rate

under Proclamation 9704, as amended, and Proclamation 9705, as amended, be lower than 25 percent. Rate adjustments shall also be limited to imports of aluminum and steel that qualify for preferential tariff treatment under the USMCA and that were smelted and cast or melted and poured in Canada or Mexico. Any adjustment by the Secretary shall be consistent with the need to address the national security threats I have found under section 232, including in Proclamation 9704, as amended; Proclamation 9705, as amended; Proclamation 9888, as amended; and this proclamation.

(14) The Secretary shall continue to monitor imports of MHDVs, certain MHDVPs, and buses. The Secretary also shall, from time to time, in consultation with any senior executive branch officials the Secretary deems appropriate, review the status of such imports with respect to the national security. The Secretary shall inform the President of any circumstances that, in the Secretary's opinion, might indicate the need for further action by the President under section 232. The Secretary shall also inform the President of any circumstance that, in the Secretary's opinion, might indicate that the increase in duty rate provided for in this proclamation is no longer necessary.

(15) As of the effective date of this proclamation, only manufacturing drawback claims made in accordance with subsections (a) and (b) of section 313 of the Tariff Act of 1930, as amended, 19 U.S.C. 1313(a)–(b), and no other drawback, shall be available with respect to the duties imposed on MHDVPs pursuant to this proclamation and on automobile parts pursuant to Proclamation 10908, as amended. The Secretary may adjust a company's offset accrual amount as necessary to avoid awarding excessive offset accrual benefits for United States-assembled vehicles production that receives drawback benefits upon exportation.

(16) The Secretary, in consultation with the Chair of the United States International Trade Commission and the Commissioner of CBP, shall determine the modifications necessary to the HTSUS to effectuate this proclamation and shall make such modifications to the HTSUS through notice in the *Federal Register*.

(17) To the extent consistent with applicable law and the purpose of this proclamation; Proclamation 9704, as amended; Proclamation 9705, as amended; and Proclamation 10908, as amended, the Secretary and the Secretary of Homeland Security are directed and authorized to take all actions that are appropriate to implement and effectuate this proclamation and any actions contemplated by this proclamation; Proclamation 9704, as amended; Proclamation 9705, as amended; and Proclamation 10908, as amended,

including, consistent with applicable law, the issuance of regulations, rules, guidance, and procedures and the temporary suspension or amendment of regulations, within their respective jurisdictions, and to employ all powers granted to the President under section 232. The Secretary and the Secretary of Homeland Security may, consistent with applicable law, including 3 U.S.C. 301, redelegate any of these functions within their respective departments. All executive departments and agencies shall take all appropriate measures to implement and effectuate this proclamation and Proclamation 10908, as amended.

(18) The Secretary may issue regulations and guidance consistent with this proclamation, including to address operational necessity.

(19) CBP may take any necessary or appropriate measures to administer the tariffs imposed by this proclamation.

(20) Any provision of previous proclamations and Executive Orders that is inconsistent with the actions taken in this proclamation is superseded to the extent of such inconsistency. If any provision of this proclamation or the application of any provision to any individual or circumstance is held to be invalid, the remainder of this proclamation and the application of its provisions to any other individuals or circumstances shall not be affected.

IN WITNESS WHEREOF, I have hereunto set my hand this seventeenth day of October, in the year of our Lord two thousand twenty-five, and of the Independence of the United States of America the two hundred and fiftieth.

DONALD J. TRUMP

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Fact Sheet: President Donald J. Trump Ensures National Security and Economic Resilience
Through Section 232 Actions on Processed Critical Minerals and Derivative Products

The White House

April 15, 2025

BOLSTERING AMERICA’S CRITICAL MINERALS FUTURE: Today, President Donald J. Trump signed an Executive Order launching an investigation into the national security risks posed by U.S. reliance on imported processed critical minerals and their derivative products.

- The Order directs the Secretary of Commerce to initiate a Section 232 investigation under the Trade Expansion Act of 1962 to evaluate the impact of imports of these materials on America’s security and resilience.
- This investigation will assess vulnerabilities in supply chains, the economic impact of foreign market distortions, and potential trade remedies to ensure a secure and sustainable domestic supply of these essential materials.
- The investigation will culminate in a report detailing risks and providing recommendations to strengthen domestic production, reduce dependence on foreign suppliers, and enhance economic and national security.
- If the Secretary of Commerce submits a report finding that imports of critical-mineral articles threaten to impair national security and the President decides to impose tariffs, any resulting tariff rate imposed under Section 232 would take the place of the current reciprocal tariff rate, pursuant to President Trump’s April 2 order.

COUNTERING THREATS TO NATIONAL SECURITY AND ECONOMIC STABILITY:

President Trump recognizes that an overreliance on foreign critical minerals and their derivative products could jeopardize U.S. defense capabilities, infrastructure development, and technological innovation.

- Critical minerals, including rare earth elements, are essential for national security and economic resilience.
 - Processed critical minerals and their derivative products are key building blocks of our defense industrial base and integral to applications such as jet engines, missile guidance systems, advanced computing, radar systems, advanced optics, and secure communications equipment.
- The United States remains heavily dependent on foreign sources, particularly adversarial nations, for these essential materials, exposing the economy and defense sector to supply chain disruptions and economic coercion.
- Foreign producers have engaged in price manipulation, overcapacity, and arbitrary export restrictions, using their supply chain dominance as a tool for geopolitical and economic leverage over the United States.
- A few months ago, China banned exports to the United States of gallium, germanium, antimony, and other key high-tech materials with potential military applications.
- Just this week, China suspended exports of six heavy rare earth metals, as well as rare earth magnets, in order to choke off supplies of components central to automakers, aerospace manufacturers, semiconductor companies and military contractors around the world.

STRENGTHENING AMERICAN INDUSTRY: This Executive Order builds on previous actions taken by the Trump Administration to ensure U.S. trade policy serves the nation's long-term interests.

- On Day One, President Trump initiated his America First Trade Policy to make America's economy great again.
- On Liberation Day, President Trump imposed a 10% tariff on all countries and individualized reciprocal higher tariffs on nations with which the U.S. has the largest trade deficits in order to level the playing field and protect America's national security.
 - More than 75 countries have already reached out to discuss new trade deals.
 - As a result, the individualized higher tariffs are currently paused amid these discussions, except for China, which retaliated.

- China faces up to a 245% tariff on imports to the United States as a result of its retaliatory actions.
 - This includes a 125% reciprocal tariff, a 20% tariff to address the fentanyl crisis, and Section 301 tariffs on specific goods, between 7.5% and 100%.
- President Trump signed proclamations to close existing loopholes and exemptions to restore a true 25% tariff on steel and elevate the tariff to 25% on aluminum.
- President Trump unveiled the “Fair and Reciprocal Plan” on trade to restore fairness in U.S. trade relationships and counter non-reciprocal trade agreements.
- President Trump signed a memorandum to safeguard American innovation, including the consideration of tariffs to combat digital service taxes (DSTs), fines, practices, and policies that foreign governments levy on American companies.
- President Trump signed similar Executive Orders launching investigations into how imports of copper and imports of timber, lumber, and their derivative products threaten America’s national security and economic stability.



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Comprehensive Information on the California Vehicle Market

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New Vehicle Registrations Predicted to Decline in Second Half of '25

KEY TRENDS IN NEW VEHICLE MARKET



Market got off to a strong start in first half of this year

State new light vehicle registrations increased 6.6 percent during the first six months of this year versus a year earlier, identical to the U.S. market.

New vehicle sales outlook expected to take a turn

The prospects of higher tariffs will likely lead to rising vehicle prices, and at least in the short run, increasing inflation, lower economic growth, and stagnant household disposable income, all negatives for new vehicle sales. In addition, sales were pulled ahead this year as shoppers advanced purchases due to the anticipation of higher vehicle prices resulting from tariffs.

Registrations expected to decline in second half of 2025

New vehicle registrations in the second half of the year are projected to decline by about nine percent from the year earlier. Annual total is projected to fall just short of the 1.75 million units in 2024.

There is heightened uncertainty with the new vehicle sales outlook

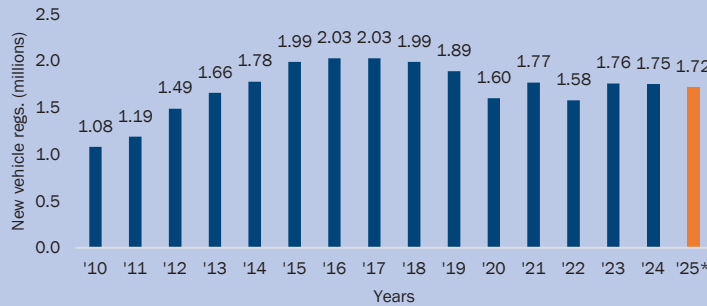
At present, this forecast is a worst case scenario. Baseline assumption is that there will be a measurable increase in tariffs that will remain in place for an extended period. If tariffs revert to levels at the beginning of this year, state registrations could exceed 1.8 million units

Hybrid vehicles post big gains; ZEV share continues to slide

Hybrid vehicle registrations increased 54 percent in the first half of this year and accounted for 19.2 percent of the market. ZEV share in 2Q '25 fell to 18.2 percent, but is likely to increase in 3Q as consumers purchase vehicles before federal government incentives expire at the of September.

California Annual New Light Vehicle Registrations - 2010 thru 2025

ANNUAL TRENDS



Historical Data sourced from Experian Automotive. *2025 forecast by Auto Outlook. Projections do not reflect potential sales reductions due to non-economic regulatory impacts. Historical figures have been updated since the previous release.

California and U.S. New Light Vehicle Registrations
Year to date 2024 and 2025 thru June

TWO YEAR PERSPECTIVE



	California			U.S.		
	YTD '24	YTD '25	Change	YTD '24	YTD '25	Change
Registrations						
TOTAL	886,492	944,834	6.6%	7,730,864	8,240,579	6.6%
Car	245,231	249,010	1.5%	1,475,524	1,448,691	-1.8%
Light Truck	641,261	695,824	8.5%	6,255,340	6,791,888	8.6%
Domestic	294,654	304,007	3.2%	3,219,946	3,441,745	6.9%
European	131,748	134,257	1.9%	788,862	807,849	2.4%
Japanese	375,255	409,547	9.1%	2,924,754	3,091,737	5.7%
Other Asian	84,835	97,023	14.4%	797,302	899,248	12.8%
Market Share						
Car	27.7	26.4	-1.3	19.1	17.6	-1.5
Light Truck	72.3	73.6	1.3	80.9	82.4	1.5
Domestic	33.2	32.2	-1.0	41.7	41.8	0.1
European	14.9	14.2	-0.7	10.2	9.8	-0.4
Japanese	42.4	43.3	0.9	37.8	37.5	-0.3
Other Asian	9.6	10.3	0.7	10.3	10.9	0.6

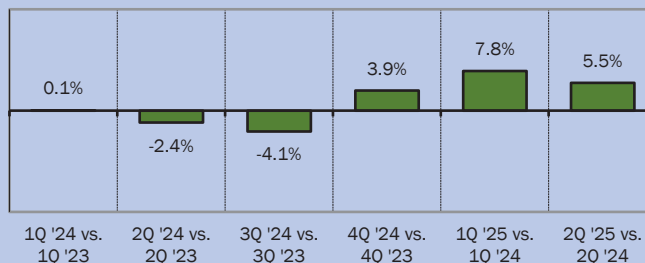
Data sourced from Experian Automotive. Other Asian brands includes Genesis, Hyundai, Kia, and VinFast.

California Quarterly New Light Vehicle Registrations
Percent Change vs. Year Earlier

QUARTERLY RESULTS



% change vs. year earlier



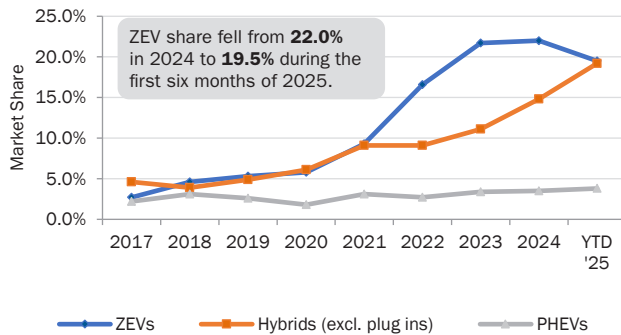
Data sourced from Experian Automotive.

Vehicle Powertrain Dashboard

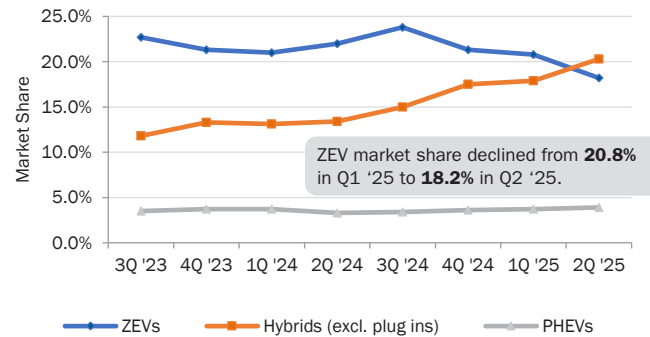


Electric and Hybrid Vehicle Market Share

Annual



Quarterly

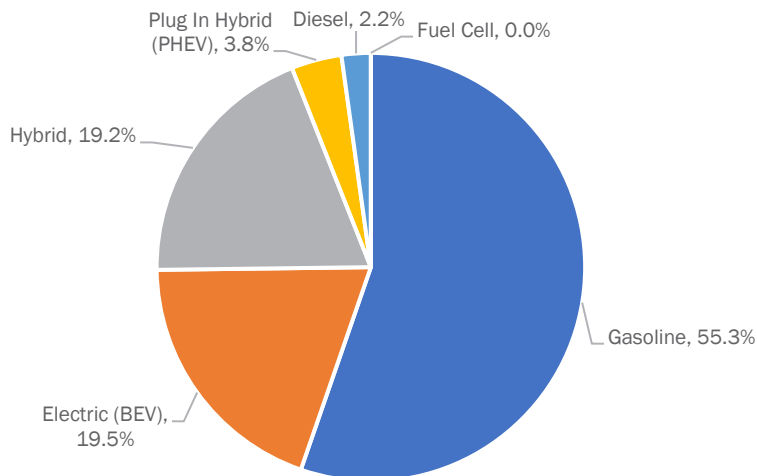


Annual Registrations and Market Share					
	2021	2022	2023	2024	YTD '25
ZEV registrations	164521	262317	382481	385907	184234
ZEV share	9.3%	16.6%	21.7%	22.0%	19.5%
Hybrid regs. (excl. plug ins)	160033	144413	196245	258467	181192
Hybrid share (excl. plug ins)	9.1%	9.1%	11.1%	14.8%	19.2%
PHEV regs.	54265	42473	60685	61305	36266
PHEV share	3.1%	2.7%	3.4%	3.5%	3.8%

Quarterly Registrations and Market Share					
	2Q '24	3Q '24	4Q '24	1Q '25	2Q '25
ZEV registrations	101170	101544	93406	96015	88219
ZEV share	22.0%	23.8%	21.3%	20.8%	18.2%
Hybrid regs. (excl. plug ins)	61696	64071	76684	82700	98492
Hybrid share (excl. plug ins)	13.4%	15.0%	17.5%	17.9%	20.3%
PHEV regs.	15001	14732	15672	17269	18997
PHEV share	3.3%	3.4%	3.6%	3.7%	3.9%

Data sourced from Experian Automotive. ZEVs are full battery electric vehicles and include fuel cell vehicles. PHEVs are plug in hybrids. Hybrid vehicle registrations and market share excludes mild hybrids.

Market Share for all Powertrain Types - YTD 2025 thru June



- Gasoline powered vehicles accounted for 55.3 percent of state new vehicle registrations during the first six months of this year.
- ICE market share (including gasoline and diesel vehicles) was 57.5 so far this year, down from 61.7 percent in the first half of 2024 and 88.4 percent in 2018.
- Combined share for BEVs, PHEVs, hybrids, and fuel cell vehicles was 42.5 percent in the first half of 2025, up from just 11.6 percent in 2018.

Data sourced from Experian Automotive.

California and U.S. Markets

19.5%

California
ZEV market share
YTD 2025



7.8%

U.S.
ZEV market share
YTD 2025



28.6%

California share of
U.S. ZEV registrations
YTD 2025



Data sourced from Experian Automotive.

Vehicle Powertrain Dashboard



Make and Model Registrations for Hybrids, ZEVs, and PHEVs in California

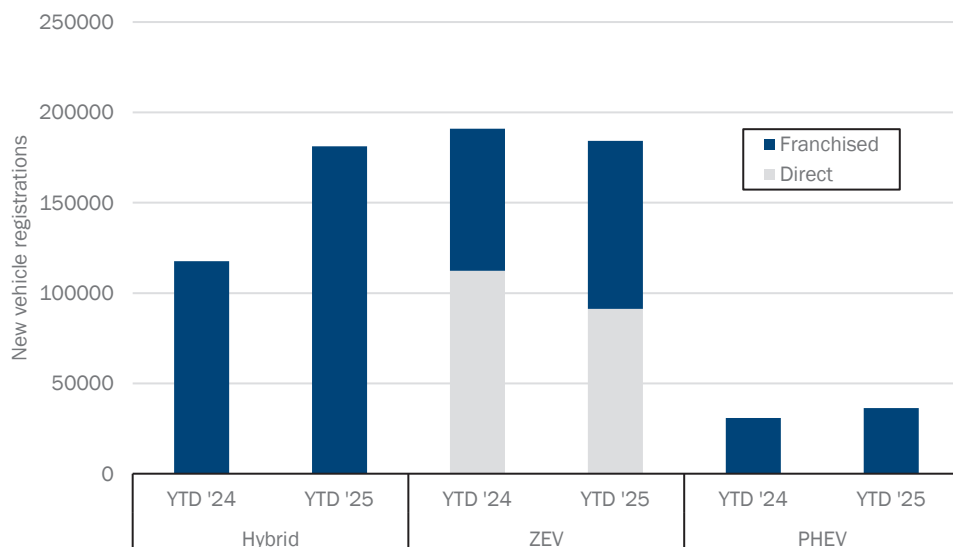
	Registrations			Market Share (%)		
	YTD '24	YTD '25	% Change	YTD '24	YTD '25	Change
TOTAL	190,957	184,234	-3.5			
Acura	18	3,321	-	0.0	1.8	1.8
Audi	5,584	4,774	-14.5	2.9	2.6	-0.3
BMW	9,710	10,662	9.8	5.1	5.8	0.7
Cadillac	2,398	3,580	49.3	1.3	1.9	0.6
Chevrolet	5,592	10,096	80.5	2.9	5.5	2.6
Dodge	0	405	-	0.0	0.2	0.2
Ford	8,636	9,164	6.1	4.5	5.0	0.5
Genesis	957	947	-1.0	0.5	0.5	0.0
GMC	772	1,923	149.1	0.4	1.0	0.6
Honda	277	6,000	-	0.1	3.3	3.2
Hyundai	10,885	10,439	-4.1	5.7	5.7	0.0
Jaguar	823	670	-18.6	0.4	0.4	0.0
Jeep	0	586	-	0.0	0.3	0.3
Kia	7,337	4,459	-39.2	3.8	2.4	-1.4
Lexus	2,338	1,570	-32.8	1.2	0.9	-0.3
Maserati	0	4	-	0.0	0.0	0.0
Mazda	3	2	-33.3	0.0	0.0	0.0
Mercedes	9,111	6,813	-25.2	4.8	3.7	-1.1
MINI	525	409	-22.1	0.3	0.2	-0.1
Nissan	2,760	4,358	57.9	1.4	2.4	1.0
Other	3,497	2,500	-28.5	1.8	1.4	-0.4
Polestar	974	690	-29.2	0.5	0.4	-0.1
Porsche	1,026	2,636	156.9	0.5	1.4	0.9
Ram	3	4	33.3	0.0	0.0	0.0
Rivian	6,899	5,551	-19.5	3.6	3.0	-0.6
Subaru	1,130	1,670	47.8	0.6	0.9	0.3
Tesla	101,991	83,375	-18.3	53.4	45.3	-8.1
Toyota	3,278	2,928	-10.7	1.7	1.6	-0.1
Volkswagen	3,905	3,306	-15.3	2.0	1.8	-0.2
Volvo	528	1,392	163.6	0.3	0.8	0.5

Top 25 Selling Hybrid, ZEV, and PHEV Models - YTD 2025 thru June

Rank	Model	Type	Regs.
1	Tesla Model Y	ZEV	44,112
2	Tesla Model 3	ZEV	31,394
3	Toyota Camry	Hybrid	30,464
4	Honda CR-V	Hybrid	20,075
5	Toyota RAV4	Hybrid	16,683
6	Honda Civic	Hybrid	10,685
7	Honda Accord	Hybrid	9,592
8	Toyota Corolla	Hybrid	8,211
9	Hyundai Ioniq 5	ZEV	7,498
10	Toyota Sienna	Hybrid	7,259
11	Toyota Prius	Hybrid	7,081
12	Ford Maverick	Hybrid	6,024
13	Honda Prologue	ZEV	5,931
14	Ford Mustang Mach-E	ZEV	5,594
15	Chevrolet Equinox	ZEV	5,584
16	BMW i4	ZEV	5,396
17	Hyundai Tucson	Hybrid	4,698
18	Lexus NX	Hybrid	4,487
19	Lexus RX	Hybrid	4,427
20	Toyota Grand Highlander	Hybrid	4,416
21	Jeep Wrangler	PHEV	4,322
22	Rivian R1S	ZEV	4,071
23	Nissan Ariya	ZEV	3,798
24	Hyundai Santa Fe	Hybrid	3,750
25	Tesla Cybertruck	ZEV	3,622

ZEVs are full battery electric vehicles (BEVs) and fuel cell vehicles. PHEVs are plug in hybrids. Data sourced from Experian Automotive.

Alternative Powertrain Sales by Type of Selling Dealership - YTD '24 and '25, thru June



Data sourced from Experian Automotive.

- ❑ The graph on the left shows new vehicle registrations for Hybrids, ZEVs, and PHEVs broken down by type of selling dealership. Franchised dealerships accounted for more than **77 percent** of combined sales for all three alternative powertrain types.
- ❑ Franchised dealership share of the ZEV only market increased to **50.5 percent** so far this year, up from **41.2 percent** a year earlier.
- ❑ Sales of ZEVs at franchised dealerships increased **18.3 percent** so far this year, compared to the **18.8 percent** drop for direct sellers.

MODEL RANKINGS

Tesla Model Y and Toyota RAV4 are Top-Sellers in California New Vehicle Market

The table below shows the top five selling models during the first six months of 2025 in 18 segments. In addition to unit registrations, it also shows each model's market share in its respective segment.



BEST SELLERS IN PRIMARY SEGMENTS

Small Cars: Honda Civic	Full Size Pickup: Ford F-Series
Mid-Size and Large Cars: Toyota Camry	Compact SUV: Toyota RAV4
Near Luxury Cars: Tesla Model 3	2 Row Mid-Size SUV: Hyundai Santa Fe
Comp./Mid Size Pickup: Toyota Tacoma	Luxury Mid-Size SUV: Lexus RX

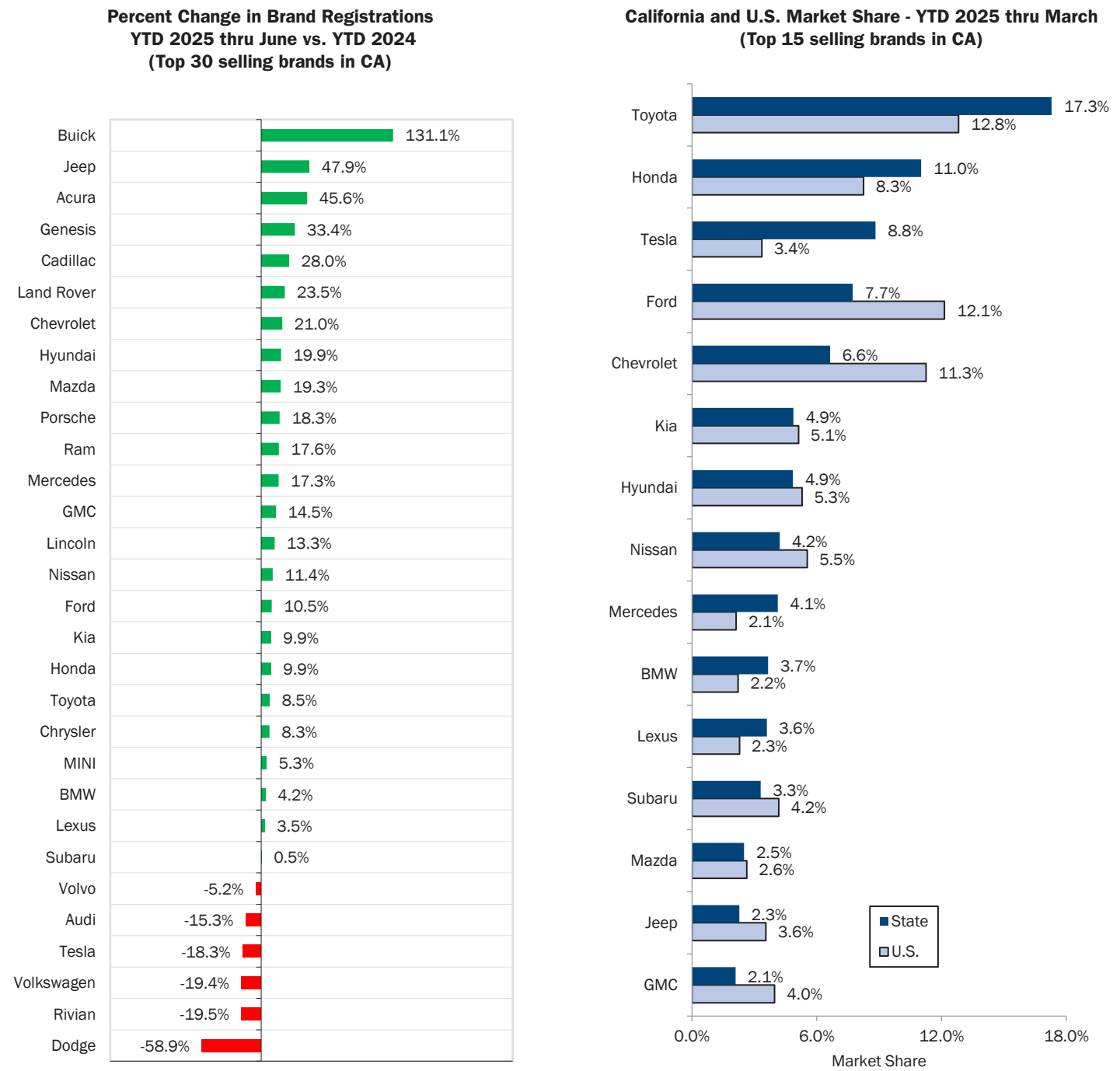
Top Selling Models in Each Segment - New Retail Light Vehicle Registrations (YTD '25 thru June)

Small Cars			Mid Size and Large Cars			Sports/Pony Cars			Near Luxury Cars		
Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share
Honda Civic	28531	30.4	Toyota Camry	30490	47.3	Ford Mustang	2227	43.7	Tesla Model 3	31394	50.6
Toyota Corolla	19384	20.6	Honda Accord	14476	22.5	Toyota 86	1138	22.3	BMW i4	5396	8.7
Toyota Prius	9280	9.9	Nissan Altima	6532	10.1	Mazda MX5	699	13.7	Lexus ES	5233	8.4
Kia K4/Forte	8475	9.0	Hyundai Sonata	4579	7.1	Subaru BRZ	373	7.3	Mercedes C-Class	3816	6.2
Nissan Sentra	7448	7.9	Kia K5	3854	6.0	Nissan Z	323	6.3	BMW 3-Series	3001	4.8
Luxury and High End Sports Cars			Compact/Mid Size Pickup			Full Size Pickup			Mini Van		
Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share
Lucid Air	1898	8.1	Toyota Tacoma	21845	49.5	Ford F-Series	20346	26.3	Toyota Sienna	7259	38.0
Mercedes CLE-Class	1857	7.9	Ford Maverick	7917	18.0	Chevrolet Silverado	17985	23.2	Honda Odyssey	4457	23.3
BMW 5-Series	1835	7.8	Chevrolet Colorado	3504	7.9	Ram Pickup	10350	13.4	Kia Carnival	4156	21.7
Mercedes E-Class	1812	7.7	Ford Ranger	2827	6.4	GMC Sierra	10289	13.3	Chrysler Pacifica	2498	13.1
BMW i5	1696	7.2	Nissan Frontier	2161	4.9	Toyota Tundra	8614	11.1	Volkswagen ID.Buzz	568	3.0
Large Van			Subcompact SUV			Compact SUV			2 Row Mid Size SUV		
Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share
Ford Transit Connect	4602	35.2	Honda HR-V	10667	16.0	Toyota RAV4	33960	20.0	Hyundai Santa Fe	6433	15.2
Mercedes Sprinter	3083	23.6	Subaru Crosstrek	9568	14.4	Honda CR-V	29618	17.4	Subaru Outback	6169	14.5
Ram Promaster	1614	12.3	Chevrolet Trax	8669	13.0	Chevrolet Equinox	10580	6.2	Honda Prologue	5931	14.0
Ford E-Series	1373	10.5	Toyota Corolla Cross	8013	12.0	Hyundai Tucson	9070	5.3	Ford Mustang Mach-E	5594	13.2
Chevrolet Express	1104	8.4	Nissan Kicks	4493	6.7	Jeep Wrangler	8516	5.0	Jeep Grand Cherokee	3853	9.1
3 Row Mid Size SUV			Large SUV			Luxury Subcompact SUV			Luxury Compact SUV		
Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share
Ford Explorer	7158	12.1	Ford Bronco	6867	26.2	Mercedes EQB	2604	18.3	Tesla Model Y	44112	52.2
Toyota Grand Highlan	7117	12.0	Chevrolet Tahoe	4165	15.9	Audi Q3	2045	14.4	Lexus NX	8340	9.9
Honda Pilot	6910	11.7	Toyota Land Cruiser	3583	13.7	Mercedes GLA-Class	2027	14.3	Mercedes GLC-Class	7207	8.5
Kia Sorento	5516	9.3	Chevrolet Suburban	3114	11.9	BMW X1	1553	10.9	BMW X3	4044	4.8
Kia Telluride	5075	8.6	Ford Expedition	1933	7.4	Lexus UX	1385	9.8	Porsche Macan	3644	4.3
Luxury Mid Size SUV			Luxury Large SUV			Top Selling Passenger Cars			Top Selling Light Trucks		
Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share	Model	Regs.	Share
Lexus RX	9153	16.0	Rivian R1S	4071	18.5	Tesla Model 3	31394	12.6	Tesla Model Y	44112	6.3
Mercedes GLE-Class	5695	9.9	Lexus TX	3158	14.4	Toyota Camry	30490	12.2	Toyota RAV4	33960	4.9
BMW X5	5206	9.1	Land Rover Range Rover	2770	12.6	Honda Civic	28531	11.5	Honda CR-V	29618	4.3
Acura ZDX	3321	5.8	Cadillac Escalade	2751	12.5	Toyota Corolla	19384	7.8	Toyota Tacoma	21845	3.1
BMW iX	2847	5.0	BMW X7	1927	8.8	Honda Accord	14476	5.8	Ford F-Series	20346	2.9

Data sourced from Experian Automotive. Figures for Prius include Prius Prime.

BRAND SUMMARY

Registrations Increased by More Than 20 Percent for Seven Brands; Toyota and Honda are Market Leaders



Registrations increased by more than 20 percent for Buick, Jeep, Acura, Genesis, Cadillac, Land Rover, and Chevrolet



Toyota, Honda, Tesla, Ford, and Chevrolet were market share leaders in California.

BRAND REGISTRATIONS

Detailed Results for All Brands in California Market

California New Car and Light Truck Registrations												
	Second Quarter						Year to date thru June					
	Registrations			Market Share (%)			Registrations			Market Share (%)		
	2Q '24	2Q '25	% Change	2Q '24	2Q '25	Change	YTD '24	YTD '25	% Change	YTD '24	YTD '25	Change
TOTAL	459,009	484,044	5.5				886,492	944,834	6.6			
Acura	3,273	5,374	64.2	0.7	1.1	0.4	6,591	9,596	45.6	0.7	1.0	0.3
Alfa Romeo	232	126	-45.7	0.1	0.0	-0.1	547	287	-47.5	0.1	0.0	-0.1
Audi	8,809	7,336	-16.7	1.9	1.5	-0.4	18,381	15,570	-15.3	2.1	1.6	-0.5
BMW	16,596	16,884	1.7	3.6	3.5	-0.1	33,135	34,523	4.2	3.7	3.7	0.0
Buick	1,368	3,593	162.6	0.3	0.7	0.4	2,669	6,168	131.1	0.3	0.7	0.4
Cadillac	3,510	4,258	21.3	0.8	0.9	0.1	6,865	8,784	28.0	0.8	0.9	0.1
Chevrolet	27,218	34,031	25.0	5.9	7.0	1.1	51,857	62,722	21.0	5.8	6.6	0.8
Chrysler	1,341	1,065	-20.6	0.3	0.2	-0.1	2,494	2,701	8.3	0.3	0.3	0.0
Dodge	4,080	1,691	-58.6	0.9	0.3	-0.6	9,028	3,709	-58.9	1.0	0.4	-0.6
Ford	32,534	38,680	18.9	7.1	8.0	0.9	66,020	72,956	10.5	7.4	7.7	0.3
Genesis	1,820	2,264	24.4	0.4	0.5	0.1	3,574	4,769	33.4	0.4	0.5	0.1
GMC	9,170	9,754	6.4	2.0	2.0	0.0	17,245	19,753	14.5	1.9	2.1	0.2
Honda	49,651	54,278	9.3	10.8	11.2	0.4	94,718	104,059	9.9	10.7	11.0	0.3
Hyundai	21,748	24,420	12.3	4.7	5.0	0.3	38,234	45,829	19.9	4.3	4.9	0.6
Infiniti	1,114	888	-20.3	0.2	0.2	0.0	2,461	1,811	-26.4	0.3	0.2	-0.1
Jaguar	866	235	-72.9	0.2	0.0	-0.2	1,509	1,062	-29.6	0.2	0.1	-0.1
Jeep	6,914	11,973	73.2	1.5	2.5	1.0	14,496	21,443	47.9	1.6	2.3	0.7
Kia	23,226	22,816	-1.8	5.1	4.7	-0.4	41,918	46,053	9.9	4.7	4.9	0.2
Land Rover	3,429	3,938	14.8	0.7	0.8	0.1	6,820	8,422	23.5	0.8	0.9	0.1
Lexus	16,811	18,416	9.5	3.7	3.8	0.1	32,808	33,951	3.5	3.7	3.6	-0.1
Lincoln	1,274	1,782	39.9	0.3	0.4	0.1	2,597	2,943	13.3	0.3	0.3	0.0
Maserati	327	161	-50.8	0.1	0.0	-0.1	715	310	-56.6	0.1	0.0	-0.1
Mazda	9,898	11,732	18.5	2.2	2.4	0.2	19,823	23,641	19.3	2.2	2.5	0.3
Mercedes	16,345	19,585	19.8	3.6	4.0	0.4	33,235	38,996	17.3	3.7	4.1	0.4
MINI	912	1,237	35.6	0.2	0.3	0.1	2,179	2,294	5.3	0.2	0.2	0.0
Mitsubishi	786	937	19.2	0.2	0.2	0.0	1,455	2,086	43.4	0.2	0.2	0.0
Nissan	20,080	19,592	-2.4	4.4	4.0	-0.4	35,741	39,814	11.4	4.0	4.2	0.2
Polestar	590	374	-36.6	0.1	0.1	0.0	974	690	-29.2	0.1	0.1	0.0
Porsche	3,964	4,291	8.2	0.9	0.9	0.0	7,786	9,210	18.3	0.9	1.0	0.1
Ram	4,450	5,571	25.2	1.0	1.2	0.2	10,177	11,968	17.6	1.1	1.3	0.2
Rivian	3,739	2,668	-28.6	0.8	0.6	-0.2	6,899	5,551	-19.5	0.8	0.6	-0.2
Subaru	16,570	15,203	-8.2	3.6	3.1	-0.5	31,024	31,173	0.5	3.5	3.3	-0.2
Tesla	52,119	41,138	-21.1	11.4	8.5	-2.9	101,991	83,375	-18.3	11.5	8.8	-2.7
Toyota	78,964	86,683	9.8	17.2	17.9	0.7	150,634	163,416	8.5	17.0	17.3	0.3
Volkswagen	8,280	5,516	-33.4	1.8	1.1	-0.7	16,967	13,668	-19.4	1.9	1.4	-0.5
Volvo	3,917	3,450	-11.9	0.9	0.7	-0.2	7,589	7,191	-5.2	0.9	0.8	-0.1
Other	3,084	2,104	-31.8	0.7	0.4	-0.3	5,336	4,340	-18.7	0.6	0.5	-0.1

Data sourced from Experian Automotive.

The table above shows new light vehicle (car and light truck) registrations in California. Figures are shown for the Second Quarters of 2024 and 2025, and year-to-date totals. Vehicle registrations are recorded based on when the vehicle title information is processed by the state, which typically occurs after the vehicle is sold. The top ten ranked brands for change in market share are shaded yellow. Historical figures have been updated since the previous release.

California Auto Outlook

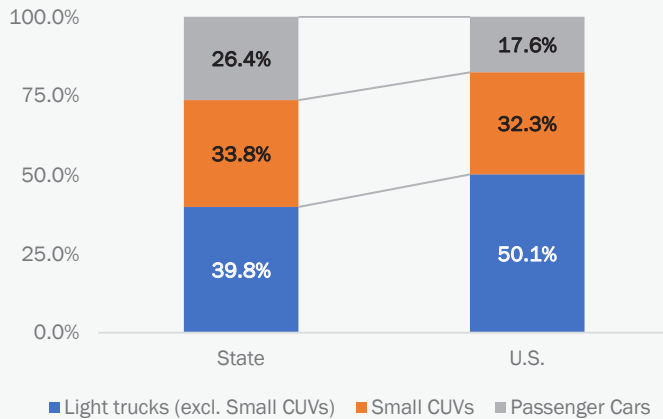
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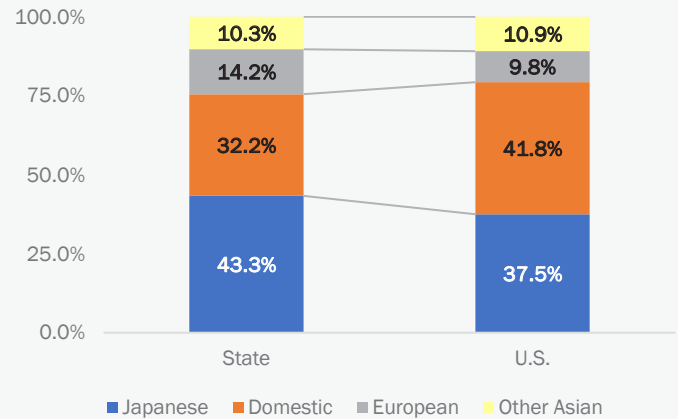
VEHICLE AND BRAND SEGMENTS

Passenger Car Market Share in California Exceeds U.S. Levels

Market Share by Type of Vehicle - YTD '25 thru June


Combining the blue and orange sections in the graph above corresponds to the standard industry definition of light trucks. Small crossovers are broken out, however, since many are more similar to compact hatchbacks than to many trucks. State passenger car share was **26.4%** so far this year, well above the **17.6%** share in the U.S.

Data sourced from Experian Automotive.

Market Share by Brand Category - YTD '25 thru June


Japanese brand market share in the state was higher than U.S. levels: **43.3%** vs. **37.5%**. State Domestic brand share (which includes Tesla and Rivian) was **32.2%**. European brands accounted for a higher share of the state market than in the Nation. Note: Other Asian includes Genesis, Hyundai, Kia, and VinFast. Data sourced from Experian Automotive.

REGIONAL MARKETS IN CALIFORNIA

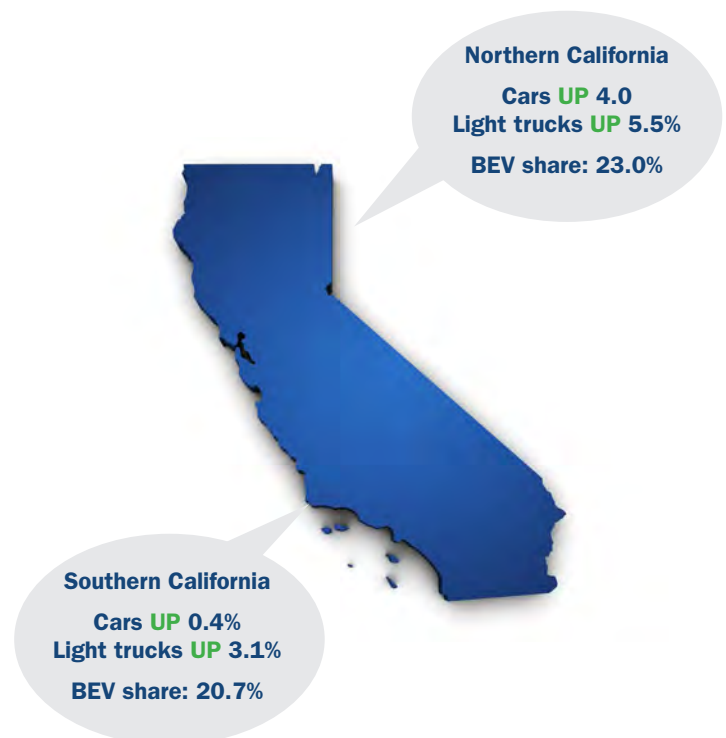
Northern California New Retail Market Improved by 5.1% in First Half 2025

BEV share in Southern California fell to 20.7%

New Retail Registrations (excluding fleets) YTD thru June			
North and South California	YTD '24	YTD '25	% chg.
Statewide Total	780,286	810,582	3.9%
Cars	216,201	219,569	1.6%
Light Trucks	564,085	591,013	4.8%
Northern California	263,849	277,284	5.1%
Cars	67,627	70,357	4.0%
Light Trucks	196,222	206,927	5.5%
Southern California	516,437	533,298	3.3%
Cars	148,574	149,212	0.4%
Light Trucks	367,863	384,086	4.4%
Selected Regional Markets			
San Francisco Bay	149,327	154,340	3.4%
Cars	39,060	40,699	4.2%
Light Trucks	110,267	113,641	3.1%
LA and Orange Counties	299,217	306,220	2.3%
Cars	87,969	88,956	1.1%
Light Trucks	211,248	217,264	2.8%
San Diego County	72,477	74,301	2.5%
Cars	18,274	17,773	-2.7%
Light Trucks	54,203	56,528	4.3%

Data sourced from Experian Automotive.

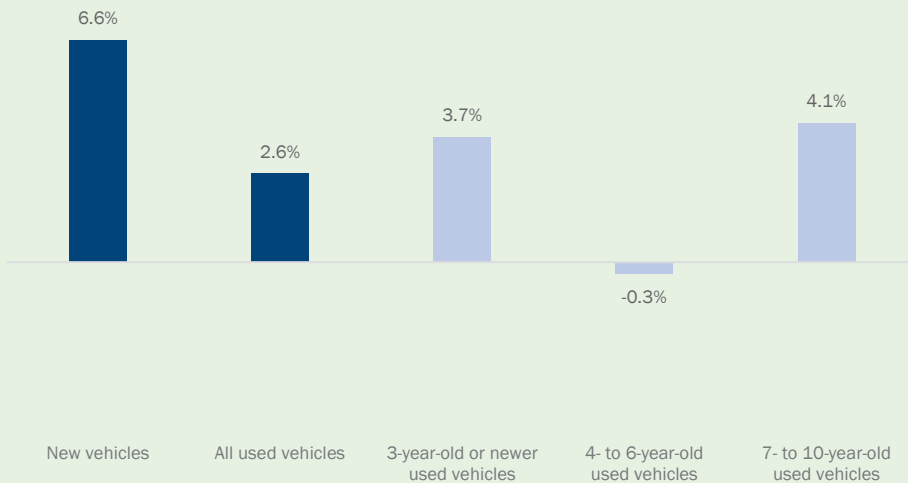
Percent Change in New Retail Registrations - YTD '25 vs. YTD '24



CALIFORNIA USED VEHICLE MARKET

Used Vehicle Market Increased Slightly in First Half of This Year

Percent Change in New and Used Vehicle Registrations
YTD 2025 thru June vs. YTD 2024



Data sourced from Experian Automotive.

THREE KEY TRENDS IN USED VEHICLE MARKET



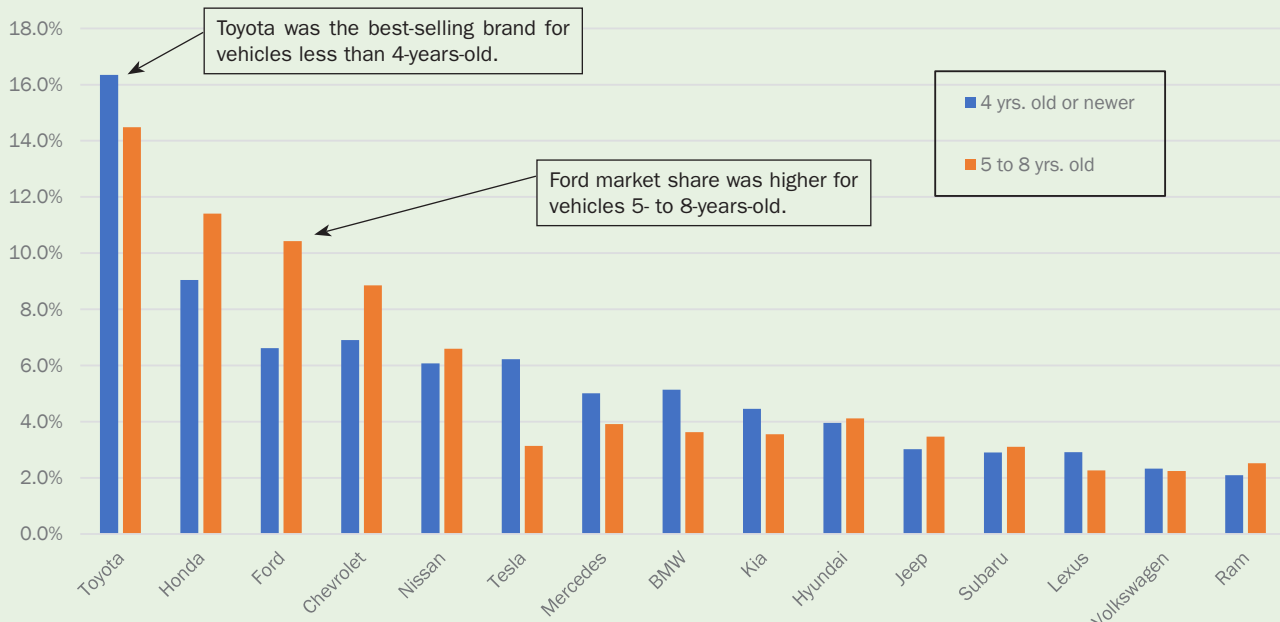
- 01.** The state used vehicle market increased 2.6 percent during the first six months of this year versus year earlier. The new vehicle market was up 6.6 percent.
- 02.** As shown on the graph to the left, registrations for 7- to 10-year-old used vehicles increased 4.1 percent so far this year. The 4- to 6-year old market declined slightly.
- 03.** Toyota, Honda, Ford, Chevrolet, Nissan, Tesla, Mercedes, BMW, Kia, and Hyundai were the top 10 sellers during the first half of this year (see graph below).

USED VEHICLE BRAND MARKET SHARE

Toyota is Top Seller in California Used Vehicle Market

The graph below shows used light vehicle registrations by brand for two age categories: vehicles less than 4-years-old and vehicles 5- to 8-years-old. Brands are positioned from left to right based on overall market share.

Brand Market Share for Top 15 Selling Brands, by Vehicle Age (YTD '25 thru June)

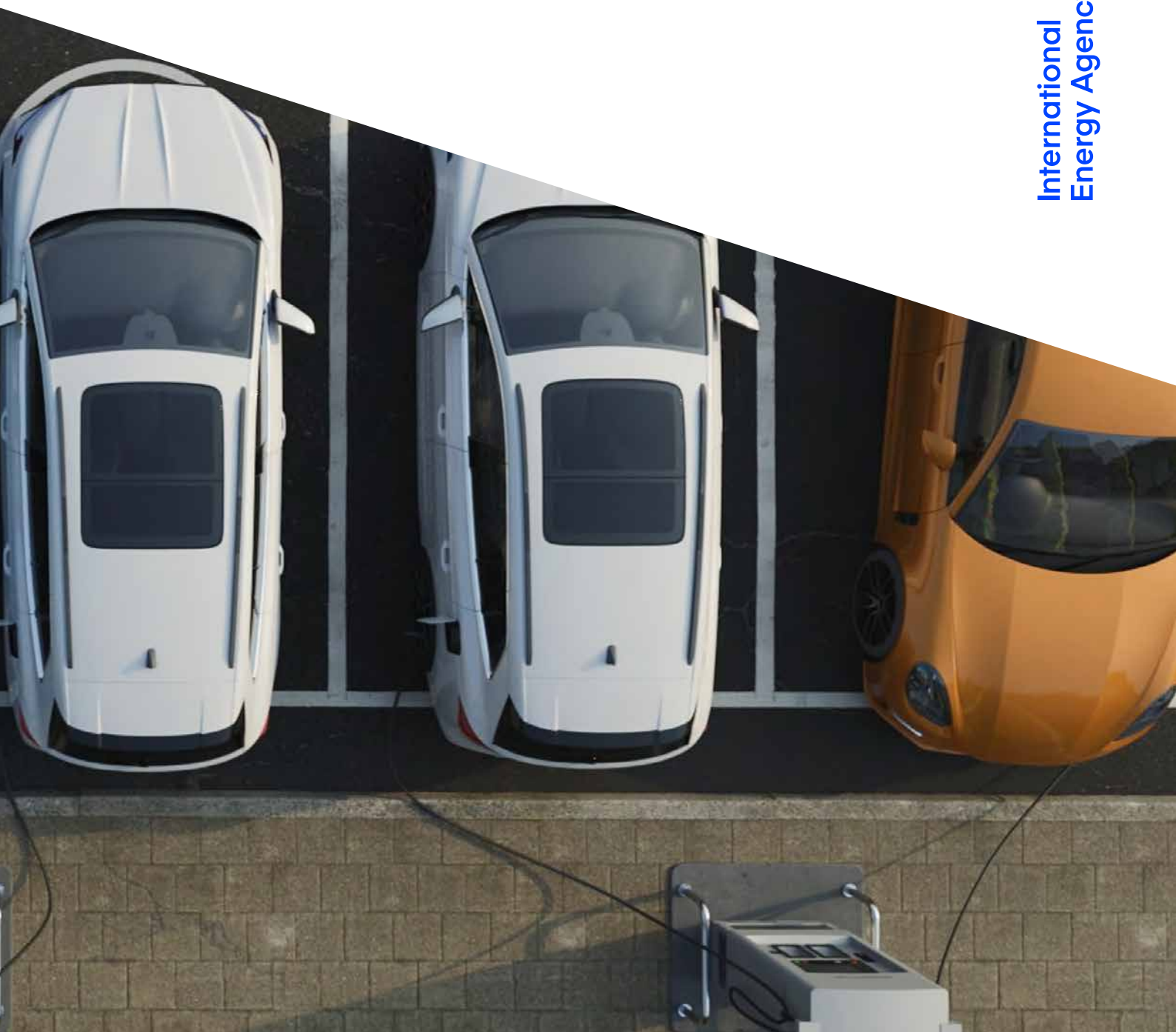


Data sourced from Experian Automotive.

Global EV Outlook 2025

Expanding sales in diverse markets

International
Energy Agency



INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 32 Member countries, 13 Association countries and beyond.

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Abstract

The Global EV Outlook is an annual publication that reports on recent developments in electric mobility around the world. It is developed with the support of members of the Electric Vehicles Initiative (EVI).

The report draws on the latest data to assess trends in electric vehicle deployment, demand for their batteries and charging infrastructure. It considers recent policy developments and industry strategies shaping the outlook for electric vehicles in different markets. This edition features analysis of electric vehicle affordability, manufacturing and trade of electric cars and their batteries, and the total cost of ownership of electric heavy-duty trucks across various markets, and makes projections to 2030.

The report is complemented by updated versions of two online tools: the Global EV Data Explorer and the Global EV Policy Explorer, which allow users to further explore EV statistics and projections, and policy measures worldwide.

Acknowledgements, contributors and credits

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Electric Vehicles Initiative

The Electric Vehicles Initiative (EVI) is a multi-governmental policy forum established in 2010 under the Clean Energy Ministerial (CEM). Recognising the opportunities offered by EVs, the EVI is dedicated to accelerating the adoption of EVs worldwide. To do so, it strives to better understand the policy challenges related to electric mobility, to help governments address them and to serve as a platform for knowledge-sharing among government policy makers. The EVI also facilitates exchanges between government policy makers and a variety of other partners on topics important for the transition to electric mobility, such as charging infrastructure and grid integration as well as EV battery supply chains.

The International Energy Agency serves as the co-ordinator of the initiative. Governments that have been active in the EVI in the 2024-25 period include Canada, Chile, People's Republic of China (hereafter "China"), Finland, France, Germany, India, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, United Kingdom and United States.

The Global EV Outlook annual series is the flagship publication of the EVI. It is dedicated to tracking and monitoring the progress of electric mobility worldwide and to informing policy makers on how to best accelerate electrification of the road transport sector.



Executive summary

Electric car sales continue to break records globally, particularly in China and other emerging economies

Electric car sales exceeded 17 million globally in 2024, reaching a sales share of more than 20%. Just the additional 3.5 million electric cars sold in 2024 compared with the previous year is more than the total number of electric cars sold worldwide in 2020. China maintained its lead, with electric cars accounting for almost half of all car sales in 2024; the over 11 million electric cars sold in China last year were more than global sales just 2 years earlier. As a result of continued strong growth, 1 in 10 cars on Chinese roads is now electric. Europe saw sales stagnate in 2024 as subsidy schemes and other supportive policies waned, but the sales share of electric cars remained around 20% as stronger sales in some countries compensated for lower sales in others. In the United States, electric car sales grew by about 10% year-on-year, reaching more than 1 in 10 cars sold.

Emerging markets in Asia and Latin America are becoming new centres of growth, with electric car sales jumping by over 60% in 2024 to almost 600 000 – about the size of the European market 5 years earlier. In Southeast Asia, electric car sales grew by nearly 50% to represent 9% of all car sales in the region, with notably higher sales shares in Thailand and Viet Nam. In Brazil, the largest car market in Latin America, electric car sales more than doubled to 125 000 in 2024, reaching a sales share of over 6%. Sales in Africa also more than doubled, too, mostly thanks to growing sales in Egypt and Morocco, though electric cars still represent less than 1% of total car sales across the continent. Policy support and relatively affordable electric car imports from China played a central role in increasing sales in some emerging electric vehicle (EV) markets, accounting for 85% of electric car sales in both Brazil and Thailand, for example. Across all emerging economies outside of China, Chinese imports made up 75% of the increase in electric car sales in 2024.

Expected growth in electric car sales is led by China and Europe, alongside a surge in emerging economies

Electric car sales in 2025 are expected to exceed 20 million worldwide to represent more than one-quarter of cars sold worldwide. Sales were up 35% year-on-year in the first three months of 2025, with record first-quarter sales in all major markets. In China, the continuation of incentives for replacing older vehicles and falling electric car prices mean electric cars are projected to reach around

60% of total car sales in the country in 2025. Emissions standards in the European Union and the United Kingdom will require higher shares of zero-emission car sales in 2025. Building on more than 20% year-on-year sales growth observed in the first quarter, these policy pushes are expected to drive up electric car sales in Europe in 2025 to reach a sales share of 25%, despite flexibility given to automakers for meeting the 2025 EU emissions reduction target. While the 2025 outlook for electric car sales in the United States is uncertain based on today's policy direction, sales are currently expected to maintain the 10% growth observed in the first quarter; as consumers take advantage of existing tax credits in view of their potential repeal, electric car sales are projected to reach 11% of total car sales over the full year. In emerging economies other than China, sales are expected to continue growing strongly, increasing by 50% to reach 1 million in 2025.

Despite uncertainties in the outlook, the share of electric cars in overall car sales is set to exceed 40% in 2030 under today's policy settings. China is poised to continue leading in electric car sales to 2030, achieving a sales share of around 80% on the back of significant market momentum and competitively-priced EVs. In Europe, carbon dioxide (CO₂) targets support the achievement of a sales share of close to 60% by 2030, slightly below last year's projection. The sales share in the United States grows much more modestly than in our *Outlook* last year, reaching around 20% by 2030 based on today's policy direction – less than half the share projected for 2030 last year. In Southeast Asia, meanwhile, electric car sales are boosted by strong policy support and available domestic manufacturing capacity: by 2030, one in four cars sold in the region is poised to be electric. Two/three-wheelers – an important mode of road transport in the region – electrify faster: by 2030, almost 1 in 3 such vehicles sold are electric. Across all vehicle modes, the deployment of EVs replaces the use of more than 5 million barrels of oil per day globally in 2030, an important energy security consideration. Half of these savings are the result of EV adoption in China.

Uncertainty about the evolution of trade and industrial policy, downside risks to the economic outlook, and lower oil prices could affect EV uptake – but also car markets overall. Higher tariffs might increase the price of cars, including electric cars, and their components; lower GDP growth could dampen car sales; and lower oil prices affect the fuel cost savings from the use of electric cars. The way these factors will play out in practice is uncertain, but on aggregate they look to pose risks for overall car sales volumes more than for the share of EVs. In China, continued political support and competitive EV prices suggest that EV sales can withstand such headwinds. In Europe, where price differentials with conventional cars are larger, the combination of longer-term policy ambition and examples of policy responses from the pandemic suggest that sustaining EV sales is possible. Low oil prices can reduce fuel savings offered by battery electric cars, but even at global benchmark oil prices of USD 40 per barrel, there would be

significant fuel cost savings in all major EV markets when charging at home. In China, public fast charging costs around twice as much as home charging, but it would still offer savings for EV owners compared with driving a conventional car.

Global trade of electric cars is growing as manufacturers eye new markets

China continues to be the world's EV manufacturing hub and is responsible for more than 70% of global production. Car manufacturers headquartered in China predominantly cater to the domestic market, accounting for around 80% of domestic sales in 2024 and almost all of the 25% growth in global EV production. In the European Union, production stalled at 2.4 million electric cars in 2024. North America saw contrasting trends: US production declined whereas Mexico's output doubled, supported by comparatively low manufacturing costs. Roughly 70% of Mexico's output was from US-headquartered manufacturers. Production also increased by 15% in Asia Pacific countries other than China, reaching about 1 million electric cars, mostly from incumbent carmakers from Japan and Korea.

Global trade of electric cars increased 20% in 2024; imports now represent almost one-fifth of global electric car sales. At 40% (nearly 1.25 million electric cars), China accounted for the largest share of global exports in 2024. The European Union also remained a net exporter of electric cars: exports reached over 800 000, mostly destined for other European countries (such as the United Kingdom) and North America. EU imports were below 700 000, of which 60% came from China. The United States remained a net importer of electric cars; imports increased by nearly 40% in 2024, while exports fell by nearly 15%.

Chinese EV export markets are diversifying as Chinese automakers make headway in Brazil, Mexico and Southeast Asia. Several potential markets for Chinese EV exports have recently adopted or are considering the use of tariffs. This has prompted Chinese manufacturers to either frontload their exports before such tariffs come into force (as in Brazil) or to seek new markets for their available output. Today, overseas manufacturing capacity from Chinese manufacturers supplies about 5% of electric car sales in emerging markets and is set to grow further.

Competition and declining battery prices are improving affordability, though progress is uneven

As a global average, the price of battery electric cars fell in 2024, but the purchase price gap with conventional cars persisted in many markets. The average battery electric car price in Germany, for example, remained 20% higher than that of its conventional counterpart. In the United States, battery electric cars remained 30% more expensive, dampening future sales growth expectations. In

contrast, two-thirds of all electric cars sold in China in 2024 were priced lower than their conventional equivalents, without considering purchase incentives for EVs. This helped boost sales even as government incentives decreased.

Chinese electric car models are typically cheaper than the average EV in emerging markets, bolstering the competitive position of the Chinese industry. In Thailand, the average price of a battery electric car has now reached parity with an average conventional car, and the Chinese electric cars available are, on average, even cheaper. In Brazil, the price gap between battery electric cars and conventional cars shrank to 25% in 2024 from over 100% in 2023 as Chinese electric car imports grew to 85% of the country's EV sales. Similarly, the average price premium of battery electric cars in Mexico fell to 50% in 2024 from more than 100% in 2023 as Chinese imports reached two-thirds of sales.

Low critical mineral prices and increasing competition between battery manufacturers drove down battery pack prices in all markets in 2024, albeit with significant variations. In China, prices fell by about 30%, compared with 10-15% in Europe and the United States. The faster pace of cost reductions in China – enabled by strong competition, increasing manufacturing efficiency and supply chain integration, and access to a skilled workforce – is increasing the competitive advantage of Chinese battery manufacturers.

Improving charging coverage, capacity and integration is key to growing adoption of electric vehicles

Public charging stations have doubled in the past 2 years to keep up with growing EV sales. China and the European Union have maintained a steady pace of charger deployment compared with the number of EVs on the road. However, in both the United States and United Kingdom, which have higher rates of access to home chargers than China, public charger build-out has not kept pace with EV deployment, and the number of electric light-duty vehicles per public charging point increased in 2024.

Charging capacity is an important measure of the adequacy of public charging networks. The number of ultra-fast chargers, with power ratings of 150 kilowatts (kW) and above, grew by about 50% in 2024 and now account for nearly 10% of all public fast chargers. Public slow chargers in urban areas are a solution for EV owners without access to home charging, but fast chargers along highways help enable long-distance trips. In Europe, over three-quarters of all highways have a fast-charging station at least every 50 kilometres, compared with less than half of US highways. Globally, public charging capacity for light-duty EVs would need to grow by almost ninefold to 2030 to support EV sales implied by stated policies. Even so, EVs are set to account for only 2.5% of total global electricity demand in 2030.

Government efforts to promote interoperability, standardisation, smart charging and vehicle-to-grid integration can ease the transition to EVs for drivers and grid operators. Technologies such as smart chargers and vehicle-to-grid-capable EV models are becoming more available, but new market structures and legal frameworks will be needed for vehicles to maximise the potential benefits for the grid. China and the United Kingdom stand out for policy implementation and demonstration projects in this area. Battery technology innovations in recent years are also enabling safe high-power charging that could be as quick as refuelling a conventional car, but fully realising these advances hinges on deploying adequate infrastructure.

The value proposition for electric trucks is improving, even for long-haul operations

Electric truck sales grew by nearly 80% globally in 2024 to reach close to 2% of total truck sales. Spurred by a new scrappage scheme for conventional trucks, China's electric truck sales doubled to 75 000 vehicles, representing over 80% of global sales in 2024. In Europe and the United States, electric truck sales in 2024 remained similar to 2023 levels. The number of battery electric truck models available has grown from less than 70 in 2020 to more than 400, increasing the number of applications that can be met by electric trucks.

The total cost of ownership of a battery electric heavy-duty truck is already lower than for a diesel equivalent in China in certain cases. The purchase price of battery electric heavy-duty trucks remains two to three times higher than equivalent diesel trucks in major markets, which can discourage fleet operators, who often operate under tight margins. However, greater efficiency and lower energy costs – even including the cost of a high-power charger – make battery electric trucks more attractive the more they are used. By 2030, battery electric trucks in Europe and the United States are expected to reach parity on the total cost of ownership with diesel trucks for long-haul operations, as they already have in China, and are set to remain more cost-effective than hydrogen fuel cell trucks. However, the specific application and use profile of trucks are key factors for determining which powertrain technology is most suitable, meaning case-by-case analysis may be needed to evaluate the costs of various alternatives.

Mandated rest periods for truck drivers can play an important role in reducing the opportunity cost of charging en route. For long-haul trucking, the wait time for recharging an electric truck can pose difficulties for logistics operators. However, the 45-minute rest period mandated in the European Union can accommodate the addition of around 150 km of driving range for a heavy-duty truck using a 350 kW charger, and up to about 400 km if a megawatt charger is used. While the United States and China also have mandated rest periods, the design of the EU policy is currently most conducive to supporting EV adoption.

1. Trends in electric car markets

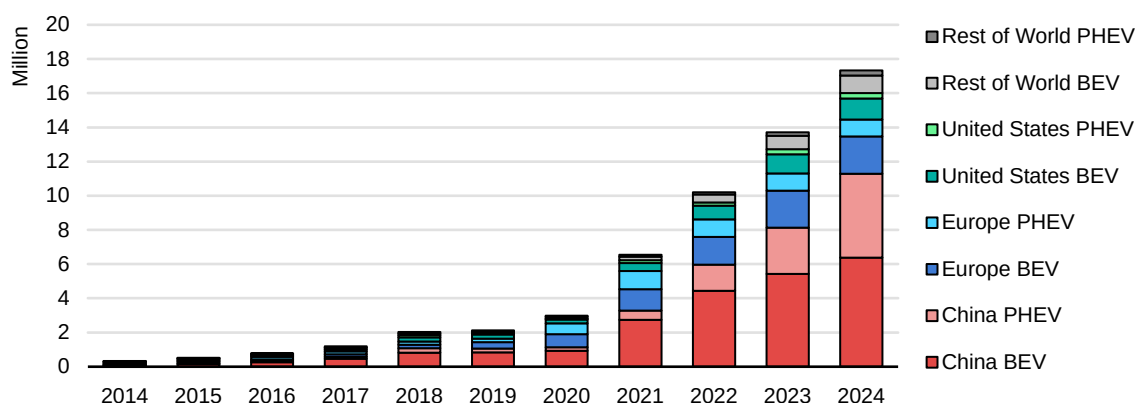
Electric car sales

Global electric car sales exceeded 17 million in 2024

More than 20% of new cars sold worldwide were electric

Electric car sales topped 17 million worldwide in 2024, rising by more than 25%.¹ Just the additional 3.5 million cars sold in 2024 compared to 2023 outnumber total electric car sales in the whole of 2020. China maintained its lead among major markets, with electric car sales exceeding 11 million – more than were sold worldwide just 2 years earlier. Global sales were slightly tempered by stagnating growth in Europe, as subsidies were phased out or reduced in several major markets, and as the EU CO₂ targets for cars remained the same between 2023 and 2024. Electric car sales continued to increase in the United States although growth was about one-quarter that of the previous year. Significantly, outside of these three major markets, there was a record increase in sales of nearly 40% to reach 1.3 million, closing in on the United States' sales of 1.6 million electric cars.

Global electric car sales, 2014-2024



IEA. CC BY 4.0.

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle. Includes new passenger cars only.

Sources: IEA analysis based on country submissions and data from the European Automobile Manufacturers Association (ACEA), European Alternative Fuels Observatory (EAFO), EV Volumes and Marklines.

¹ In this report “sales” represents an estimate of the number of new vehicles hitting the roads. Where possible, data on new vehicle registrations is used. In some cases, only data on retail sales (such as sales from a dealership) are available. New car sales or registrations exclude used cars. Unless otherwise specified, the term electric vehicle is used to refer to both battery electric and plug-in hybrid electric vehicles but does not include fuel cell electric vehicles. For a brief description of the trends related to fuel cell electric vehicles, see the box at the end of [Section 4](#).

The rapid growth in electric car sales over the past 5 years has had a significant impact on the global car fleet: At the end of 2024, the electric car fleet had reached almost 58 million, about 4% of the total passenger car fleet and more than triple the total electric car fleet in 2021. Notably, the global stock of [electric cars displaced](#) over 1 million barrels per day of oil consumption in 2024. Of course, the stock of electric cars is not spread evenly across the world – in China, for example, around one in ten cars on the road is now electric, whereas in Europe the ratio is closer to one in twenty.

Almost half of China's car sales were electric in 2024, representing almost two-thirds of electric cars sold globally

Electric car sales in China increased by almost 40% year-on-year in 2024, further driving up China's share of global electric car sales. In 2021, China accounted for half of global electric car sales; this share grew to almost two-thirds in 2024. On a monthly basis, sales of electric cars have overtaken conventional car sales in the country since July 2024, bringing the share of electric car sales close to 50% for the full year. In China, 2024 marks the fourth consecutive year in which the electric car sales share grew by approximately 10 percentage points year-on-year.

The growth in China reflects in no small part the [growing price competitiveness](#) of battery electric cars with conventional cars in the country. In addition, China's electric car market benefitted from the introduction of a [trade-in scheme](#) in April 2024. The scheme, which is part of a wider economic stimulus package, applies to the purchase of conventional and electric cars alike, but with different levels of financial support. Following a [retroactive increase](#), the scheme offers CNY 20 000 (Yuan renminbi) (USD 2 750) for consumers that replace an older vehicle (conventional or electric) with a new electric car, and CNY 15 000 (USD 2 050) for replacement with a new conventional vehicle. In 2024, about [6.6 million](#) consumers applied for the incentive, 60% of whom bought an electric car. As such, more than one-third of the over 11 million new electric car sales in the country benefitted from this incentive.

In recent years, sales of plug-in hybrid electric cars have been growing faster than sales of battery electric cars in China. The share of plug-in hybrid electric vehicle (PHEV) sales, excluding extended-range EVs (EREVs)², in China's total electric car sales has risen from about 15% in 2020 to nearly 30% in 2024. Meanwhile, the share of EREVs has more than quadrupled since 2020, surpassing 10% in

² If not otherwise specified, PHEVs includes EREVs. Extended-range EVs are a subset of plug-in hybrid electric vehicles that have both an internal combustion engine (ICE) and a plug-in rechargeable battery. Throughout this report, EREVs refer to plug-in [series](#) hybrid powertrain configurations where the ICE only operates without direct mechanical connection to the wheels to recharge the battery through an electric generator. Other plug-in hybrid configurations (such as parallel and series-parallel [configurations](#)) fall under the "standard" PHEV category. EREVs generally feature larger battery and longer electric range than standard PHEVs.

2024. The acceleration of PHEV sales in China led the share of electric car sales that are battery electric to fall from 80% in 2020 to below 60% in 2024, though in absolute terms battery electric car sales increased sevenfold over the same period, demonstrating their continued appeal to new customers.

In Europe, electric car sales stagnated in 2024 as policy support waned in major car markets

About one in five new cars sold on the European market was electric in 2024, maintaining the sales share of the previous year. The electric sales share increased in 2024 in 14 out of 27 EU member states, while it either stalled or decreased in the rest, including in several larger markets, such as Germany and France, largely as a result of subsidies being phased out or reduced. In [Germany](#), subsidies ceased at the end of 2023, while [France](#) has progressively reduced its subsidy over the years. At the start of 2024, France limited the amount of environmental bonus available to higher-income car buyers and reduced the number of vehicles eligible for the subsidy.

Besides subsidies, the policy design of the European Union CO₂ standards may also have held back further growth of the electric car market in 2024. As new targets come into effect every 5 years, car makers had [no incentive](#) to push sales of electric cars further in 2024 (in anticipation of strengthened targets in 2025). This is in contrast to markets such as the United Kingdom, where annually increasing targets move original equipment manufacturers (OEMs) towards electrification each year. In March 2025, the European Commission published its [Industrial Action Plan](#) for the European automotive sector, in which it proposed to amend the CO₂ emission performance standards for cars and vans, granting them additional flexibilities by averaging their performance over a 3-year period.

In the United Kingdom – the second-largest car market in Europe – electric car sales reached a share of nearly 30%, up from 24% in 2023. The year 2024 was the first under the [Vehicle Emissions Trading Scheme](#), which required 22% of all new registrations to be BEV or fuel cell electric vehicle (FCEV). When accounting for the scheme's flexibilities, which allows OEMs to borrow credits from future years, they were able to [comply](#) with a battery electric car sales share of close to 20%. Norway reached near-total electrification of sales, with [88%](#) of car sales being battery electric and just under 3% plug-in hybrid. As a result of the growing stock of electric cars, Norway's oil consumption for road in 2024 decreased by [12%](#) compared to 2021. From April 2025, [a tax increase](#) on conventional internal combustion engine (ICE) cars and PHEVs is expected to further increase the battery electric share towards meeting the Norwegian government's 2025 goal of 100% zero-emissions car sales. In Denmark, the electric sales share increased by 10 percentage points to reach 56%, with nearly 100 000 electric cars sold.

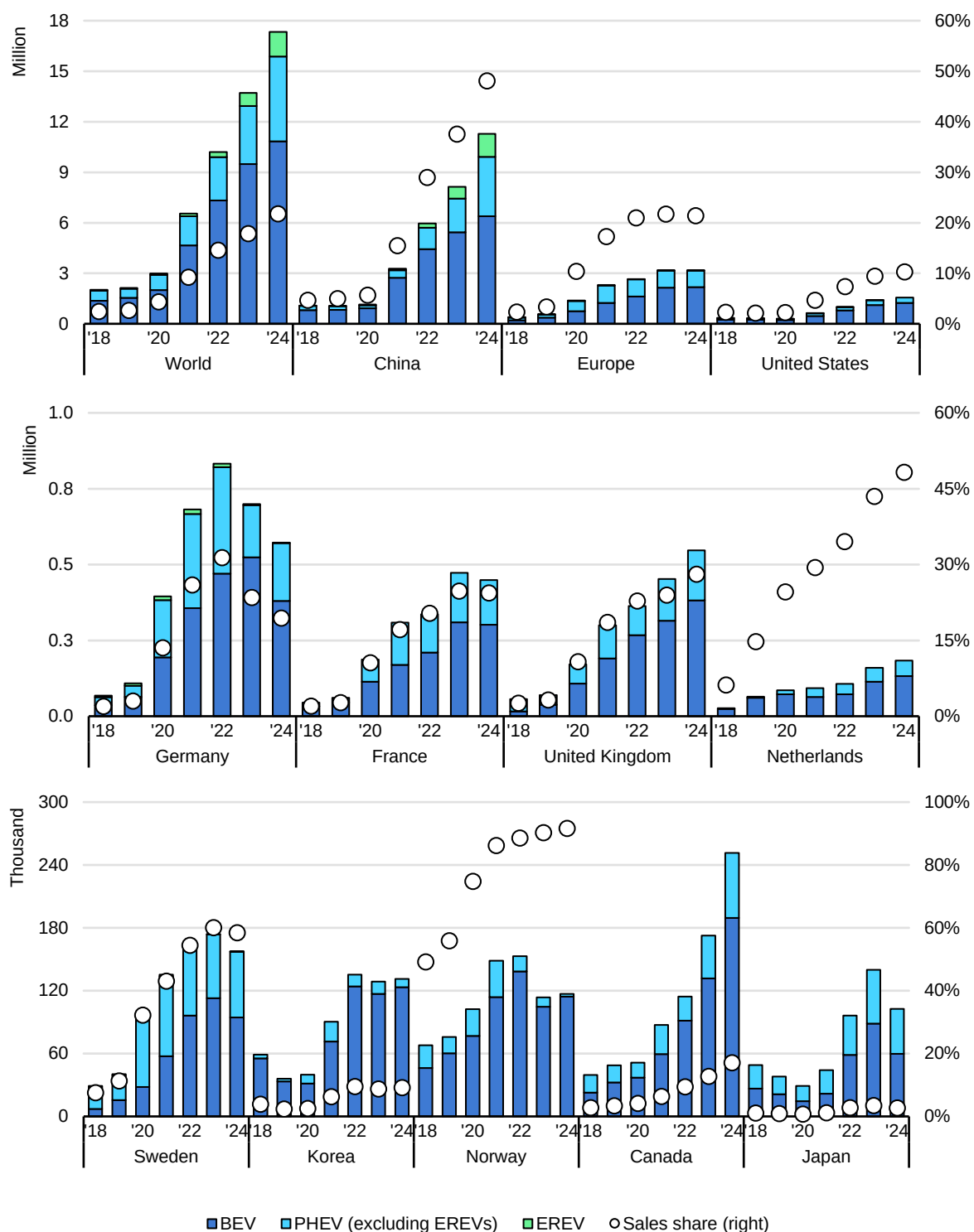
The market share of electric cars continued to expand in the United States

In the United States, electric car sales increased to 1.6 million in 2024, with the sales share growing to more than 10%. However, growth in electric car sales slowed down significantly in 2024, increasing by just 10% compared to 40% in 2023. In spite of this, electric car sales did boost the overall car market, as sales of conventional cars stagnated.

A total of 24 new electric car models were launched in 2024, increasing model availability by 15% compared to 2023, providing consumers with more choices and further increasing competition. While the Tesla Model Y and Model 3 have been the two best-selling models in the United States since 2020, the 110 new models that have entered the market since then have driven the market share of Tesla down from 60% in 2020 to 38% in 2024. Furthermore, 2024 was the first year in which Tesla saw a drop in sales in the United States, while other OEMs saw sales increase by 20% on aggregate.

A modification to the US Clean Vehicle Tax Credit at the start of 2024 enabled buyers to receive an instant discount (up to USD 7 500 for a new electric car and USD 4 000 for a used electric car) at the point of sale, which may have served to entice interested buyers. However, not all electric cars were eligible for the credit: in 2024 about 20 electric models (not accounting for different trim levels) out of a total 110 were eligible, which translated to over half of US electric car sales. The real share that benefitted from the tax credit may be even higher. In 2023, provisions were introduced on leased electric cars to [reclassify](#) them as commercial vehicles, thereby making them eligible for the tax credit without having to meet requirements on local manufacturing. As a result, by 2024, nearly [half](#) of all EVs sold were leased, more than double the share seen 3 years earlier. In addition to the federal tax credit, in 2024, [27 states offered additional incentives](#), rebates and exemptions promoting electric car adoption.

Electric car registrations and sales share in selected countries and regions, 2018-2024



IEA. CC BY 4.0.

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle, EREV = extended-range electric vehicle.

Sources: IEA analysis based on country submissions and data from [ACEA](#), [EAFO](#), [EV Volumes](#) and [Marklines](#).

Emerging markets saw a strong uptick in electric car sales

Electric car sales shares doubled in a number of emerging markets

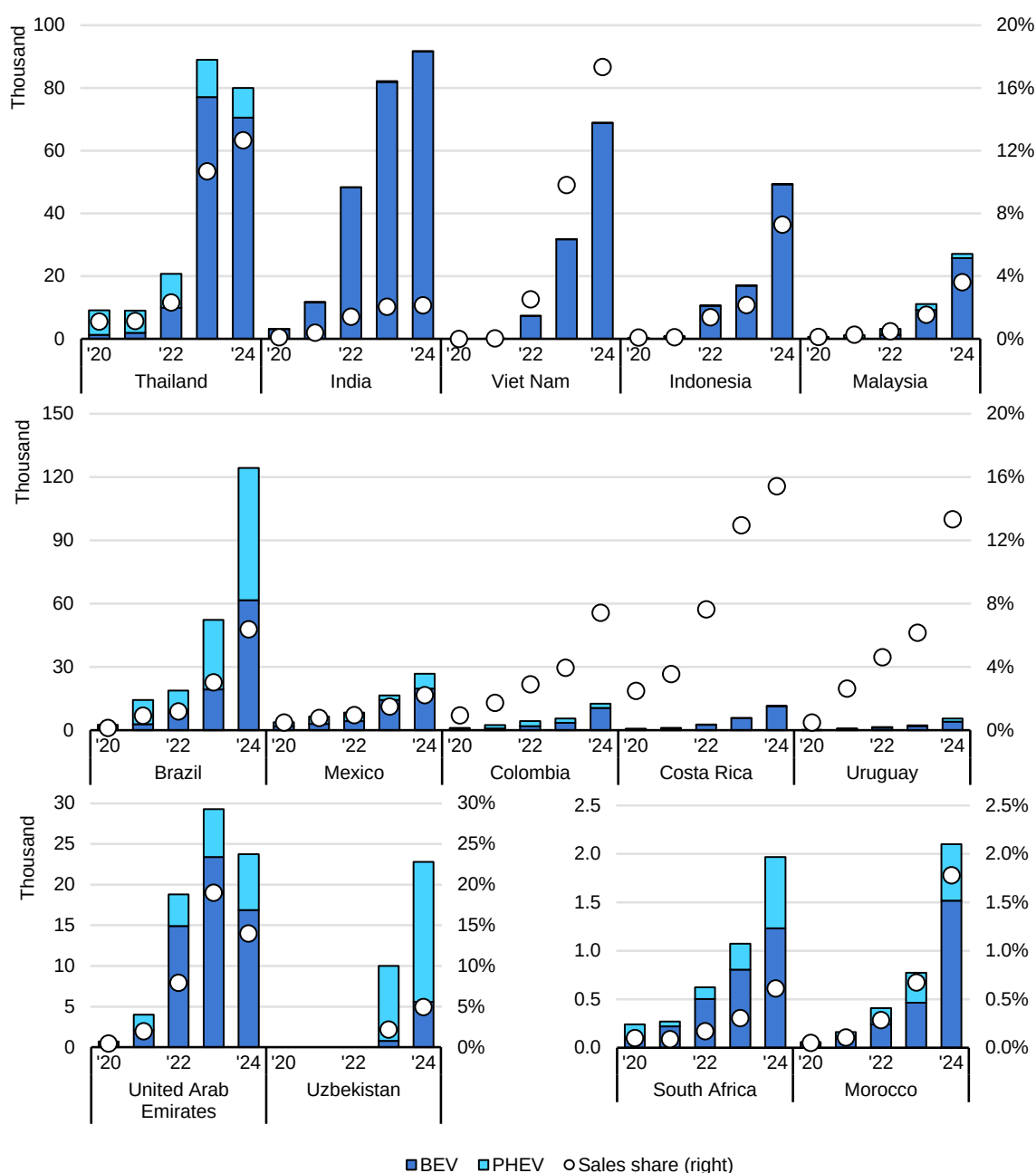
In emerging and developing economies in Asia, Latin America and Africa, electric car sales increased by over 60% year-on-year in 2024, and the sales share almost doubled from 2.5% to 4%. This rapid growth has been strengthened by policy incentives and the growing presence of relatively affordable electric cars from Chinese OEMs.

Emerging and developing economies in **Asia** (excluding China) saw a large increase in electric car sales, reaching almost 400 000 in 2024, up over 40% from 2023. However, in India, total electric car sales and their share of sales increased only slightly, approaching 100 000 (or 2%) in 2024. Thailand remained the largest EV market in Southeast Asia, despite a 10% drop in electric car sales. This decline was outweighed by an even steeper 26% drop in conventional car sales, largely due to [stricter lending criteria](#), meaning the electric sales share rose to 13% in 2024, up from 11% the previous year. Within the region, Indonesia and Viet Nam also stood out, respectively tripling and nearly doubling their sales numbers and reaching sales shares comparable to countries such as Spain or Canada. In many Southeast Asian countries, BEVs are the most popular electric car type, with over 90% of all electric car sales being fully electric.

In **Latin America**, sales volumes and penetration rates doubled in many countries, with electric cars reaching a market share of 4% in 2024. Brazil towered over other countries in the region with nearly 125 000 electric car sales, more than twice the number of 2023 sales, and the electric sales share doubled to 6.5%. Costa Rica, Uruguay and Colombia also achieved impressive sales shares of around 15%, 13% and 7.5%, respectively. These increases are in large part the result of government [incentives](#) such as tax exemptions, reduced registration fees, a relaxation of traffic restrictions for EVs, and relatively high fossil fuel prices.

In **Africa**, electric car sales more than doubled to reach nearly 11 000 in 2024. Sales shares remained low, at under 1%, though there was growth in several countries, such as Morocco and Egypt, where new electric car sales increased to more than 2 000.

Electric car registrations and sales shares in selected countries, 2020-2024



IEA. CC BY 4.0.

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle.

Sources: IEA analysis based on country submissions and data from ACEA, EAFO, EV Volumes, Marklines, [Asomove](#), [AleTech](#), [Andemos](#), OICA, [AFMA](#), [Gaikindo](#) and [AIVAM](#), sales of other macro regions can be found in the [Global EV Data Explorer](#).

Emerging electric car brands are seeing local and even international success

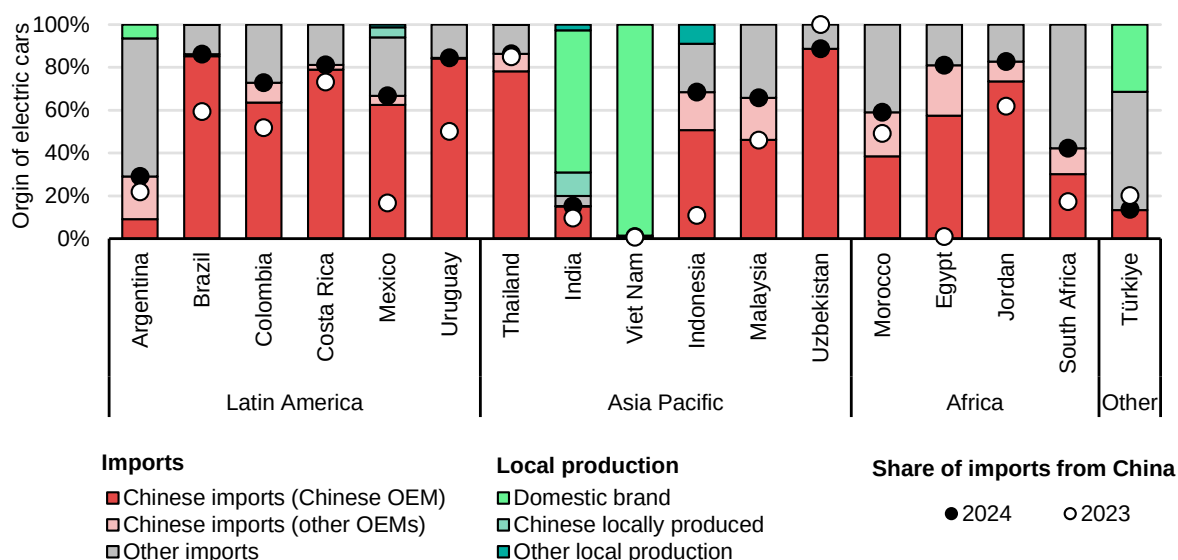
Recent years have seen the birth of several new electric car brands in emerging markets, such as VinFast in Viet Nam, Togg in Türkiye, and [Tito](#) in Argentina, helping to drive up sales. In **Viet Nam**, local brands underpinned the near doubling

of the electric sales share in 2024 to reach 17%. VinFast has also started to export to 11 different countries, with the largest share of exports going to Southeast Asian countries such as Indonesia (44%) and Malaysia (22%), but also to the United States (22%). The company has announced plans to [double](#) domestic production in Viet Nam, as well as expanding manufacturing into [India](#) and Indonesia.

Türkiye continues to deploy the domestically produced Togg electric cars, increasing its total production by 50% year-on-year. The increase in domestic production and in imports resulted in the country reaching an electric sales share of 10% in 2024. In July 2024, the Turkish government announced a [USD 5 billion](#) package to boost its annual production to 1 million electric cars per year.

India's electric car market is predominantly supplied by Indian OEM Tata. In addition, at the end of 2023, Indian steelmaker JSW signed a joint venture with SAIC Motor, a Chinese OEM, to work together on car production under the name MG Motor. In 2024, the joint venture produced about half of its electric cars sold in India domestically, while the other half were imported from China. At the end of 2024, [JSW](#) also announced the launch of its own EV brand, and is in talks with partners such as BYD and Geely regarding [collaboration](#) on technology transfer.

Origin of electric cars sold in selected markets, 2024, and share of total imports from China, 2023 and 2024



IEA. CC BY 4.0.

Notes: Chinese OEMs include BAIC, Geely-Volvo, GWM, GAC, BYD, Chery Automobile, JAC, Neta Auto, Seres Group, FAW, Changan, Dongfeng, Jiangling Motors, SAIC, Leap Motor, Xiaopeng, Aiyas Automobile. The domestic brands are Tata Motors, Mahindra & Mahindra (India); Togg Inc. (Türkiye); VinFast (Viet Nam) and Tito (Argentina).

Sources: IEA analysis based on data from EV Volumes.

Overseas expansion plans of Chinese producers, prompted by changes to import tariffs, drove sales in emerging markets

Another notable trend from 2024 was the numerous manufacturing announcements from Chinese OEMs in countries such as Brazil, Thailand, Indonesia and Malaysia, where temporary exemptions from import tariffs for electric cars are coming to an end. In 2024, electric car sales in **Brazil** more than doubled, with over 85% of new electric cars coming from China. A key factor behind this impressive growth was electric cars being exempt from import duties of 35%, though this exemption started to be gradually removed in 2024 and is set to end by the middle of 2026. By then, automakers [BYD](#) and [GWM](#) will have begun producing models in Brazil, with a range tailored to the Brazilian market, such as BYD's [Song Pro](#), which will be flex-fuel compatible.

In **Thailand**, Chinese imports play a key role in electrification, accounting for 85% of electric car sales. However, as in Brazil, this share is expected to decline due to changes introduced in the [EV 3.5 program](#), under which import taxes on electric cars will be reintroduced at the end of 2025 and existing subsidies of up to THB 100 000 (Thai baht) (USD 2 800) per imported car will be gradually phased out. To continue to qualify for the [exemption and subsidy](#), OEMs must commit to producing at least two battery electric vehicles (BEVs) domestically by the end of 2026 for every imported BEV sold in 2024 and 2025.

In **Indonesia**, electric car sales tripled in 2024 while the conventional market contracted by 20%, leading to an electric sales share of over 7%. The government has supported adoption by reducing the VAT rate on electric cars from 11% to 1% since 2023. However, what has potentially had an even [greater impact](#) on reducing the cost of electric cars for Indonesian buyers – and thus stimulating EV sales – has been the government waiving [import taxes](#) for EVs from car makers that invest in local electric car manufacturing from the start of 2024. Chinese car manufactures such as [BYD](#) and [GAC Aion](#) profited from this reduction, as did European OEM [Stellantis](#). As a result, Chinese electric car imports increased 18-fold to 34 000 by the end of 2024.

In **Malaysia**, electric car sales more than doubled in 2024 and the sales share increased from less than 2% in 2023 to nearly 4% in 2024. Much of this success is due to imported electric cars being [exempt from import taxes and excise duties](#) until the end of 2025. Ahead of the tax exemption ending, Chinese car producer Geely, together with Proton (a Malaysian automotive company), will start domestically [producing](#) the e.MAS 7 by the end of 2025, backed by [an investment](#) from Geely. Malaysian OEM [Perodua](#) will also start producing its first electric car at the end of 2025, with a price of RM 80 000 (Malaysia ringgit) (USD 18 000).

More affordable electric cars and local policies have reshaped the EV landscape in more emerging markets

Policy measures such as [tax incentives](#) for electric cars contributed to the doubling of electric car sales seen in **Colombia** and **Costa Rica** in 2024. Colombia also proposed to increase [import tariffs](#) on all hybrid vehicles at the end of 2024, in a push to shift more sales towards BEVs. More than 70% of all electric cars sold in these two countries were imported from China, with Chinese imports to Colombia more than tripling in 2024, while imports from other countries grew by just 30%. In **Uzbekistan**, electric car sales shares doubled and the [average price of an imported electric car](#) fell almost threefold between 2023 and 2024.

In **Africa**, local policies and changing trade regimes are reshaping the electric car market. Developments such as the ban on imports of petrol and diesel cars introduced in **Ethiopia** at the start of 2024 have resulted in a reported deployment of [100 000](#) electric vehicles.³ While model availability appears to be reasonable in the country, there are [reports](#) that garages struggle to source components for repairs, and that deployment of chargers outside of the capital has not kept pace with electric car sales. In **Morocco** and **Egypt**, efforts by car manufacturers to expand their production lines for batteries and/or electric cars in order to facilitate exports to the European Union have also pushed up domestic deployment, with the sales share reaching just under 2%. **Nigeria** is now looking into strengthening its EV manufacturing capacity with support from Morocco, and in 2024, signed the [Zero Emission Vehicles Declaration](#) to work towards all new sales of cars and vans being zero emission by 2040.

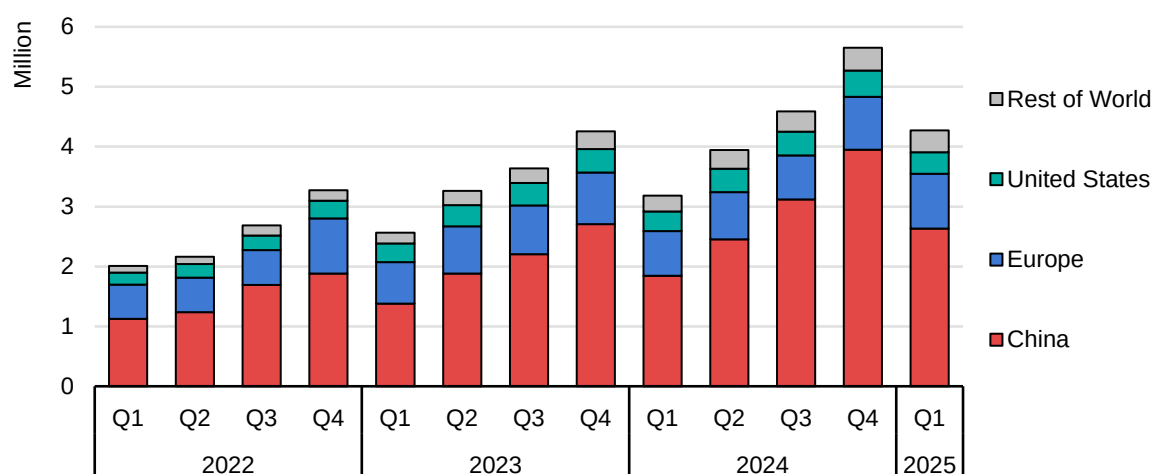
First quarter sales hint at strong sales for 2025, despite many uncertainties

Electric car sales increased 35% in the first quarter of 2025 compared to the same period in 2024

More than 4 million electric cars were sold in the first quarter of 2025 as sales grew by 35% compared to the first quarter of 2024, which was higher than the growth rate observed in the first quarters of the previous 2 years. Over 1 million more electric cars were sold in the first three months of 2025 compared to the same period in 2024 and about 60% of these were sold in China.

³ Data on electric car deployment in Ethiopia is difficult to obtain, and sources are not well aligned. The Ministry of Transport of Ethiopia reports a stock of 100 000 electric vehicles but does not define how many of these are cars. In contrast, EV Volumes reports about 1 300 electric car sales in the past 5 years.

Quarterly electric car sales, 2022-Q1 2025



IEA. CC BY 4.0.

Sources: IEA analysis based on data from EV Volumes.

Between January and March 2025, China averaged monthly sales of around 875 000 electric cars, with total sales of more than 2.5 million. While the electric sales share was less than 45% in January, it reached more than 50% in both February and March. Across the full first quarter, the share of electric car sales was similar to that of 2024.

In Europe, electric car sales reached more than 900 000 in the first quarter of 2025, 625 000 of which were sold in the European Union. The electric sales share has also been increasing, averaging one in four cars sold in Europe in the first three months of 2025. In the United Kingdom, electric cars represented 30% of cars sold in the first quarter, while in the European Union the share was less than 25%.

More than 360 000 electric cars were sold in the United States in the first three months of 2025, around 10% more than during the same period the previous year. Total car sales grew at a similar rate, meaning the electric car sales share in the United States remained around 10%, the average across 2024.

Several emerging electric car markets continued to see strong growth in the first quarter of 2025. In Brazil, for example, electric car sales exceeded 30 000 across the first three months of 2025, 40% more than during the same period in 2024. Sales in India grew 45% year-on-year, nearing 35 000 electric car sales for the first quarter of 2025. Electric car sales in Viet Nam also approached 35 000 for the first quarter – nearly four times as many as were sold during the first quarter of 2024 – leading sales across Southeast Asia to double to over 100 000 between January and March 2025.

Electric car sales are expected to exceed 20 million in 2025, representing one-quarter of total car sales

For the full year 2025, electric car sales are expected to increase by 25% globally, which is similar to the growth rate from the 2024. As a result, electric car sales top 20 million worldwide. While sales volumes may be impacted by economic and policy [uncertainties](#), more than one in four cars sold in 2025 is expected to be electric.

Building on strong sales in the first quarter of 2025, China is expected to sell over 14 million electric cars across the full year – more than were sold globally in 2023. Sales of both electric and conventional cars are supported by the extension of the trade-in scheme for older vehicles. The sales share of electric cars in China is expected to reach around 60% in 2025.

The European Commission announced in March 2025 that OEMs would be given flexibilities in meeting the 2025 CO₂ targets for cars and vans. On this basis, OEMs now only need to achieve the 15% emissions reduction target (compared to the 2021 baseline) on average over 2025-2027. This announcement was made in response to [auto industry claims](#) that the 2025 target would be unachievable, and would thus incur significant financial penalties that would damage the already struggling European auto industry. As yet, it is unclear how different OEMs will approach meeting the 3-year average target, in terms of the degree of under-performance that could be accepted in 2025 but would then need to be compensated for in the following 2 years.

The new phase of the CO₂ targets in the European Union is expected to drive up electric car sales, although the new flexibilities mean OEMs have less of an incentive to bring lower-priced electric cars to market this year. Given that a purchase premium for electric cars [persists](#) in Europe, the phase-out of EV purchase subsidies in some European countries could place downward pressure on sales, but there are signs to the contrary. At the end of 2024, the electric car purchase subsidy in the [Netherlands](#) came to an end, but electric car sales in the country in the first quarter of 2025 were about 10% higher than during the same period of 2024. In Italy, direct purchase subsidies for electric cars are no longer being renewed after 2024, though the government does aim to support the domestic production of EVs. In the first three months of 2025, electric car sales in Italy were up almost 50%.

Over the course of the year, electric car sales are expected to reach around 4 million across Europe. In line with this, the share of electric cars sales would increase several percentage points compared to 2024, to around 25%. The increase in electric car sales across Europe is boosted by the UK Vehicle Emissions Trading Scheme, which sets the target of 28% battery electric car sales in 2025.

In the United States, [Executive Order 14154](#) directed the government to reconsider market interventions that favour EVs. Legislation has since been proposed that would end the Clean Vehicle Tax Credit for both cars and light commercial vehicles. In 2025, this proposal may result in consumers that have been considering buying an electric car rushing to do so before the tax credit is removed. A dampening effect on EV sales in the United States is expected only once the tax credit is repealed, and the timeline for that is uncertain. In addition, [tariffs](#) for conventional and electric cars have also been announced, which may result in lower car sales. For the full year, electric car sales in the United States are expected to grow almost 10% in 2025, with a slight increase in the electric car sales share.

Across the rest of the world, electric car sales are expected to grow by over 30% to around 1.8 million. This would mean electric cars account for 6% of all car sales outside of the three major EV markets in 2025, up from 5% in 2024. The strong growth seen in Southeast Asia and Brazil is expected to continue, reaching sales of more than 0.5 million combined in 2025.

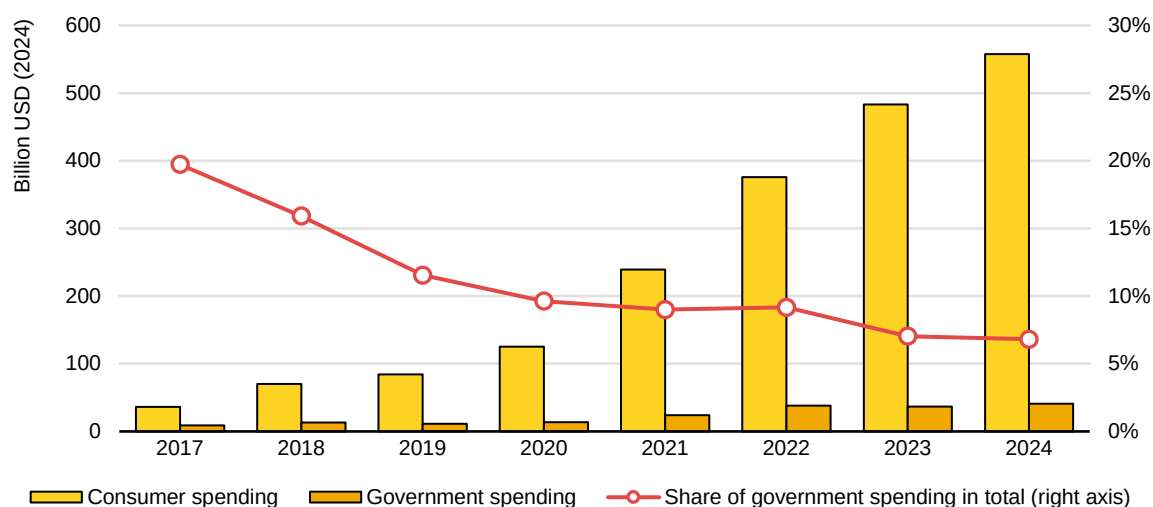
Government spending on electric cars

Subsidy phase-outs are leading to ever lower shares of government spending in the EV market

As electric car sales have grown over the past decade, government spending per vehicle, in the form of purchase subsidies and tax incentives, has steadily declined – a trend that accelerated in 2022 as subsidies were phased out.

In 2024, government spending accounted for less than 7% of total spending on electric cars globally, compared to 20% in 2017. In absolute terms, annual government spending on electric cars has hovered around the USD 38 billion mark since 2022. At the same time, total consumer spending on electric cars globally has grown continuously to reach USD 560 billion in 2024.

Global consumer and government spending on electric cars, 2017-2024



IEA. CC BY 4.0.

Notes: Government spending is the sum of direct central government spending through purchase incentives and foregone revenue due to purchase and registration taxes waived specifically for new electric cars. Only central government purchase support policies for electric cars are taken into account. Spending on charging is not included. Consumer spending is the total expenditure based on model price, minus government incentives. Values and trends may change slightly relative to previous publications following methodology improvements and better coverage of government support schemes.

Sources: IEA analysis based on EV Volumes and national policy documents.

China has had the largest absolute public spending since 2020, despite its subsidy scheme coming to an end in December 2022 after 12 years. Other incentives have remained in place – notably, electric cars being exempt from the 10% purchase tax that applies to other vehicles. In 2024, China introduced a trade-in subsidy with a higher premium for the purchase of EVs. The additional expenditure to support EV purchases is estimated to be around USD 2.7 billion for 2024.⁴ Nevertheless, Chinese government expenditure per vehicle dropped 25% between 2022 and 2024. China has the highest share of subsidies going to PHEVs, at nearly 45%, as a result of the 10% purchase tax exemption being applied to PHEVs, which are on average more expensive than BEVs. In contrast, government incentives for PHEVs have almost disappeared from other key markets.

In Europe, subsidy schemes were significantly reshaped in 2023 and 2024. The most abrupt change was in Germany, where the EUR 4 500 per-vehicle subsidy was reduced to zero as of December 2023 – which was followed by a drop in EV market share of 4 percentage points in 2024. As a result, the German government

⁴ The [original](#) funding allocation for the car trade-in subsidies in 2024 was close to CNY 11.2 billion (USD 1.5 billion), however, for the full year, [6.6 million](#) cars were traded in. The additional expenditure for electric car purchases is estimated by applying the CNY 5 000 subsidy differential to the [60%](#) of trade-ins that were for the purchase of an electric car.

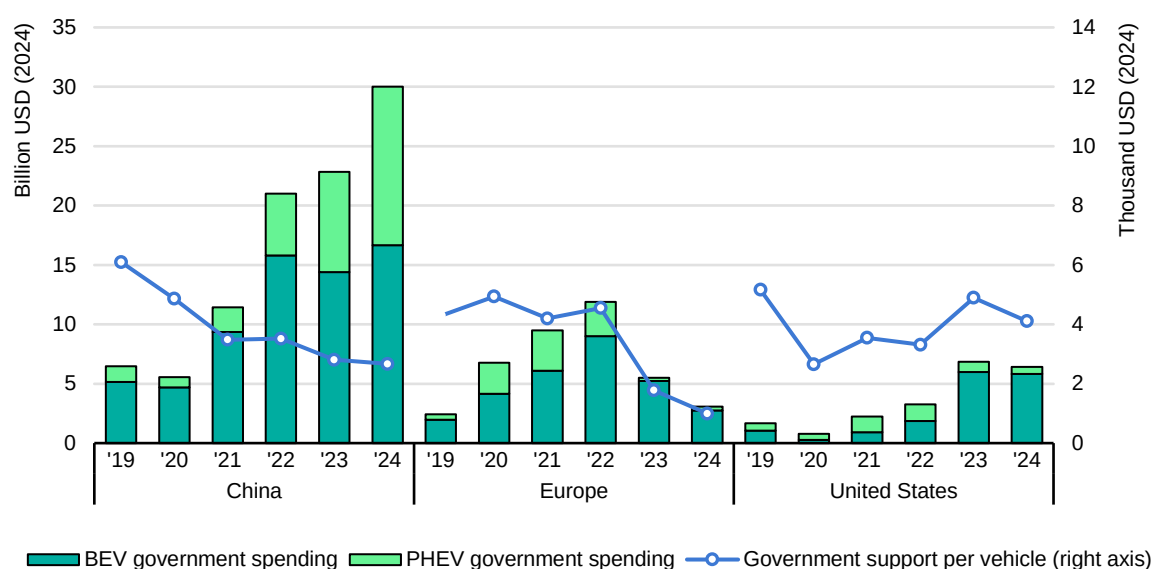
has introduced new [tax benefits](#) for companies buying EVs, effective from July 2024 through to 2028. Company cars account for about [two-thirds](#) of registrations in the country.

In the United Kingdom, all subsidies were removed at the end of 2022 but electric car sales have continued to increase, thanks in part to the [Vehicle Emissions Trading Schemes](#), which set targets for zero-emission car sales starting from 2024. In addition, the growth in EV sales was underpinned by a set of tax rebates for company cars, which represented about [60%](#) of total car registrations in 2024. When factoring in all [government tax incentives](#), an ICE car would incur more than [10 times](#) the company car tax of an equivalent BEV, compared to Germany where this ratio is around [4](#).

Similarly, Sweden ended its subsidy programme offering up to SEK 60 000 (Swedish kronor) (USD 5 800) per electric car in November 2022. Absolute volumes of electric car sales in the country decreased 10% in 2024, though the country's EV sales share fell only very slightly due to a drop in overall car sales. In several other European countries, subsidies were either reduced in absolute terms, or their conditions have become more stringent, with a faster roll-back of subsidies for PHEVs. As a result, the average subsidy per vehicle in Europe has fallen rapidly, from more than USD 4 500 per vehicle in 2022 to around USD 1 000 in 2024. The phase-down or interruption of subsidy schemes in Europe has had differing consequences on EV market shares at the national level, but the rapid decrease in subsidies has not been followed by an equivalent decrease in EV market share, providing an encouraging sign of market resilience.

In the United States, the introduction of the Inflation Reduction Act expanded the number of vehicles eligible for tax credits in 2023. However, the list of vehicles eligible for the USD 7 500 tax credit has since changed repeatedly as Internal Revenue Service guidelines have been implemented. The average tax credit in 2024 was approximately USD 4 000 per vehicle, since not all electric cars were eligible and some were eligible for only USD 3 750. In both 2023 and 2024, the United States had the highest per-vehicle subsidy of the three major EV markets.

Government spending on electric cars by region and powertrain, 2019-2024



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Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle. Government spending is the sum of direct central government spending through purchase incentives and foregone revenue due to purchase and registration taxes waived specifically for new electric cars. Only central government purchase support policies for electric cars are taken into account. Spending on charging is not included. Consumer spending is the total expenditure based on model price, minus government incentives. Excludes incentives for company cars. Values and trends may change slightly relative to previous publications following methodology improvements and better coverage of government support schemes.

Sources: IEA analysis based on EV Volumes and national policy documents.

2. Trends in the electric car industry

Manufacturing and trade

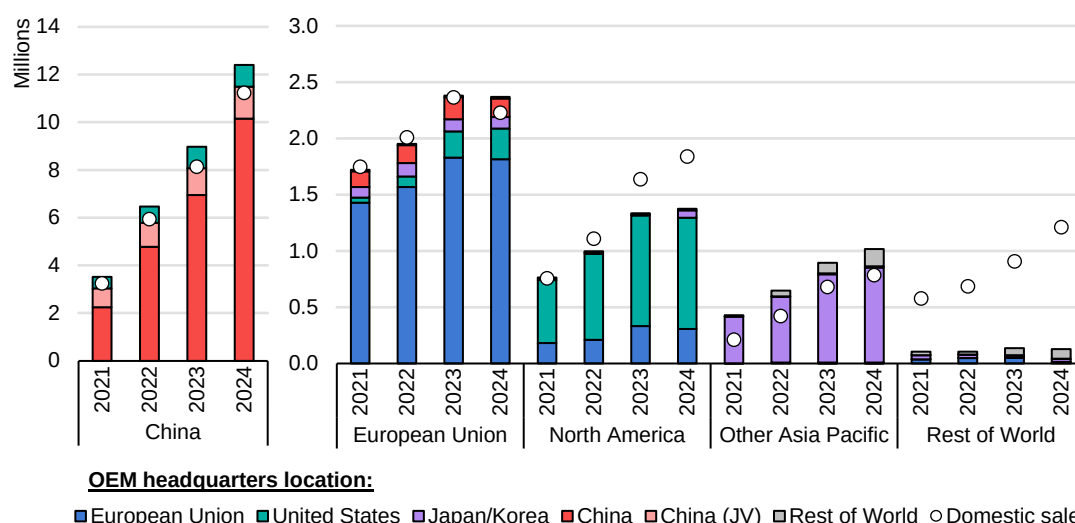
Steady growth in global electric car production masks differences at the regional level

A total 17.3 million electric cars were produced worldwide in 2024, about one-quarter more than in 2023, largely as a result of increased production in **China**, which reached 12.4 million electric cars. China remains the world's electric car manufacturing hub, accounting for more than 70% of global production in 2024. Production in China has been increasingly shaped by the expansion of domestic manufacturers. In 2024, Chinese OEMs accounted for more than 80% of domestic production, up from roughly two-thirds in 2021. Despite the numerous recently announced foreign direct investment plans from Chinese OEMs, their overseas production has yet to ramp up. Electric car production by Chinese OEMs operating outside China accounted for less than 2% of their global output in 2024.

In the world's second-largest electric car manufacturing region, the **European Union**, production stagnated at 2.4 million cars in 2024, but surpassed domestic sales by more than 5%. Domestic carmakers were behind nearly 80% of the region's total output, but there were contrasting trends among EU OEMs. While German OEMs marked a 5% year-on-year increase in their EU output, other EU OEMs (Stellantis and Renault) saw their regional production drop by over 15%, producing about 420 000 electric cars, or less than 20% of the region's output. Meanwhile, there was a sixfold increase in EU production by US OEMs between 2021 and 2024, predominantly led by Tesla and Ford. This contributed to the share of foreign OEMs in EU production reaching about 20% in 2024.

Elsewhere in Europe, the United Kingdom saw its electric car output drop 30% year-on-year in 2024 to around 80 000 electric cars, while Türkiye's production grew to 45 000, with two-thirds produced by domestic manufacturer Togg.

Production of electric cars by region and location of car manufacturer headquarters, 2021-2024



IEA. CC BY 4.0.

Notes: OEM = original equipment manufacturer; JV = joint venture. Other Asia Pacific includes Australia, New Zealand, Japan, Korea, India and Southeast Asia. North America includes Canada, the United States and Mexico. Tesla is the only foreign OEM producing electric cars in China that is not part of a joint venture with a Chinese OEM.

Sources: IEA analysis based on EV Volumes.

Manufacturing trends in **North America** showed notable contrasts. The gap between domestic production and sales in North America has increased steadily over the past 3 years. In 2024, despite electric car production falling 7% in the United States, overall output across the region remained unchanged year-on-year, as the decline in US output was offset by Mexico doubling its production to 220 000 electric cars. US-headquartered carmakers ramping up their manufacturing operations in Mexico were responsible for 70% of the country's total output, followed by Japanese and EU OEMs contributing equally to the remaining 30%. Meanwhile, Canada's output paled in comparison to its neighbours, remaining constant from 2023 at 25 000 vehicles.

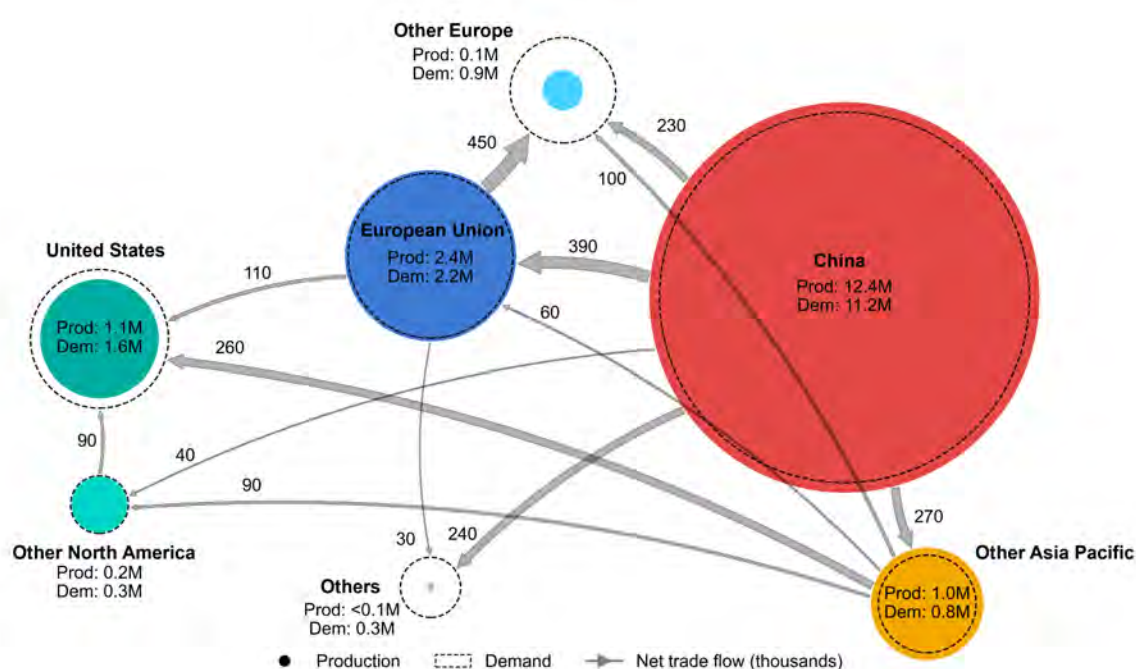
Electric car production also increased in **Asia Pacific** countries other than China to reach about 1 million. While incumbent carmakers such as Japan's Toyota and Korea's Hyundai were behind most of the region's output, emerging EV players like VinFast in Viet Nam or Tata in India were responsible for an increasing share of production, growing from 10% in 2023 to 15% in 2024. In India, in particular, domestic OEMs (Tata and Mahindra) accounted for more than 80% of the 75 000 electric cars produced domestically in 2024.

Global trade of electric cars grew nearly 20% in 2024

China and the European Union remained the world's largest EV exporters, while Mexico ramped up exports to the United States

Global electric car exports¹ surged by nearly 20% in 2024, reaching about 3.2 million electric cars and accounting for almost 20% of global sales, a share similar to that seen in 2023 and 2022. As with manufacturing, **China** accounted for the largest share, with 40% of global exports, or nearly 1.25 million electric cars.

Production, demand and net trade of electric cars in major global markets, 2024



IEA. CC BY 4.0.

Notes: Prod = production; Dem = demand; M = million cars. Net trade flows are in thousand vehicles and rounded to the nearest 10 000. Net trade flows under 20 000 vehicles are not shown. Stockpiling (the difference between exports and actual sales) of electric cars is not taken into account, and trade flows represent the number of electric cars manufactured in one country or region and sold in another region or country. "Other Asia Pacific" comprises Australia, New Zealand, Japan, Korea, India and Southeast Asia. "Other North America" includes Canada and Mexico. Other Europe includes Norway, Iceland, Israel, Switzerland, Türkiye, the United Kingdom and other European countries that are not EU member states.

Source: IEA analysis based on EV Volumes.

In 2024, the **European Union** saw its exports grow 9% year-on-year to nearly 830 000 electric cars. The key destination markets for EU-made electric cars remained unchanged, with other European countries accounting for almost 60%

¹ Unless specified otherwise, exports and imports of electric cars are calculated based on the sales of vehicles manufactured in a different location to the country in which they are sold. Global car exports and imports are assessed at the country level, except for the European Union, where internal trade between member states is excluded.

of exports (40% to the United Kingdom), followed by North America, accounting for about one-quarter of EU exports. The European Union remained a net exporter of electric cars in 2024, despite importing about 680 000 electric cars. While imports from China remained steady in 2024 at more than 400 000 electric cars (60% of EU imports), the share of Chinese OEMs in imports from China grew to two-thirds in 2024, up from 50% in the previous year. The Chinese OEM Geely accounted for almost 40% of these imports, mainly through its brand Volvo Cars, while Tesla's share decreased from 30% to 20% as more than half of its EU sales in 2024 were produced at its German assembly plant. **Other European countries** rely significantly on imports, primarily from the European Union. The majority of production elsewhere in Europe is based in the **United Kingdom** and **Türkiye**, but these countries were responsible for less than 15% of regional sales in 2024. China was the second-largest trade partner for electric cars, accounting for more than one-quarter of the 840 000 electric cars imported by non-EU European countries in 2024.

The **United States** remained a net importer of electric cars in 2024. Exports fell nearly 15% year-on-year to less than 200 000 electric cars, while imports grew 40% to 630 000. In 2024, **Mexico** became the United States' largest electric car trade partner, with net exports to the United States reaching 145 000 vehicles. Imports from Mexico grew threefold compared to 2023, representing more than two-thirds of Mexico's output. This surge was primarily driven by US OEMs (accounting for 70% of Mexico's exports to the United States) and Japanese OEMs (20%). Japan and Korea, previously the largest net exporters to the United States, each accounted for net exports of roughly 135 000 vehicles in 2024. Despite being the top source of imports in gross terms, the European Union ranked fourth in net electric car exports to the United States in 2024, totalling about 110 000 vehicles. Meanwhile, 40% of US-made electric car exports went to **Canada** in 2024, making it the largest US export market.

Japan and Korea accounted for the majority of the nearly 640 000 electric cars exported from the Asia Pacific region excluding China in 2024, primarily through their domestic manufacturers, with an increase of 15% from 2023. The United States was the main destination market for these exports, accounting for more than a quarter of the 1 million electric cars produced in the region. Europe followed, importing another quarter of the region's production.

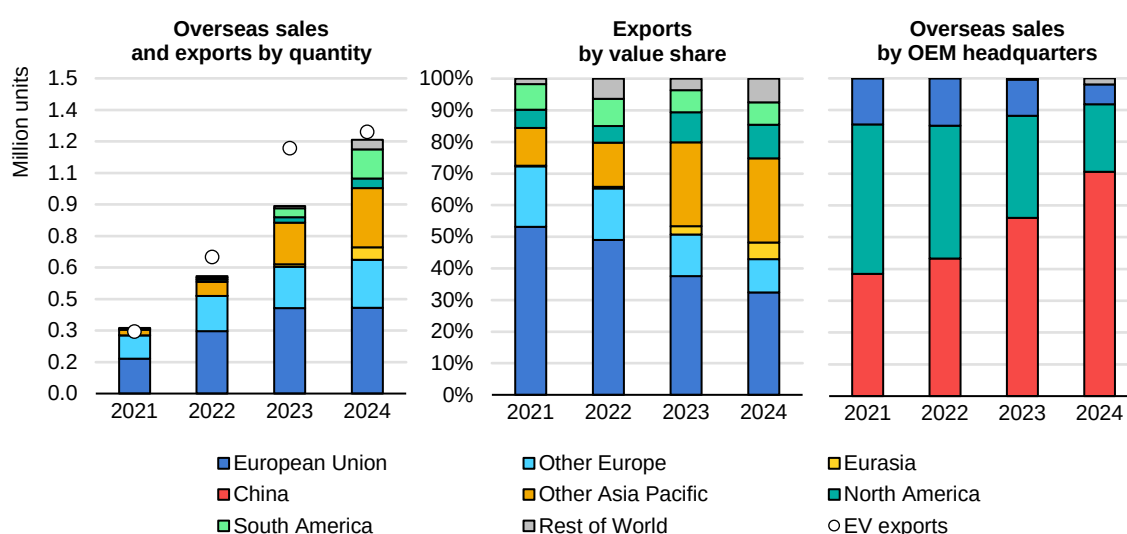
Chinese exports are increasingly driven by domestic OEMs as their destinations diversify

While it remains the world's largest exporter of electric cars, China experienced a noticeable slowdown in export growth in 2024. According to the China Association of Automobile Manufacturers (CAAM), the country exported over 1.15 million

electric cars in 2023, marking a staggering 80% growth from 2022. However, in 2024, annual export growth fell to just 7%, split unevenly across destination markets.

Several factors contributed to this slowdown. Firstly, the increase in trade restrictions resulting from tariff hikes in major export markets prompted Chinese OEMs to frontload their exports before such tariffs came into force. In [Brazil](#) for example, although Chinese imports saw strong year-on-year growth, with an increase of 120% in 2024, they dropped sharply by a factor of eight in the second half of the year following the reinstatement of tariffs. Europe remained the most important export market for Chinese-made electric cars, but weakening demand, [reluctance](#) of European consumers to buy Chinese EV brands and new countervailing duties in the European Union led the share of value attributed to Europe in total Chinese EV exports to fall from over 70% in 2021 to roughly 40% in 2024. As a result, Chinese exports increasingly shifted towards emerging markets such as Mexico (+370%), Southeast Asia (+10%), Russian Federation (hereafter: Russia) and countries in the Caspian Sea region.

Sales of Chinese-made electric cars outside China by region (left), export value shares per destination region (centre), and overseas sales by location of original equipment manufacturer headquarters (right), 2021-2024



IEA. CC BY 4.0.

Notes: EV = Electric Vehicles, which include electric cars only in this figure; OEM = original equipment manufacturer. Left and right figures use EV Volumes to represent the sales of Chinese-made electric cars in overseas markets by destination market and OEM headquarters location. Discrepancies with EV exports reported by China Association of Automobile Manufacturers (CAAM) (white dot) are explained by stockpiling of unsold Chinese electric cars in export markets. The exports by value in the central figure are taken from General Administration of Customs of the People's Republic of China (GACC) trade tables queried with HS codes 870360 and 870380, which also include low-speed EVs. Other Asia Pacific includes Australia, New Zealand, Japan, Korea, India and other Southeast Asian countries. Eurasia includes the Caspian regional grouping and Russia.

Sources: IEA analysis based on EV Volumes, CAAM and GACC.

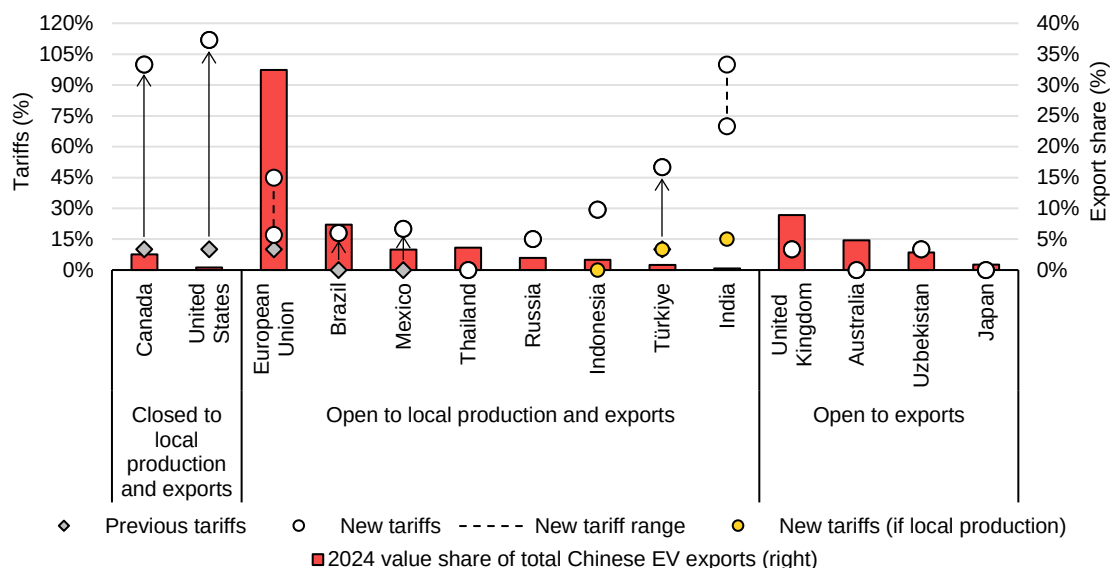
Inventory build-up by Chinese OEMs also contributed to the slowdown in Chinese export growth. In 2023, sales of Chinese-made electric cars outside China fell short by 275 000 cars compared to CAAM's reported exports. This led to clogged destination seaports, particularly in [Europe](#) and [Brazil](#), and limited the capacity for additional imports in 2024 until excess [inventory](#) was cleared. However, this stockpile helped sustain overseas sales growth of 35% for Chinese-made electric cars in 2024, while exports grew only 7%.

Chinese OEMs accounted for 70% of 2024 total electric car exports from China, up from 55% in 2023. To sustain their export momentum, Chinese OEMs are investing in [expanding shipping capacity](#) through roll-on/roll-off (Ro-Ro) car carriers. In 2025, BYD commissioned the world's largest Ro-Ro [vessel](#), bringing its total shipping capacity to more than 30 000 electric cars. Meanwhile, a leading Chinese car shipping company, [COSCO Shipping Car Carriers](#), announced plans to expand its fleet to handle up to 700 000 cars annually. Despite the 2024 export slowdown, this surge in shipping capacity positions Chinese OEMs for renewed growth, playing a crucial role in facilitating exports from China and emerging manufacturing hubs like Southeast Asia.

Tightening trade restrictions are pushing Chinese OEMs to expand their overseas manufacturing footprint

As Chinese electric car production continues to outpace domestic demand, Chinese OEMs are increasingly looking abroad to capture a larger share of the global electric car market. However, tariff changes across several regions are making it more difficult for Chinese-made electric cars to remain competitive in key destination markets. In 2024, multiple regions introduced new tariffs on Chinese electric car imports. This included the [European Union](#), which imposed OEM-specific countervailing duties on Chinese battery electric car imports, aimed at offsetting alleged manufacturing subsidies received by OEMs in China. Meanwhile, the [United States](#) and [Canada](#) implemented new tariffs exceeding 100% in 2024, with further increases to tariffs on Chinese imports [announced](#) in 2025 in the United States, effectively deterring future Chinese electric car imports. [Mexico](#) and [Brazil](#), both of which have recently experienced a surge in Chinese EV imports, have also approved tariff hikes. In 2024, Mexico ended its 15-20% tariff exemption on EV imports from countries without a free trade agreement, including China. Brazil reinstated 10% import tariffs on electric cars in 2024, with plans to gradually raise them every 6 months to reach 35% by the middle of 2026.

Changes in tariffs on Chinese electric vehicle imports in selected regions, 1 January 2024-1 January 2025



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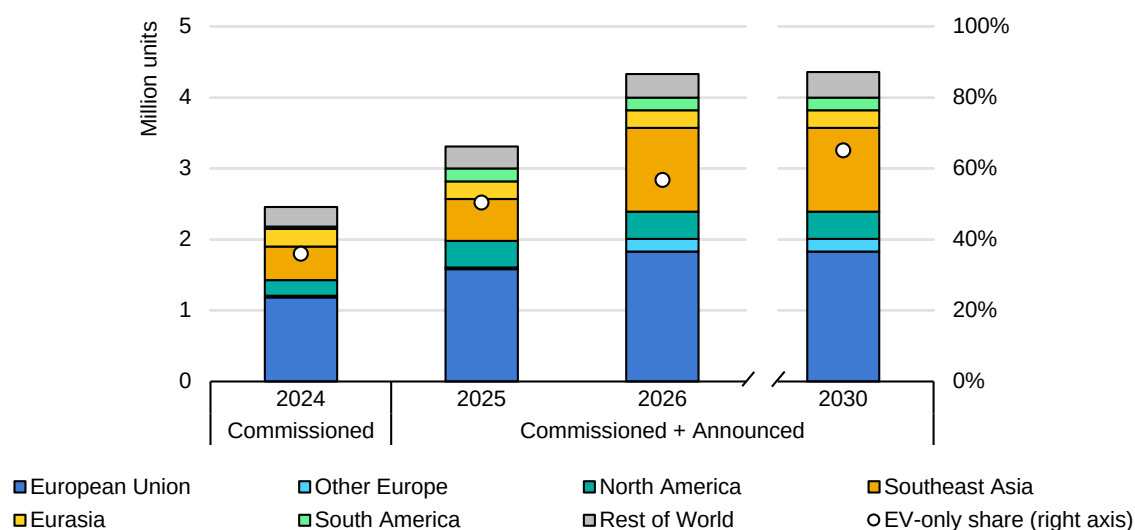
Notes: Previous tariffs refer to tariffs in place on 1 January 2024 while new tariffs refer to those in place on 1 January 2025. [Indonesia](#) has set a waiver on electric vehicle (EV) import duties for original equipment manufacturers (OEMs) committing to produce locally until 1 January 2026. The free trade agreement between [Thailand](#) and China reduces the usually applied tariff rate from 80% to 0%. In June 2024, [Türkiye](#) imposed a 40% additional tariff on China-made cars and, one month later, [exempted](#) vehicles imported under investment incentive certificates. [Brazil](#)'s import duties on EVs are set to 18% (20% for plug-in hybrids) in the first half of 2025 and will gradually increase to 35% by 2026. The [European Union](#)'s import duties apply only to battery electric cars and vary across OEMs. [Russia](#)'s 15% tariff on EV imports does not include the [recycling fee](#) which amounts to USD 4 400 (RUB 360 000 Russian rubles) per imported EV. The [Indian](#) government announced a decrease in [import duties](#) to 15% for manufacturers committing to produce locally within 3 years with a minimum investment of about USD 500 million. 2024 value of Chinese EV exports is taken from General Administration of Customs of the People's Republic of China (GACC) interactive trade tables queried with HS codes 870360 and 870380.

Sources: IEA analysis based on [ITC \(Market Access Map\)](#), GACC.

These additional export costs are prompting Chinese OEMs to establish new overseas manufacturing capacities. The assembly plants being planned are intended to both directly supply local markets (like BYD's plant in [Brazil](#)) and produce EVs for exports, thereby limiting exposure to tariff hikes targeting imports from China (such as from BYD's plant in [Türkiye](#) for exports to the European Union).

Most of the overseas production capacity owned by Chinese OEMs today is in the European Union, primarily through Volvo Cars' assembly plants, which produced more than 160 000 electric cars last year. By 2026, when including both EV-only assembly plants and dual EV/ICE assembly plants, overseas manufacturing capacity belonging to Chinese OEMs is expected to almost double to reach over 4.3 million vehicles per year. Europe and Southeast Asia are likely to remain the primary locations of these new electric car assembly plants, with almost half of the total Chinese overseas manufacturing capacity being located in Europe by 2026.

Commissioned and committed announced overseas electric vehicle manufacturing capacity of Chinese original equipment manufacturers, 2024-2030



IEA. CC BY 4.0.

Notes: EV = electric vehicle. Manufacturing capacity refers to plants producing EVs, either exclusively or alongside internal combustion engine cars without specifying the EV share. The EV-only share is calculated as the share of EV-only commissioned and announced assembly plants in total manufacturing capacity shown. Volvo brand commitments to reach a 50% and 90% EV share in its 2025 and 2030 sales, respectively, are treated as EV-only manufacturing capacity and are therefore accounted for in the EV-only share. Both full-process manufacturing and knocked-down (in which pre-manufactured components are imported and assembled) types of assembly plants are considered. Announcements refer to committed investments only.

Sources: IEA analysis based on Marklines, [Atlas EV Hub](#), OEM announcements.

Thanks to policies supporting EV manufacturing, access to raw materials, and a well-established automotive industry, Southeast Asia is poised to see the largest increase in Chinese OEMs' overseas manufacturing capacity. Countries including Indonesia, Malaysia, Thailand and Viet Nam have all put in place [policies](#) either favouring domestic manufacturing over imports, or providing exemptions from import and income taxes for OEMs committing to produce domestically. As a result, the combined EV-only and dual EV/ICE manufacturing capacity of Chinese OEMs in Southeast Asia is set to increase almost threefold by 2026 to reach 1.2 million vehicles (more than one-quarter of the total overseas manufacturing capacity of Chinese OEMs).

Model availability

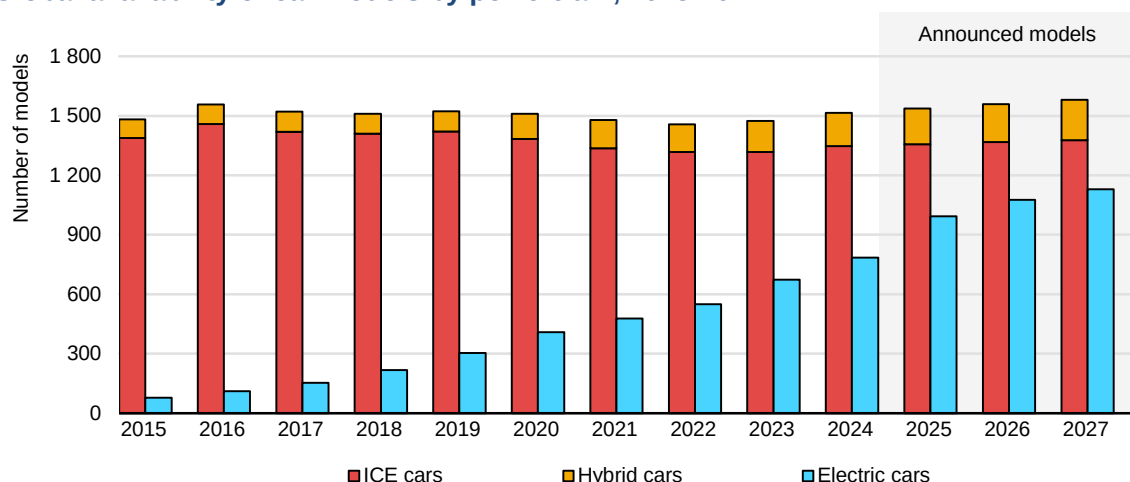
The number of electric car models keeps growing, especially for larger cars and SUVs

Available electric car models could number more than 1 000 by 2026

The number of available models for electric cars increased 15% year-on-year to reach nearly 785 in 2024. While today there are 50% fewer electric models than ICE and hybrid electric vehicle (HEV)² models, this gap is narrowing and is expected to shrink to around 30% by 2027 based on announcements by OEMs.

While its EV sales share remained largely unchanged, Europe saw the fastest increase in model availability over the past year, with a jump from 290 models to more than 360. The growth seen in 2024 is expected to almost double by 2026: As stricter emissions standards come into force in the European Union, more than 140 additional models are due to enter the market. For example, Volkswagen and Stellantis have announced plans to introduce about 35 new electric models between them by 2026.

Global availability of car models by powertrain, 2015-2027



IEA. CC BY 4.0.

Notes: ICE = internal combustion engine. Based on historic data and announced launches. Electric cars include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Hybrid cars are full hybrid models, mild hybrids are included in ICE cars. Analysis based on models for which there was at least one new registration in a given year; a model on sale but never sold is not counted, and as such actual model availability may be underestimated. Models are counted by brand model and do not include different trims. The announced models from 2025 to 2027 are based on electric model announcements and the number of ICE and hybrid models based on the trend over 2022-2024.

Source: IEA analysis based on data from EV Volumes and Marklines.

² A [hybrid electric vehicle](#) (HEV), which is powered by an ICE in combination with one or more electric motors using energy from batteries, can be in either a mild configuration or a full configuration. Mild hybrids use a battery and electric motor to help power the vehicle but cannot power the vehicle using electricity alone. A full hybrid can power a vehicle using electricity over short distances and at low speeds, thanks to its more powerful electric motor and larger battery. HEV batteries are charged through regenerative braking and by the ICE; HEVs cannot be plugged in to charge the battery and are not considered under the definition of electric vehicle.

The share of larger cars and SUVs among EV models coming onto the market continues to expand. In 2024, 70% of available EV models were large ([segments E to F](#)) cars, SUVs or pick-ups, compared to 65% in 2023. Nevertheless, there are signs that this share is levelling out in some markets. In Europe, 23 additional small electric models (segments A and B) are expected to join the 33 small models currently on the market. The United States has the lowest number of small electric models available, and nearly 90% of models available today are large cars or SUVs.

China has the most EV models across all segments

The highest model availability for electric cars can be found in China, where nearly 60% of all models on offer are electric – 5 times more than the number of electric models available in the United States. The large car and SUV segments are the most profitable for OEMs, and many have therefore developed these models as a preference. As a result, the number of small and medium models available in China is only one-third of the number of large or SUV models.

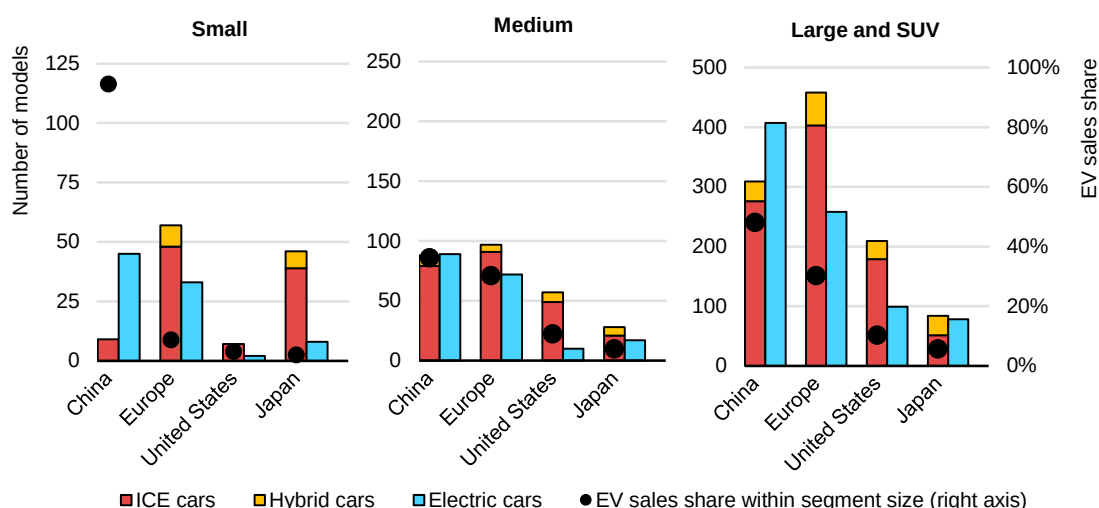
Yet despite model availability being more limited than for large cars, the small car segment is nearly fully electrified in China, with more than 90% of sales in the segment being electric. There were 45 small electric car models available in 2024, compared to fewer than 10 small conventional cars. The decline in number of conventional small models started in 2014 and by 2017 electric and conventional models were on par with around 30 models each. The small electric [Seagull from BYD](#) was one of the best-selling cars of 2024 across all segments and the best-selling small car, with about 440 000 sales. Sales came in just slightly behind the best-selling model overall, the Tesla Model Y (an SUV), which reached 485 000 sales. The fast pace of electrification of the small segment can be attributed to their affordability (see [EV affordability in China](#)), in combination with a push for local manufacturing and measures to improve air quality in China's provincial '[tier 3](#)' cities.

In contrast, in Japan and Europe, the large car segment is the most electrified, and the small car segment the least. However, this does not necessarily reflect model availability: in Japan, the share of electric models on offer in the large car segment is about 50%, but only 6% of large car sales are electric. Similarly, in Europe, where more than 40% of all small and medium models available are electric, the electric sales share in these segments is just 20%. In the United States there are nearly 100 electric large or SUV models available, which is less than half of the number of ICE and HEV models available.

Growing model availability supports EV adoption, but price appears to be the key determinant of EV penetration within small and medium size segments. People purchasing small and medium cars are likely to be more price sensitive than

buyers of larger models, making price parity particularly important for electrifying these segments. In Germany, less than 5% of small BEVs sold were cheaper than their ICE equivalent, as described in the section on [EV affordability in Europe](#).

Number of available car models by powertrain and electric vehicle sales share per size segment for selected regions, 2024



IEA. CC BY 4.0

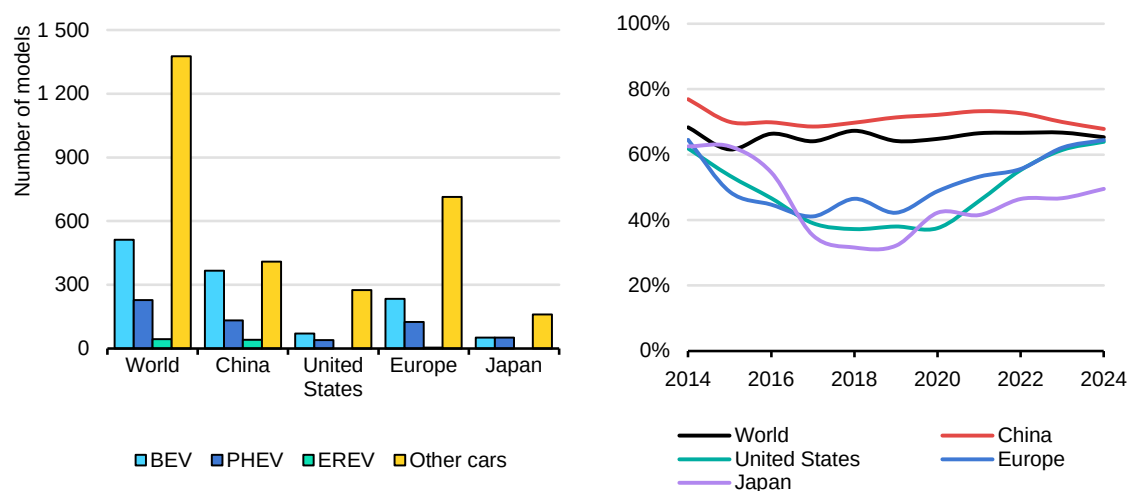
Notes: SUV = sports utility vehicle; ICE = internal combustion engine; EV = electric vehicle. Electric cars include battery electric and plug-hybrid vehicles; hybrid cars are full hybrid models; and mild hybrids are included in ICE cars. Analysis is based on models for which there was at least one new registration each year; a model on sale but never sold is not counted, and as such actual model availability may be underestimated. Models are counted by brand model and do not include different trims. Small cars include A and B segments; medium cars include C and D segments and A segments with SUV body type; large cars and SUVs include E and F segments, multi-purpose vehicles and C to B segments with SUV body type.

Source: IEA analysis based on data from EV Volumes and Marklines.

In major markets, battery electric models now represent around two-thirds of all electric car models

There are now more BEV models available than PHEV models. Over time, the share of BEV models among total electric car models in China, Europe and the United States has converged to reach a ratio of about two BEVs for every PHEV. While BEVs were the focus for OEMs in the early years (2014 and earlier), their share among electric car models then dropped in Europe, Japan and the United States, before beginning to increase again around 2020 in the United States and Europe. In Japan, the split remains at 50:50, while the average globally is more than three BEV models for every two PHEVs. Within the PHEV segment, the number of extended-range electric vehicle (EREV) models has grown in recent years, increasing by 40% from 31 models in 2023 to 43 models in 2024 (see Box [below](#)).

Number of models by powertrain in selected markets and globally, 2024 (left), and share of battery electric vehicle models in total number of electric car models (right), 2014-2024



IEA. CC BY 4.0

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle not including EREVs; EREV = extended-range electric vehicle. Other cars include hybrids and internal combustion engine cars.

Source: IEA analysis based on data from EV Volumes and Marklines.

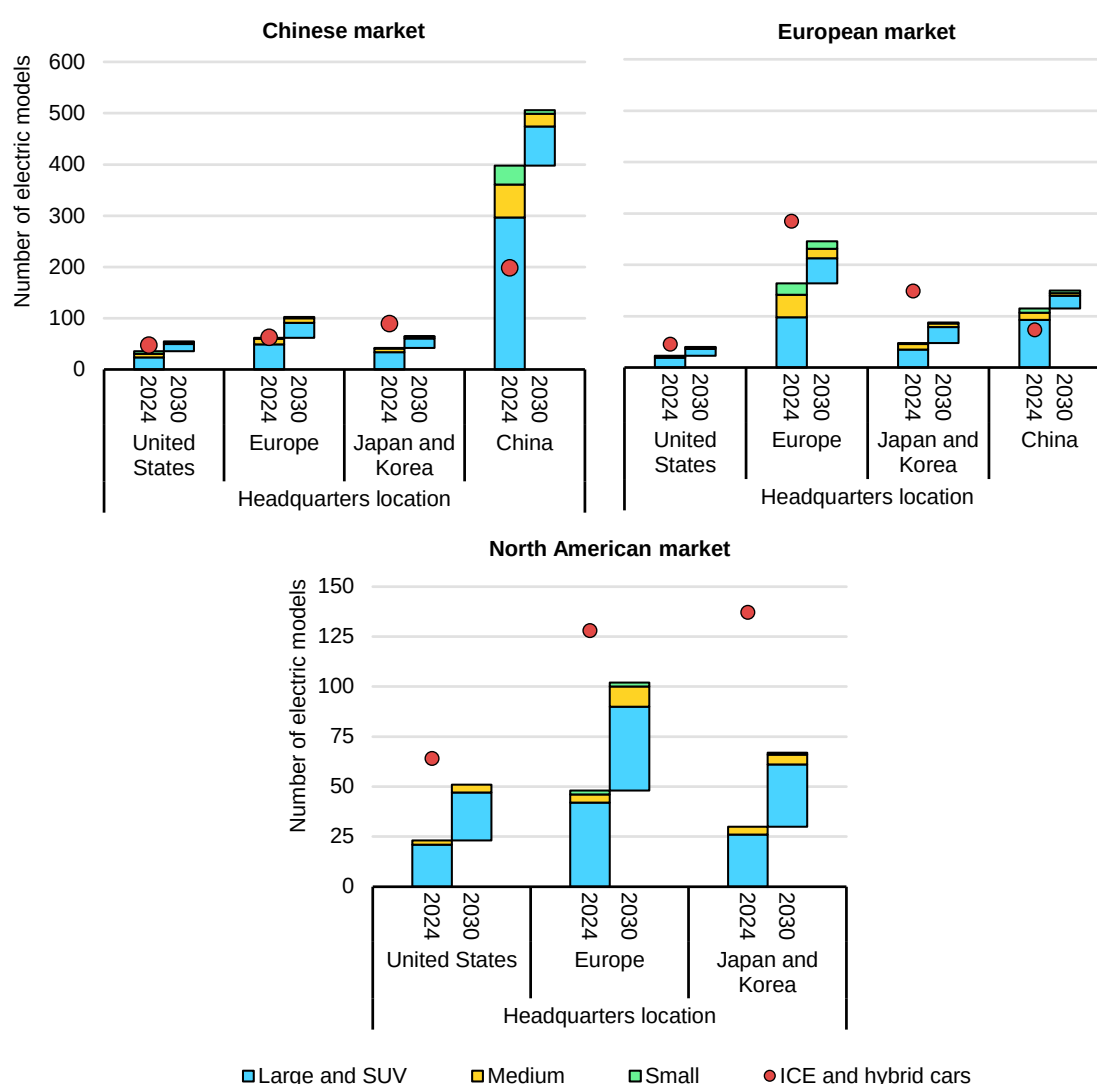
OEMs adopt different strategies for electric model announcements in different regions

The number of electric models on the **Chinese market** today is already greater than the number of ICE and hybrid models. Based on announcements, and assuming the level of ICE and hybrid models remains constant, by 2030 there will be two electric models available for every conventional car model. Domestic OEMs such as BYD and Geely already offer twice as many electric models than conventional models. This is in contrast to the offering from OEMs headquartered elsewhere in the world, which have slightly fewer electric than ICE models available in China. However, this balance is likely to shift in favour of electric by 2030, with around 80 additional electric models announced. OEMs headquartered in Europe (such as Volkswagen, BMW and Mercedes) offer the most electric models after Chinese OEMs.

Based on electric car model announcements, the gap between the number of conventional and electric models shrinks the most to 2030 in the **European market**. Chinese OEMs in this market already offer more electric models than conventional models, but European OEMs are now closing the gap by increasing their electric offerings by 50% by 2030, which is more than OEMs headquartered in other regions. About 40% of these new EV models are small or medium cars. Volkswagen and Stellantis, both of which have a greater focus on these vehicle segments than other European OEMs, are behind more than half of all announcements for small or medium models in the European market, as they are urged to release affordable models to meet their fleet-wide CO₂ target in the short term.

In the **North American market**, larger cars are the focus for many OEMs. Of the 110 electric car models available today, only 2 are small (the Mini Cooper BEV and Fiat 500 BEV), with sales totalling 3 000 in 2024 – less than 1% of all electric car sales. However, about 15% of the electric models due to enter the market in the next few years are medium sized, compared to 9% of available models today. Despite an increase of about 145 electric models by 2030, which will more than double the model availability for electric cars in the region, the number of conventional models will remain 70% higher.

Number of car models by location of manufacturer's headquarters and size segment, 2024, and announced models by 2030 for selected markets



IEA. CC BY 4.0.

Notes: SUV = sports utility vehicle; ICE = internal combustion engine. Small cars include A and B segments; medium cars include C and D segments and A segments with SUV body type; large and SUV cars include E and F segments, multi-purpose vehicles and C to B segments with SUV body type. The models from the Renault-Nissan Alliance have their headquarters assigned by brand. Brands with headquarters located in other regions such as India, Viet Nam and Chinese Taipei are not included and account for 8-12% of announcements, depending on the market. It is assumed that none of the current electric models will be phased out.

Source: IEA analysis based on data from EV Volumes.

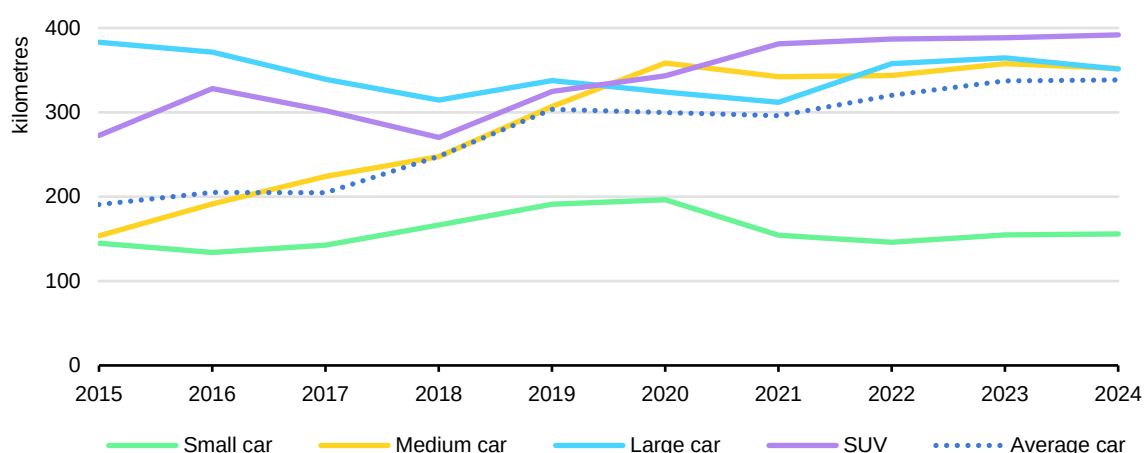
Electric vehicle range

No change to average range of battery electric cars in 2024

The sales-weighted average range (hereafter, “average range”) of battery electric cars globally remained the same in 2024, at about 340 km under on-road conditions. The average range was significantly lower for small cars, at just above 150 km, while medium and large cars, as well as SUVs, all maintained ranges above 350 km. As market competition intensifies, the fact that average range has stabilised in the past year could indicate that carmakers have found an optimal balance between range performance and vehicle manufacturing costs. This levelling-off of driving range also offers energy and environmental benefits, as longer ranges also require larger batteries, which [increase](#) vehicle energy consumption and demand for critical minerals.

In the United States and Europe, the average electric range increased by less than 5%, primarily driven by the growing interest in electric SUVs, which continued to dominate the EV market – exceeding 75% of sales in the United States and reaching around 60% in Europe. Across Europe, the average range of a battery SUV car reached almost 400 km under on-road conditions. Nevertheless, this falls short of the 500 km that respondents to a recent [survey](#) stated as their range preference. Meanwhile, in China, the average range remained stable as EV producers prioritised cost-cutting in the face of strong domestic competition.

Sales-weighted average range of battery electric cars by segment, 2015-2024



IEA. CC BY 4.0.

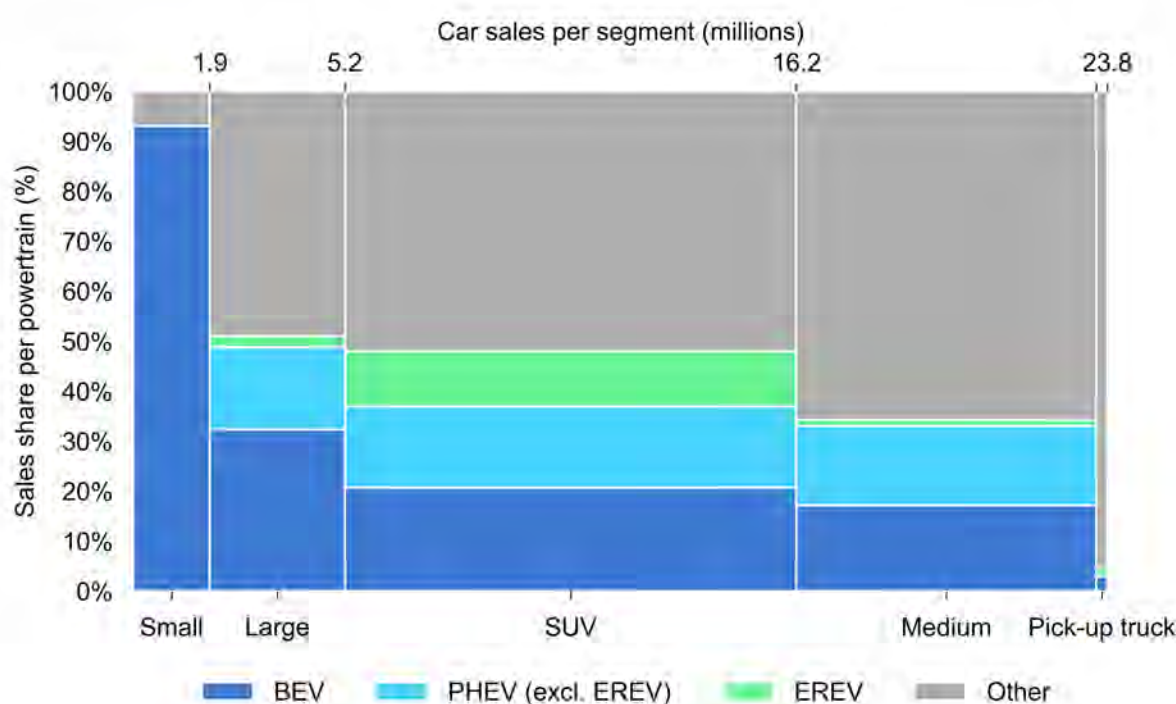
Notes: SUV = sports utility vehicle. Range is calculated using the global sales-weighted average vehicle efficiency of battery electric vehicles and their battery capacity by size segment. The vehicle efficiency considered in calculations reflects on-road driving conditions by applying a factor of 1.1 to the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) vehicle efficiency (in [kWh/100 km]). The range considers [full](#) battery utilisation, from 100% to 0% state of charge. Small cars include A and B [segments](#); medium cars include C and D segments, A segments with SUV body type and B segments with multi-purpose vehicle (MPV) body type; large cars include E and F segments, B segments with SUV body type and D segments with MPV body type; SUV includes segments C to F with SUV body type and remaining segments with MPV body type.

Source: IEA analysis based on data from [EV Volumes](#).

Plug-in hybrid electric vehicles are growing in popularity in China

Consumers purchasing large cars and SUVs in China are increasingly opting to buy plug-in hybrid electric vehicles (PHEVs) as a more flexible option. The key appeal of PHEVs lies in their ability to handle long trips even when charging infrastructure is insufficient or congested. PHEV electric range in China grew by over 20% between 2020 and 2024, reaching almost 100 km. In contrast, electric ranges stalled in Europe and the United States at about 65 km. The [environmental benefit](#) of PHEVs largely depends on charging behaviour, which can lead to real-world tailpipe CO₂ emissions that are significantly [higher](#) than type-approval values.

Total car sales in China per segment and powertrain, 2024



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Notes: BEV = battery electric vehicle; PHEV= plug-in hybrid vehicle; EREV = extended-range electric vehicle; SUV = sports utility vehicle. The width of each vehicle category in the horizontal axis is proportional to their Chinese market sales. Small cars include A and B [segments](#); medium cars include C and D segments, A segments with SUV body type and B segments with multi-purpose vehicle (MPV) body type; large cars include E and F segments, B segments with SUV body type and D segments with MPV body type; SUV includes C to F segments with SUV body type.

Sources: IEA analysis based on EV Volumes and Marklines.

Extended-range electric vehicles (EREVs) have gained ground in recent years, almost entirely as a result of growing adoption in China. Uptake has been primarily in larger and heavier high-end vehicle segments. In 2024, EREV models accounted for nearly 25% of electric SUV sales in China, and they dominated the

larger end of the electric SUV segment, making up 60% of large electric SUV sales (over 4.8 metres in length). More than 70% of the 40 EREV models available today belong to the SUV category (including multi-purpose vehicles and pick-up trucks), while the rest is mostly part of the large car segment category. In total, 14 additional EREV models are expected to be released by the end of 2025. Similarly, the four announced EREV models due for launch outside of China by 2026 (by [Scout](#) and [RAM](#) in the United States and [Changan](#) in Europe), in addition to the two already available today ([Mazda](#) and [Leapmotor](#) in Europe), are all positioned within the large pick-up truck and SUV segments.

Extended-range electric vehicles: advantages and limitations

In 2024, the average EREV in China had an electric range of about 120 km, compared to around 85 km for a standard PHEV. While the range of a standard PHEV has increased significantly in recent years, the longer electric range of EREVs could reduce charging frequency, increase the share of electric-only driving and lower reliance on liquid fuels.

As with standard PHEVs, the environmental benefits of EREVs are heavily influenced by charging behaviour and are generally [overestimated](#) in type-approval vehicle fuel economy ratings. In addition, when EREVs run on low battery, their [fuel consumption](#) compared to standard PHEVs varies depending on driving conditions. In some urban or low-power driving conditions, EREVs can be more fuel-efficient. However, in many other cases when the battery is low, the opposite is true: standard PHEVs tend to use less fuel because their engines can drive the wheels directly, unlike EREVs, which rely on a generator as an intermediate energy converter.

The components of EREVs also differ from those of standard PHEVs. EREVs require a generator, advanced power electronics and a larger battery, which can increase manufacturing costs, although the lack of traditional transmission and simpler engine design can reduce costs. Their competitiveness compared to standard PHEVs largely depends on optimising the size of the generator and battery, which are responsible for the majority of additional costs. Moreover, their chassis design, which is closer to that of a BEV than a standard PHEV, could accelerate [technology transfer](#) from rapidly evolving BEV [battery pack](#) and [chassis](#) technologies.

However, as battery electric cars continue to improve in range, charging speed and affordability, their simpler architecture and higher efficiency could outweigh the trend towards EREVs. Ultimately, wider adoption of EREVs will largely depend on the range and affordability of equivalent BEV models, as well as the availability of charging infrastructure.

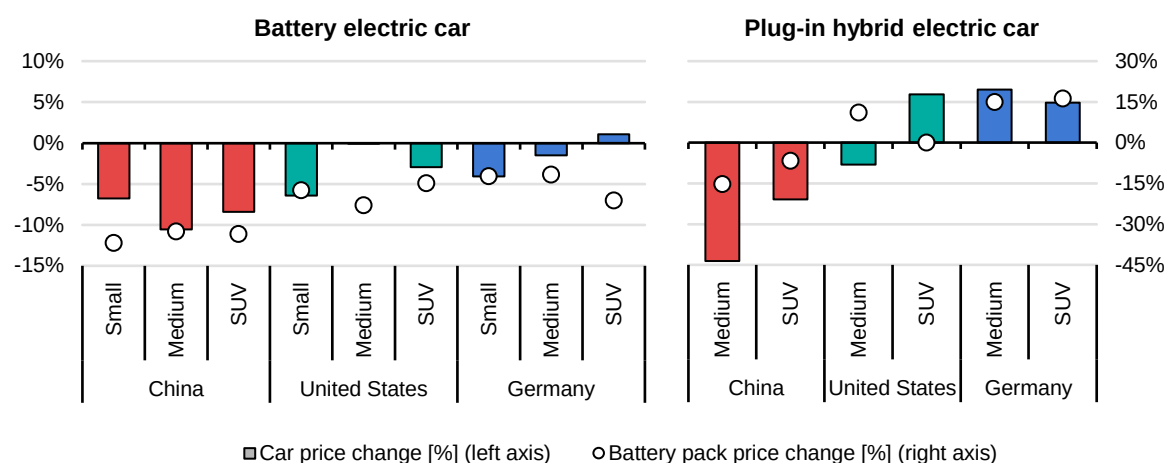
Electric car affordability

Falling battery pack prices and intensifying competition underpin progress in electric car affordability

Today, electric cars often have a lower [total cost of ownership](#) than ICE cars over the vehicle lifetime, due to reduced fuel and maintenance expenses. However, reducing the purchase price³ gap will be key to broader uptake. In Europe, for example, respondents to a 2023 [survey](#) by the European Commission identified the price of battery electric cars as the main barrier to adoption. While battery electric car prices generally fell in 2024, the price gap with ICE cars remains in most regions.

Electric car affordability has made significant strides over the past decade, primarily driven by falling battery prices, intensifying market [competition](#) and carmakers reaching economies of scale. In 2024, despite the global average battery size growing slightly, the global average battery pack price fell more than 25% compared with 2023 levels. This resulted in a global drop in electric car manufacturing costs that was reflected in the price of electric cars.

Electric car price and battery system price changes in selected countries, 2023-2024



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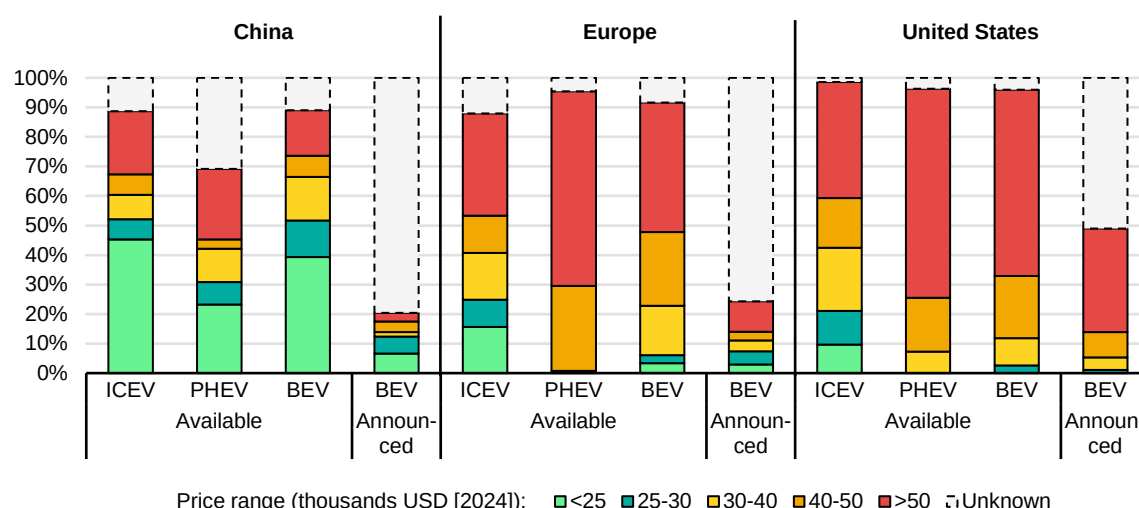
Notes: SUV = sports utility vehicle. Prices adjusted for inflation before indexing. Car price change values reflect the change in the sales-weighted average car retail price values over the 2023-2024 period. The battery pack price is calculated based on the average battery size in a given country, segment and year, multiplied by the corresponding regional pack price.

Source: IEA analysis based on data from S&P Global Mobility, BNEF and EV Volumes.

³ By price we refer to the Manufacturer Suggested Retail Price (MSRP), also known as the sticker price, which includes value-added taxes, purchase taxes and dealer markups, but excludes purchase subsidies and registration taxes. It differs from the transaction price in that it does not account for any rebates and discounts applied at the dealership.

However, the trend towards falling prices has been uneven across markets, due to differences in carmakers' pricing strategies, and in market maturity and the level of competition. For example, in China, the sales-weighted average (hereafter, "average") price of a battery electric SUV fell almost 10% year-on-year in 2024, partly due to the 30% decline in the battery pack price. Similarly, in the United States, a 15% decline in battery prices contributed to a 3% drop in the average purchase price of electric SUVs in 2024. In contrast, in Germany, the price of electric SUVs slightly increased in 2024, despite their battery pack prices declining 20%. This suggests that the battery pack price is not the only factor influencing EV prices: other component manufacturing costs, trim levels and carmakers' pricing strategies also play a significant role.

Price range distribution of available and announced car models in selected markets, 2024-2026



Price range (thousands USD [2024]): <25 25-30 30-40 40-50 >50 Unknown

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Notes: ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle. "Available" includes models sold in 2024 in selected markets. Germany, the United Kingdom and Türkiye are used as proxy countries for available models in Europe. "Announced" only includes models with known release price and expected to be launched by the end of 2026.

Source: IEA analysis based on data from S&P Global Mobility, EV Volumes and OEM announcements.

Availability of a wide range of affordable EV models will be key to unlocking mass-market adoption. In 2024, there were fewer BEV models available than ICEV models in the United States and Europe, and the range was skewed towards higher-end models with higher prices. Conversely, in China, the price distribution of available BEV models closely resembles that of ICEVs, with about 40% of available electric models priced below USD 25 000 (against 45% for ICEV models), and more than half below USD 30 000. In 2024, this price distribution was reflected in sales, with the median price paid for a battery electric car standing at around USD 24 000, about USD 700 less than for an ICE car. This trend

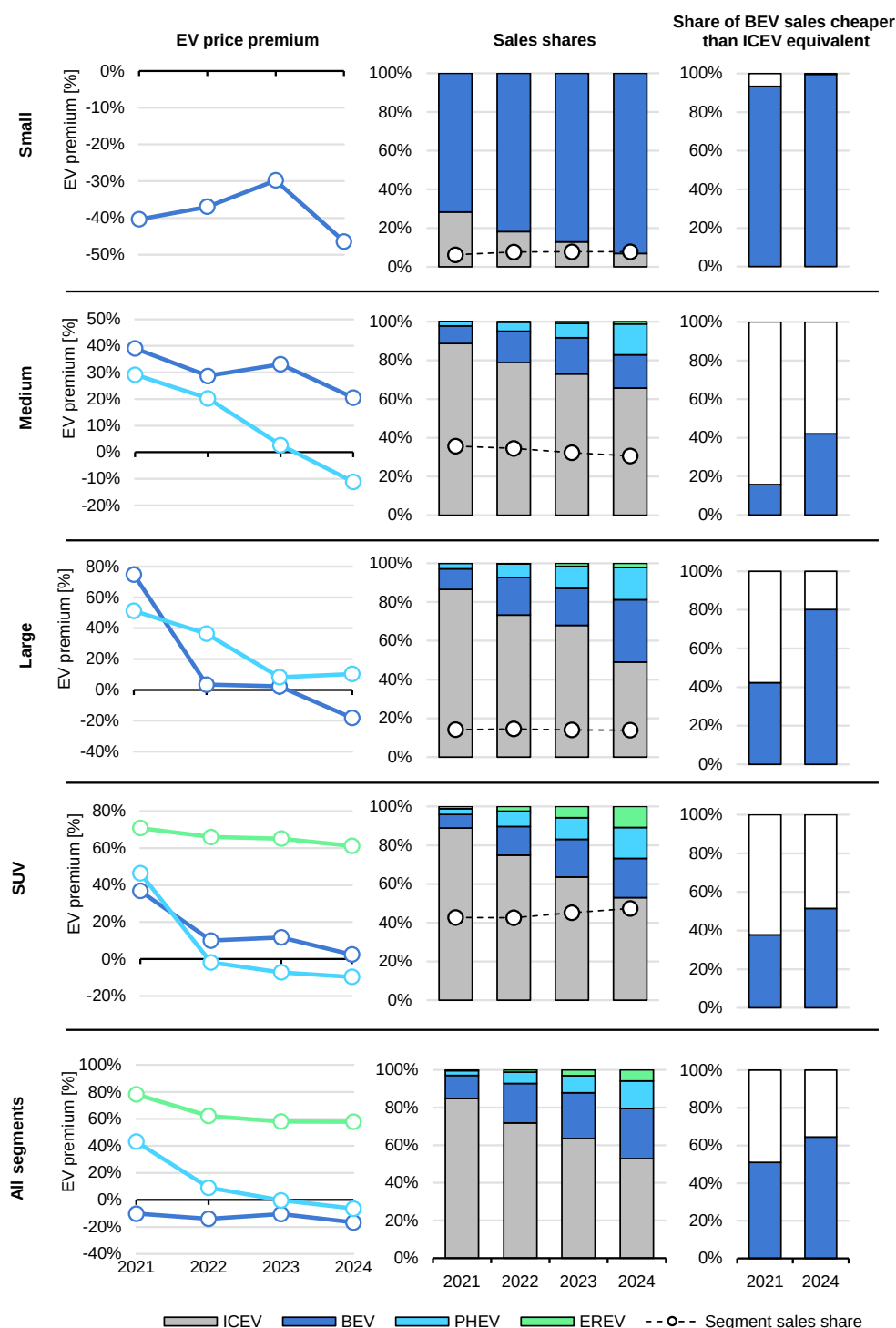
towards a larger share of more affordable models is expected to continue in the short term, as 60% of announced models with a known price are expected to launch below the USD 30 000 mark.

Contrasting trends were also seen in the affordability of plug-in hybrids. In China, prices for medium PHEVs dropped 15% from 2023 to 2024, and SUV-type PHEV prices fell 7% over the same period. However, in Germany, the average purchase price of medium and SUV-type PHEVs grew more than 5% year-on-year. This was partly driven by their average battery size growing, causing their battery pack prices to increase by about 15%. In 2024, in Europe, only 1 of the around 130 PHEV models was priced under USD 40 000, compared with more than 40 BEV and 155 ICEV models marketed below this price tag. Similarly, in the United States, the 4 cheapest PHEV models available were priced between USD 30 000 and USD 40 000, while about 60 ICEV models were marketed below this price range. The US and German markets contrasted markedly with that of China, where nearly 40 PHEV models were available with a price tag below USD 25 000, competing with more than 250 ICEV and 140 BEV models within the same price range.

Price-competitive electric cars in China are driving rapid electrification across all segments

In China, the rapid electrification of small cars has been underpinned by their unrivalled affordability. In 2024, nearly all small battery electric car models in China were priced lower than the average small ICE car, and the average purchase price was about half that of the average small ICE car. This led to the almost complete electrification – nearly 95% – of small car sales in China in 2024, up from a share of 75% 3 years earlier. Nevertheless, the small car segment makes up only a small share of the Chinese car market, accounting for less than 10% of sales in 2024.

Electric car price premium compared to conventional models per segment (left), powertrain sales shares (centre) and sales share of battery electric vehicles cheaper than conventional equivalents (right) in China, 2021-2024



IEA. CC BY 4.0.

Notes: EV= electric vehicle; ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; EREV = extended-range electric vehicle; SUV = sports utility vehicle. Price data is adjusted for inflation. Price of electric cars in data has been increased by 10% to adjust for the registration tax exemption in China. The share of battery electric cars cheaper than their conventional equivalent is calculated as the number of car sales priced lower than the sales-weighted average price of the ICE car in their segment category.

Source: IEA analysis based on data from S&P Global Mobility, EV Volumes and Marklines.

In 2024, BEVs also reached price parity with ICEVs in the SUV segment – the most popular car segment in China, accounting for half of all car sales. More than half of battery electric SUV sales were priced lower than an average ICE SUV. Plug-in hybrid SUVs were also sold at cheaper price levels than ICEV models for the third consecutive year, supporting their steady uptake in this vehicle segment. While progress on affordability has supported the growing sales shares of BEVs and PHEVs, adoption of EREVs seemed to be more a result of consumer preferences rather than purchase price competitiveness. In 2024, the average price premium of EREVs over ICEV models stood at 60%, marking slim progress from 70% three years ago. Despite their higher purchase price, the market share of EREVs within the SUV segment grew to reach 10% in 2024, suggesting that this hybrid powertrain technology is appealing to wealthier consumers who are less price sensitive and seek boosted range in high-end vehicle models.

In the medium car segment, which represents about one-third of total car sales in China, BEVs were 20% more expensive than conventional equivalents in 2024, down from 40% in 2021. PHEV prices also dropped. For the first time, the sales-weighted average price of medium PHEVs in 2024 was 10% lower than conventional models. As a result, PHEV sales in the segment more than doubled, and more than one-third of medium car sales in China in 2024 were electric.

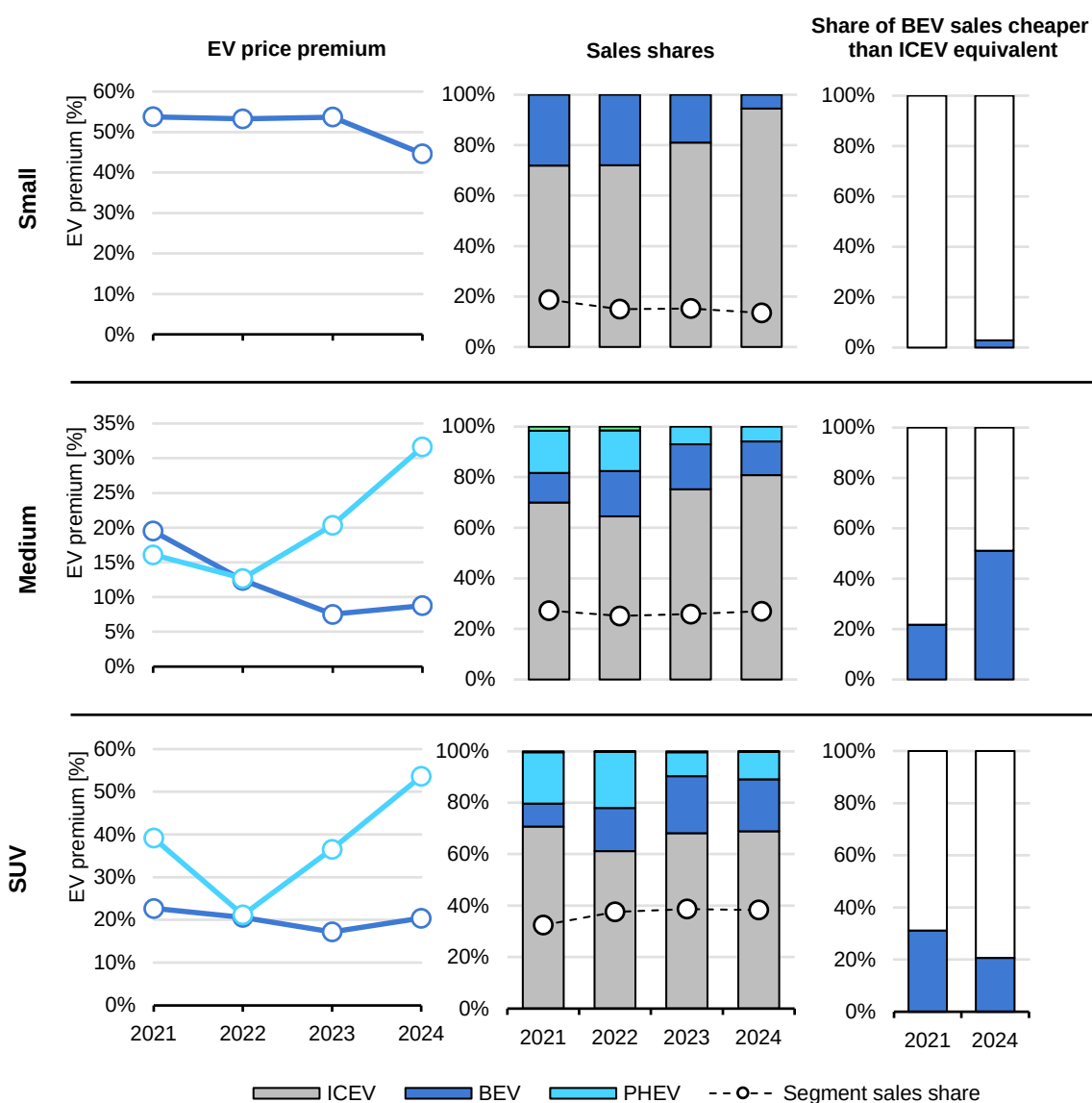
Electric car affordability improved in all car segments in China thanks to falling battery pack prices, a high level of supply chain vertical integration and [fierce competition](#) within the Chinese EV market. Overall, in 2024, close to two-thirds of the battery electric cars sold in China were cheaper than their ICE equivalents, up from half in 2021 and just 10% in 2018.

Affordability stagnates in Europe, but carmakers expand line-ups with low-cost EVs amid CO₂ standards shift

In Europe, carmakers' pricing [strategies](#) and focus on high-profit-margin premium models have led to stagnating battery electric car prices. In Germany, for example, the average price premium for small battery electric cars remained almost unchanged between 2021 and 2023, plateauing at over 50% more than equivalent small ICE models. The price premium for small battery electric cars fell slightly in 2024 to around 45%. In contrast, the price premium for battery electric SUVs increased to reach 20% in 2024, effectively reversing the small decrease seen over the 2021-2023 period. The price premium of PHEVs compared to conventional equivalents has grown consistently since 2022, reaching more than 30% for medium-size cars and 50% for SUV-type cars in 2024. This trend hindered electric car adoption in Germany in 2024, especially when combined with the phase-out of purchase subsidies in late 2023. In 2021, almost one-third of battery electric SUVs sold in the country were cheaper than their average ICE equivalent, but by 2024, this share had fallen to one-fifth.

In other European countries, the affordability of electric cars saw little change. In the United Kingdom, for instance, the average price premium of battery electric SUVs made only slim progress, dropping to 30% in 2024 from 40% in 2021. The pricing trend of plug-in hybrid SUVs was similar, with their price premium having been stuck at around 45% for the last 3 years.

Electric car price premium compared to conventional models per segment (left), powertrain sales shares (centre) and sales share of battery electric vehicles cheaper than conventional equivalents (right) in Germany, 2021-2024



IEA. CC BY 4.0.

Notes: EV = electric vehicle; BEV = battery electric vehicle; ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; SUV = sports utility vehicle. Price data is adjusted for inflation. The share of battery electric cars cheaper than their conventional equivalents is calculated as the number of car sales priced lower than the sales-weighted average price of the ICE car in their segment category.

Source: IEA analysis based on data from S&P Global Mobility, EV Volumes and Marklines.

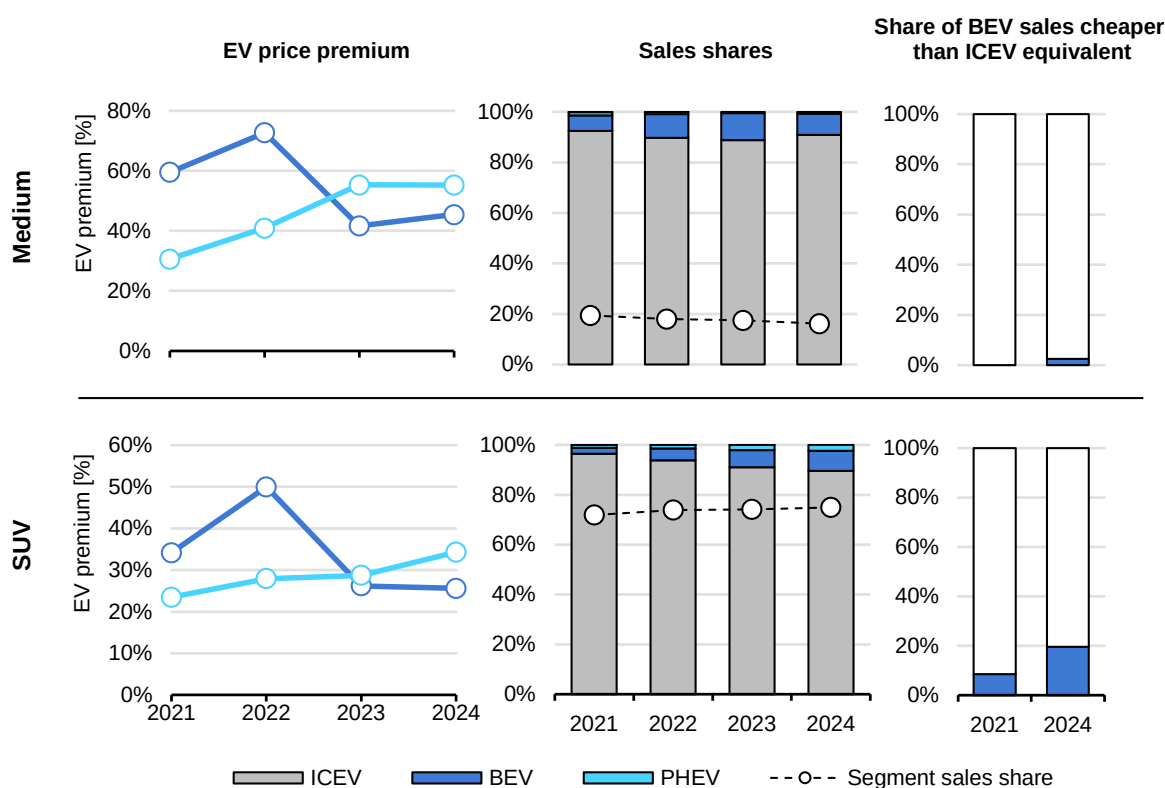
This lack of progress on affordability reflects the limited availability of cheap electric car models across Europe. In 2024, while nearly one-quarter of available ICE car models were priced below EUR 30 000, only around 5% of battery electric models were. Models priced below EUR 25 000 are expected to be key enablers of wider market adoption, but they accounted for only a slim share (3%) of available battery electric models in Europe last year. However, the new phase of the EU CO₂ standards entering into force in 2025 is expected to prompt carmakers to release more affordable electric models to boost their EV sales and comply with their respective fleet-wide CO₂ targets. So far, both European and foreign carmakers have announced launches of battery electric models for the European market priced at under EUR 25 000, including [Renault](#), [Volkswagen](#), [Hyundai](#), and [BYD](#). Overall, nearly ten battery electric models priced at under EUR 25 000 are expected to be released by the end of 2026.

Limited availability of affordable models hinders US electric car sales growth

In 2024 in the United States, about one in five electric SUVs (including pick-up trucks) was sold at a lower price than the average conventional SUV. This is particularly significant given that SUVs account for three-quarters of total car sales in the United States. Progress on battery electric car affordability has fluctuated in recent years. In 2023, the average purchase price premium of battery electric SUVs noticeably decreased to 25% from 50% in 2022, largely as a result of Tesla repeatedly slashing prices in an attempt to maintain its market lead in the United States. However, despite further price [reductions](#) to the Tesla Model Y SUV in 2024, Tesla's market share fell around 10% year-on-year. This decline outweighed the impact of the late price cuts, leaving the average price premium of battery electric SUVs in the United States unchanged from the previous year.

The contrast with conventional models is stark: in 2024, only 2 battery electric models (3% of battery electric car models) were priced below USD 30 000, compared to more than 50 ICE models (20% of available ICE models). In the short term, Honda and Volkswagen have recently announced they will launch “affordable” compact electric SUVs, bringing to market a handful of models under the USD 30 000 mark. However, most of the BEV model releases expected by 2026 that have been announced with launch prices are in the premium car category, with over 70% anticipated to have a purchase price of more than USD 50 000.

Electric car price premium compared to conventional models per segment (left), powertrain sales shares (centre) and sales share of battery electric medium cars and SUVs cheaper than conventional equivalents (right) in the United States, 2021-2024



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Notes: EV = electric vehicle; BEV = battery electric vehicle; ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; SUV = sports utility vehicle. Price data is adjusted for inflation. The share of battery electric cars cheaper than their conventional equivalent is calculated as the number of car sales priced lower than the sales-weighted average price of the ICE car in their segment category.

Source: IEA analysis based on data from S&P Global Mobility, EV Volumes and Marklines.

The average purchase price of plug-in hybrid SUVs has increased over the past 3 years. In 2024, the price was almost 10% higher than that of battery electric counterparts, and 35% higher than conventional SUV models. Fewer than 10% of the more than 50 available PHEV models were priced below USD 40 000 while 70% were above USD 50 000. This high price premium, combined with the limited availability of affordable models, remains a significant barrier to wider adoption. As a result, PHEV sales stood at 2% of total SUV sales in 2024, as in 2023.

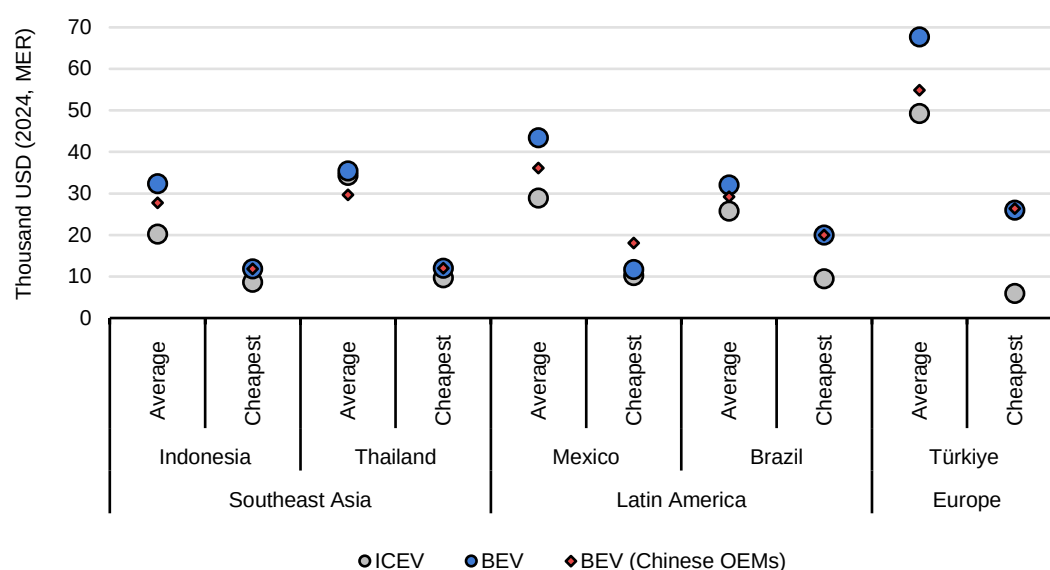
In emerging markets, affordable Chinese models are driving EV adoption

In 2024, in most emerging EV markets, the price of the cheapest battery electric car was lower than the average price of an ICE car. In some markets – such as Indonesia, Thailand and Mexico – the cheapest battery electric car models even

retailed at similar prices to the cheapest ICE models. Choosing an electric car in these markets could carry little to no price premium.

In all of the five emerging markets assessed – Brazil, India, Indonesia, Mexico and Thailand – electric models made by Chinese OEMs were, on average, cheaper than the average electric car, helping to drive uptake. The cheapest Chinese battery electric car was, in most cases, also the cheapest option on the market, so much that in **Thailand** in 2024, the average price of a Chinese EV was lower than the average price of a conventional car. In 2023 and 2024, more than four out of every five battery electric cars sold in Thailand were imported from China, bringing the average price of BEVs nearly in line with that of conventional cars. On average, medium and SUV model BEVs were more than 20% cheaper than their conventional equivalents, and the overall price premium of BEVs, across all car segments, stood below 5%.

Average and cheapest battery electric car price values by powertrain in selected emerging markets, 2024



IEA. CC BY 4.0.

Notes: ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; OEM = original equipment manufacturer. Average price refers to the sales-weighted average price of cars per powertrain. The cheapest category shows the lowest price found in data.

Source: IEA analysis based on data from S&P Global Mobility.

In **Brazil**, where Chinese electric car imports increased to reach 85% of the country's EV sales in 2024, up from about 60% in 2023, the price gap between battery electric and ICE cars shrank from more than 100% to 25% over the same period. In 2024, not only was the cheapest battery electric car model produced in China by a Chinese OEM, but Chinese BEVs also retailed at less than half the price of those produced by non-Chinese OEMs on average (most of which belong

to larger car segments). The average price of PHEVs also fell in 2024. In particular, plug-in hybrid SUVs – which accounted for nearly half of Brazil's electric car sales in 2024 – saw their price premium over ICE equivalents drop below 70%, compared to a premium of more than 80% for battery electric SUVs. This decreasing price gap boosted the adoption of PHEVs within the SUV segment, whereas BEVs gained more traction in the small and medium car segments, where their average price premium halved year-on-year to reach less than 40% in 2024.

In **Indonesia**, after import duties were waived under local investment requirements, Chinese EV imports surged to reach two-thirds of the country's EV sales in 2024, up from about 10% in 2023. Like in other emerging markets, Chinese battery electric car models became the most affordable options available, with an average price over 60% lower than BEVs from non-Chinese OEMs. As a result, the average price premium of BEVs dropped to around 50% in 2024, down from being, on average, twice as expensive as conventional cars in 2023.

In **Mexico**, the average price premium of BEVs fell to 50% in 2024 from more than 100% in 2023, as the share of Chinese imports in EV sales grew to nearly two-thirds. However, Chinese brands were not the only ones driving affordability. While the cheapest BEV model available (Renault's Kwid E-Tech Electric) was produced in China, it was sold under a European brand.

In **India**, high import duties on EVs and the availability of locally made, affordable electric models meant the share of Chinese imports in the country's EV sales remained below 15% in 2024. While the cheapest battery electric car model was produced locally by a Chinese OEM (SAIC's city car, the MG Comet EV, priced under USD 8 000), the average price of imported Chinese BEVs was twice that of those made by domestic manufacturers. In 2024, all BEV models manufactured by Indian carmakers started below USD 20 000, while none of the imported Chinese BEV models were priced under that threshold. Overall, the average price gap between battery electric and ICE cars fell below 15% for small cars and 25% for SUVs in 2024.

3. Trends in other light-duty electric vehicles

Electric two- and three-wheelers

Contrasting regional trends mean global sales of electric two- and three-wheelers remain at around 15%

Two- and three-wheelers (2/3Ws)¹ remained the most electrified road transport segment in 2024, with more than 9% of the global fleet now electric. The global sales share of electric models remained at around 15% in 2024 with total electric model sales reaching 10 million. The electric sales share stalled in 2024, mostly due to the shrinking Chinese electric 2/3W market, although growth in other regions was steady. China, India and Southeast Asia remain the world's largest 2/3W markets, accounting for around 80% of 2024 global sales, with 2/3Ws serving as the primary mode of private passenger transport in India and Southeast Asia.

Electric 2/3Ws stand out as the most affordable and accessible entry point into electric mobility. Unlike cars, many models do not rely on extensive charging infrastructure, as removable batteries allow users to charge at home, and those with private parking or garages can easily charge their electric 2/3Ws using standard sockets. The removable batteries have also led to the growing emergence of [battery swapping stations for 2/3Ws](#), which can be particularly useful for 2/3Ws that are used as taxis or for delivery services, where quick recharging is highly valued. This – combined with lower operating costs when compared to cars – means that electric 2/3Ws offer a promising solution for reducing urban emissions and improving air quality in emerging markets and developing economies, where 2/3Ws are widely used for daily transportation.

Another year of receding electric two-wheeler sales in China masks steady growth elsewhere in Asia

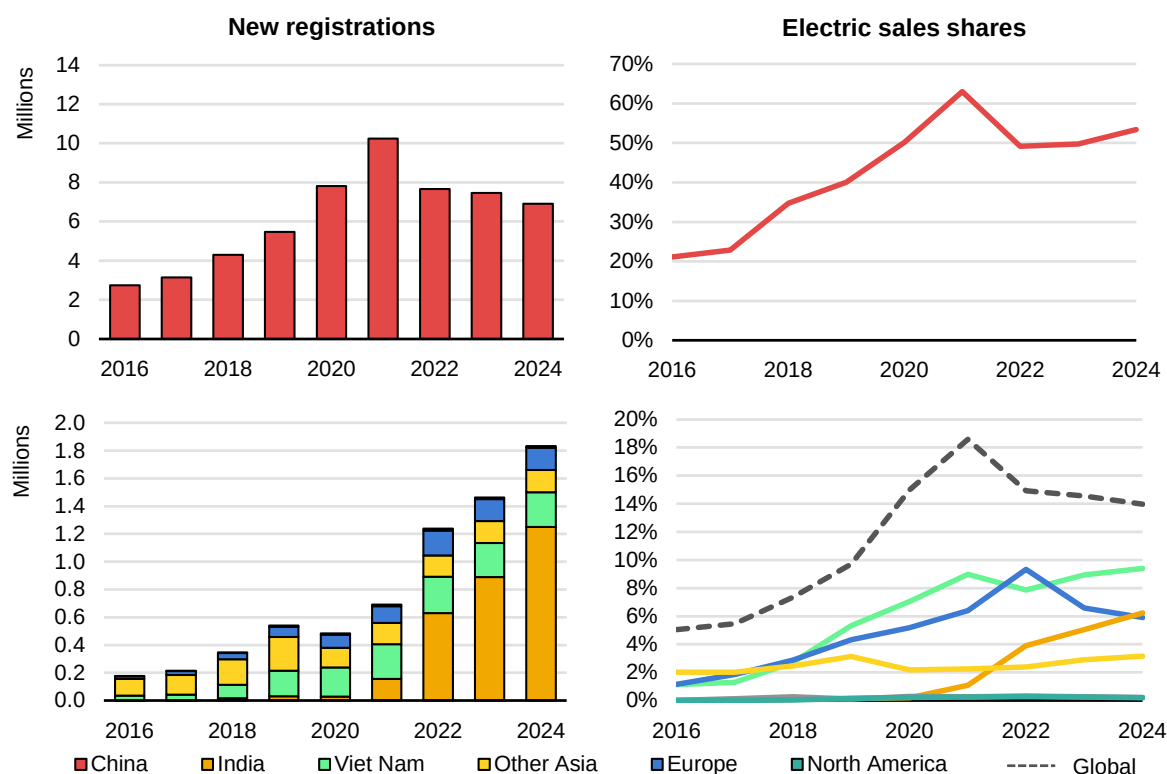
In **China**, falling sales of electric 2Ws in 2024 were the product of an overall decline in the 2W market, yet the country remains the world's largest market for electric 2Ws. Electric models have accounted for more than half of 2W sales since

¹ In this report, “two-wheelers” refers to vehicles with a top speed of at least 25 km/hr that fit the L1 and L3 classes defined by [UNECE](#). This excludes micromobility options such as electric-assisted bicycles and low-speed electric scooters. The definition of a three-wheeler is aligned with UNECE L2, L4 or L5 classes.

2020, with sales totalling about 7 million in 2024. Sluggishness in China's 2W market reflects an increasing preference for cars for personal transport, and may also be a sign that consumers are responding to tighter [restrictions](#) on 2W use in major cities. The 2W market is shifting toward higher-value motorcycle models, likely indicating a [change](#) in consumer profile. At the same time, the Chinese government launched a [trade-in programme](#) for electric bicycles in 2024, boosting their sales. Urban commuters, in particular, may be attracted by e-bikes as a lower-cost alternative that enables access to bike lanes and areas where 2Ws are banned.

As the Chinese market for electric 2Ws continues to decline, the country's OEMs are looking abroad for growth opportunities. China's largest electric 2W manufacturer, [Yadea](#), broke ground on a USD 150 million new assembly plant in Indonesia in 2024, which has a planned output of 3 million vehicles by 2028 (likely to also include e-bikes). In recent years, Chinese OEMs have also established manufacturing capacities in other large Southeast Asian electric 2W markets such as [Viet Nam](#), [the Philippines](#) and [Thailand](#), making their way into the [top five electric 2W brands](#) in each of these countries.

Electric two-wheeler sales and sales share by region, 2016-2024



IEA. CC BY 4.0.

Notes: "Other Asia" includes Afghanistan, Bangladesh, Brunei, Cambodia, Lao People's Democratic Republic, Myanmar, Mongolia, Nepal, Pakistan, Singapore, Sri Lanka and Chinese Taipei. "Two-wheeler" refers to vehicles with a top speed of at least 25 km/hr and which fit the L1 and L3 classes defined by [UNECE](#).

Sources: IEA analysis based on country submissions and data from MotorcyclesData.com and AutocarPro.in.

India's increasingly dynamic electric 2W market hosted a total of [220](#) OEMs in 2024, up from 180 in 2023, although the 4 market leaders accounted for a combined 80% of the 1.3 million electric 2Ws sold in the country in 2024 (6% of the overall 2W market). While the upfront purchase price of electric 2Ws remains higher on average than that of conventional 2Ws, increasing competition is prompting OEMs to offer more affordable electric models. For example, the Indian market leader, Ola, released its [S1X entry model](#), equipped with a 2 kWh battery and 6 kW peak power, with a sticker price of INR 70 000 (about USD 850) – lower than the average price of the five [best-selling](#) ICE 2W models. Policy support is also helping to bridge the affordability gap between electric and ICE 2W models, with the new PM Electric Drive Revolution in Innovative Vehicle Enhancement ([PM E-DRIVE](#)) policy continuing financial support formerly provided under both Faster Adoption and Manufacturing of Electric Vehicles (FAME)-II and [Electric Mobility Promotion Scheme](#) measures. This provides purchase incentives for electric 2Ws (offering purchase subsidies of up to INR 5 000/kWh for 2Ws fitted with lithium-ion batteries), as well as for 3Ws and other emerging EV categories (specifically excluding private cars), with a total budget of USD 1.3 billion. The scheme is planned to operate until March 2026 to support the roll-out of about 2.5 million electric 2Ws, up from 1 million targeted under the previous FAME-II policy. On the manufacturing side, the 80 largest electric 2W makers in India accounted for a combined production [capacity](#) of 10 million electric 2Ws in 2024, almost 8 times the domestic sales that year. Capacity is expected to increase to 17 million electric 2Ws in the near term, if all OEM announcements come to fruition.

Southeast Asia made notable progress on 2W electrification in 2024, particularly in Viet Nam, which recorded 250 000 sales (a sales share close to 10%); in Indonesia, where there were about 105 000 sales; and in the Philippines, with more than 25 000. **Indonesia** saw its electric 2W market almost double in size, but the share of electric sales remained below 2%. Nevertheless, the trend towards electrification in what is the world's third-largest 2W market is likely to continue given the strong [policy](#) support in place (in 2023, nearly USD 0.5 billion was allocated to support the deployment of 800 000 electric 2Ws over the following years), as well as the new manufacturing capacity being rolled out by established Chinese OEMs.

Viet Nam's 2W electrification success story has been underpinned by the continued roll-out of increasingly affordable electric 2W models manufactured by domestic champions like VinFast and Pega, and now also by Chinese OEMs. To date, several electric models are sold at under VND 20 million (Vietnamese dong) (USD 780) (such as VinFast's [Evo200](#) and Yadea's [Orla](#)), making them price-competitive with conventional alternatives. These affordable purchase prices are partly a result of existing battery leasing options, which reduce the vehicle purchase price and can cost consumers as little as VND 350 000 (under USD 14) per month. They can also be easily integrated with battery swap programmes. The

increasing affordability of electric models, ongoing development of charging infrastructure for models without removable batteries, and Viet Nam's ambition to fully electrify its road transport sector by 2050 is likely to drive further growth in electric 2W sales in the coming years.

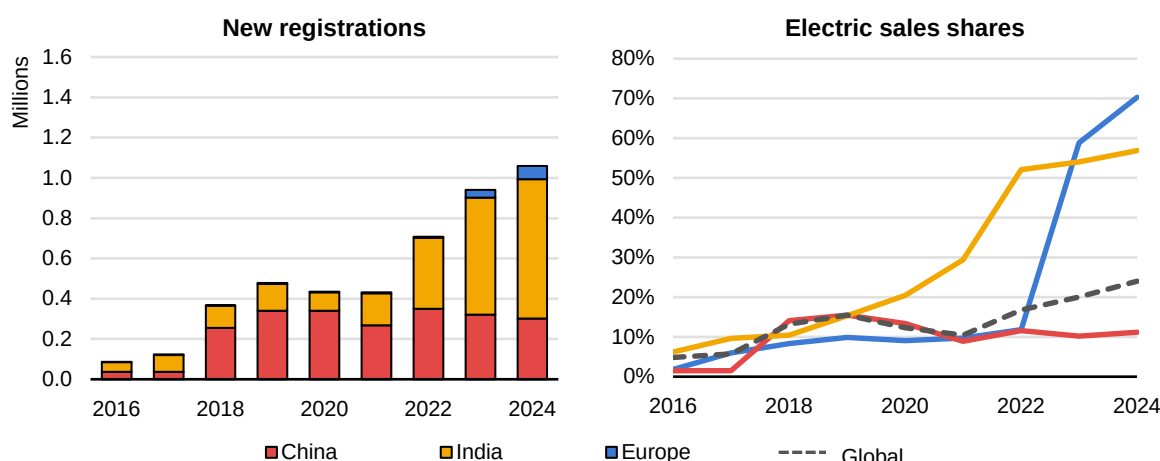
Sales of electric 2Ws in **Africa** grew nearly 40% year-on-year to reach 9 000 vehicles, marking a slim 0.5% sales share in the continent's total 2W sales. However, domestic OEMs have invested significantly in recent years to set up domestic manufacturing facilities. For example, [Spiro](#) is set to break ground on an assembly plant in Nigeria in 2025 with an expected annual output of 100 000 electric 2Ws, [100 times](#) the capacity of its assembly plants in Togo and Benin. Other electric 2W manufacturers, such as [Roam](#) in Kenya and [Ampersand](#) in Rwanda, also recently announced investments to ramp up their capacity across African countries. Beyond increasing manufacturing investments, asset financiers like [M-KOPA](#), [Mogo](#), and [Watu](#) are helping consumers and small business owners access electric motorcycles through flexible payment plans and lease-to-own schemes.

Elsewhere, in **Europe**, the average electrification rate of 2W sales has decreased to about 6%, despite the 2W market growing overall. With year-on-year sales growing to more than 50 000 electric 2Ws, Türkiye has secured its position as the leading market outside of Asia, followed by France and the Netherlands, despite those markets stagnating in 2024.

India continues to drive most growth in the global electric three-wheeler market

Despite the global three-wheeler (3W) market shrinking 5% from the previous year, electric 3W sales grew more than 10% to surpass 1 million vehicles in 2024. Electric 3W sales represented almost one-quarter of all 3W sales, up from one-fifth in 2023. The market is highly concentrated, with China and India together accounting for more than 90% of both electric and conventional 3W sales.

Electric three-wheeler sales and sales share by region, 2016-2024



IEA. CC BY 4.0.

Note: The definition of a three-wheeler is aligned with : UNECE L2, L4 or L5 classes.

Sources: IEA analysis based on country submissions and data from MotorcyclesData.com and AutocarPro.in.

Electrification of 3Ws in **China** has stagnated at less than 15% over the past 3 years. In 2023, **India** overtook China to become the world's largest market for electric 3Ws, and it maintained this position in 2024, with sales growing close to 20% year-on-year to reach nearly 700 000 vehicles. This translated into a record 57% electric sales share in 2024, 3% up on the previous year. This growing trend looks set to continue thanks to policy support under the new PM E-DRIVE scheme, which allocated budget in 2024 to support the roll-out of more than 300 000 electric 3Ws for commercial use – for which the total fleet (electric and ICE) was estimated at more than 10 million vehicles in 2023.

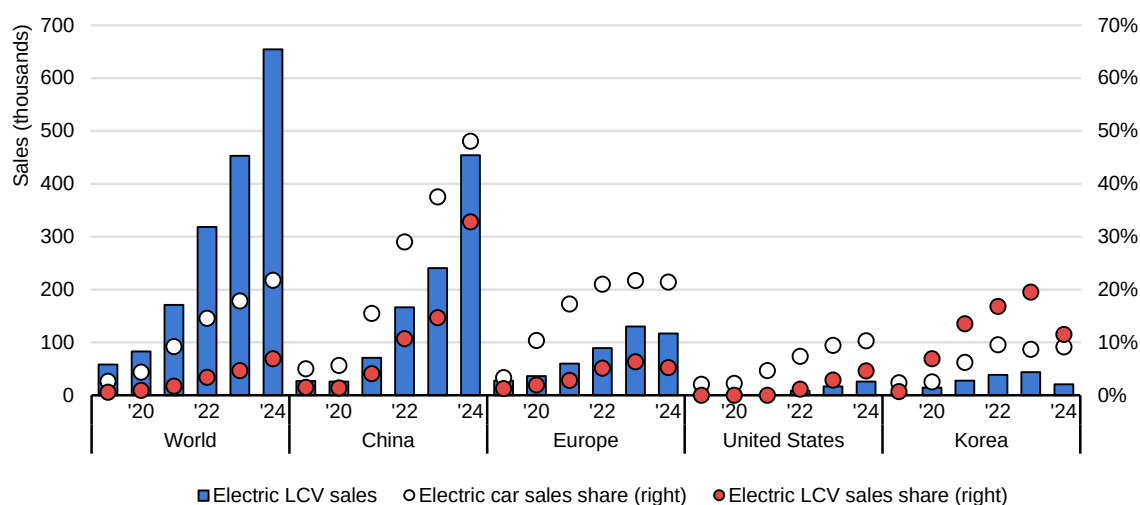
Elsewhere, in **Europe**, the electric 3W sales share has grown steeply in the past 2 years, pushed up by growth in the Turkish market. In 2024, Türkiye accounted for 60 000 electric 3Ws sold out of a total European 3W market of about 90 000.

Electric light commercial vehicles

China pushed up global electric light commercial vehicle sales in 2024, representing 70% of global sales

Sales of electric light commercial vehicles (LCVs) increased by more than 40% in 2024 to exceed 600 000, with a share of 7%, up from 5% in 2023. China and Europe remained the two largest markets for electric LCVs in 2024, but while China saw growth of almost 90%, with sales reaching roughly 450 000, sales in Europe declined by about 10% to less than 120 000. The United States emerged as the third-largest market, taking the spot from Korea, with sales of more than 25 000 and strong year-on-year growth of 55%.

Electric light commercial vehicle sales and sales shares, 2019-2024



IEA. CC BY 4.0.

Notes: LCV = light commercial vehicle, weighing less than 3.5 tonnes. In China, LCVs include small-sized buses, gasoline light-duty trucks and mini trucks. To better align with IEA classifications, diesel light-duty trucks are considered as medium-duty trucks (defined here as having a gross vehicle weight greater than 3.5 tonnes and less than 15 tonnes).

Sources: IEA analysis based on data from [EV Volumes](#), [China Commercial Vehicle Dealers Association](#), [DaaS](#), [ACEA](#), [Marklines](#) and [Korean Automobile Manufacturers Association](#).

The continued sales growth in China has been supported by LCVs being eligible for the vehicle purchase tax exemption for new energy vehicles that was put in place in [2014](#). The full tax exemption has been [extended](#) through 2025, and a 50% tax exemption will be available until the end of 2027. Preferential road rights policies, charging discounts and charging subsidies are [further supporting](#) EV adoption among commercial users.

In Europe, the electric sales shares declined in several important LCV markets, such as Germany, Norway and France, or stalled, as in the case of Sweden. However, in the United Kingdom – the largest market for electric LCVs in Europe – sales continued to grow, reaching nearly 7%. As with cars, 2024 was the first year of zero-emission van targets under the [Vehicle Emissions Trading Scheme](#), which will progressively require higher sales shares of zero-emission LCVs over the coming decade.

Some small markets such as Czechia, Greece, Hungary and especially Romania have seen notable increases, albeit starting from a very low base. Despite no new [incentives](#) being introduced between 2023 and 2024 in these markets, the growth suggests that there were some segments that could be easily electrified with existing technology. In fact, the total cost of ownership of electric LCVs is already [equal to or below](#) that of conventional alternatives for certain applications in Europe. Nevertheless, in Germany – a more developed market – the decline in sales may have been a result of [the removal of incentives](#) (which also affected LCV applications that are harder to electrify based on current pricing or model

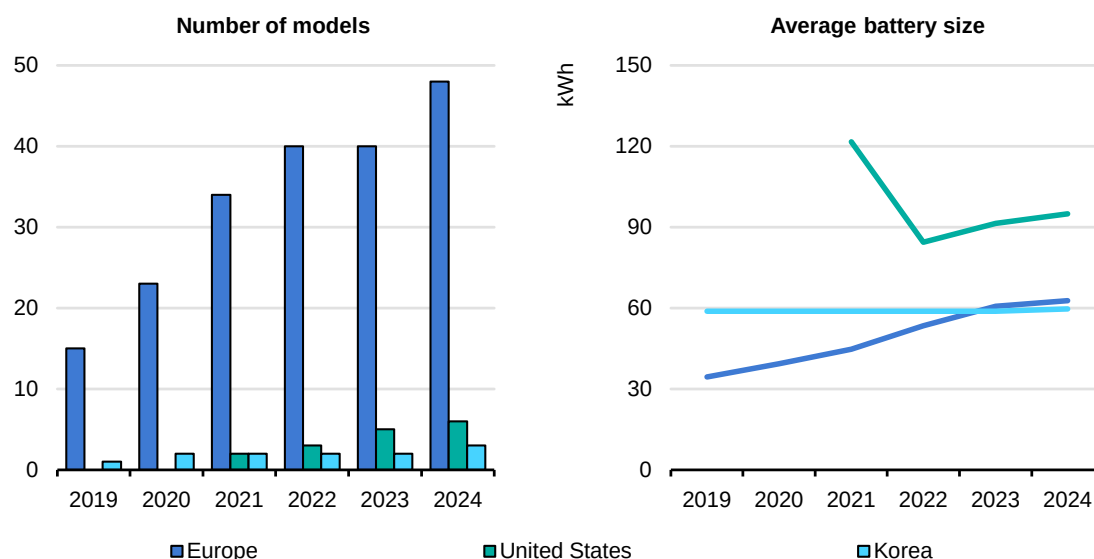
availability) and by the design of the EU CO₂ emission regulations for vans, which gave the automotive industry little incentive to accelerate sales in 2024 before the next phase [taking effect in 2025](#).

Some European cities have promoted electric LCV adoption by establishing [Low Emissions Zones \(LEZs\)](#), though there is no [uniform European regulation](#), with regulations being decided at the city level. London has the [largest LEZ in the world](#), which has favoured uptake. As of the beginning of 2025, LEZs can also be found in [Amsterdam and 14 other cities](#) in the Netherlands, as well as in Brussels, Ghent, and Stockholm. In the case of the Netherlands, the introduction of LEZs from 2025, together with the exemption of vehicle tax for LCVs being [removed](#) for ICE LCVs, led the sales share of electric LCVs to leap to [more than 90%](#) in the first quarter of 2025, compared to less than 10% on average in 2024. The number of LEZs in Europe grew significantly from 228 in 2019 to [320](#) in 2022, with more expected to come online in 2025, further encouraging uptake of EVs and improving air quality, while also potentially [reducing traffic congestion](#).

In 2023, the sales share of electric LCVs in Korea was double the level of electric passenger cars, continuing a trend that started in 2020. While the sales share of electric LCVs remained higher than cars in 2024, both the volume of sales and their sales share declined sharply. Despite strong initial adoption of electric LCVs in Korea, partially due to the availability of free commercial licence plates for electric models, drivers have since reported that [real-world range](#) and model availability is insufficient for many commercial applications, which may be influencing the slowdown. In 2023, the only electric LCVs on the market were the Kia Bongo and the Hyundai Porter, both 1-tonne trucks with a battery capacity of about 60 kWh. While these vehicles had initially been able to meet the needs of some portions of the market, boosting sales, reaching new market segments has proved difficult. In 2024, [Hyundai](#) launched the ST1 Cargo electric, which has a larger battery (76 kWh) and an advertised range of around 300 km, but also has a higher purchase price. In 2024, Korea introduced [stricter performance requirements](#) for their subsidy scheme, which effectively restricted subsidies for models with lithium iron phosphate (LFP) batteries, typically used in Chinese-manufactured models.

Across Europe, Korea and the United States, 2024 saw the introduction of around ten new electric LCV models, the majority of which were launched in European countries. Ford expanded its [e-Transit](#) line, which remains one of the world's best-sellers in the electric LCV category, offering a [30%](#) increase in range and more possible applications, such as refrigerated delivery. BYD targeted the last-mile delivery market in Europe with the [E-Vali](#), while Mercedes-Benz introduced the [eSprinter](#) in the United States.

Number of models of electric light commercial vehicles and sales-weighted average battery size in Europe, the United States and Korea, 2019-2024



IEA. CC BY 4.0.

Notes: EV = electric vehicle; LCV = light commercial vehicle, where weight is less than 3.5 tonnes. Average battery refers to sales-weighted average.

Sources: IEA analysis based on data from on [EV Volumes](#).

Electric LCV fleets are becoming increasingly popular, particularly in the parcel delivery sector, as companies strive to reduce their environmental impact and operating costs. As part of its goal to reach 100 000 electric delivery vehicles by 2030, [Amazon](#) now has 20 000 vehicles through a 2019 [agreement](#) with Rivian, which has tailored a vehicle to Amazon's needs, with the first vehicles delivered in 2021. In 2024, Rivian represented 40% of the US electric LCV market and its sales are steadily growing.

Elsewhere, [Ingka Group](#), the biggest IKEA franchisee, served 40% of home deliveries with zero-emission vehicles, advancing towards its goal of more than 90% by 2028. [Shanghai was the first city to reach this goal](#), achieving 100% EV-based deliveries as early as 2019. In India, IKEA has partnered with [EKA Mobility](#) to supply last-mile delivery with electric vans, while in Korea, DHL has partnered with [Kia](#) to deploy the forthcoming Kia PV5 tailored to DHL needs from 2026.

4. Trends in heavy-duty electric vehicles

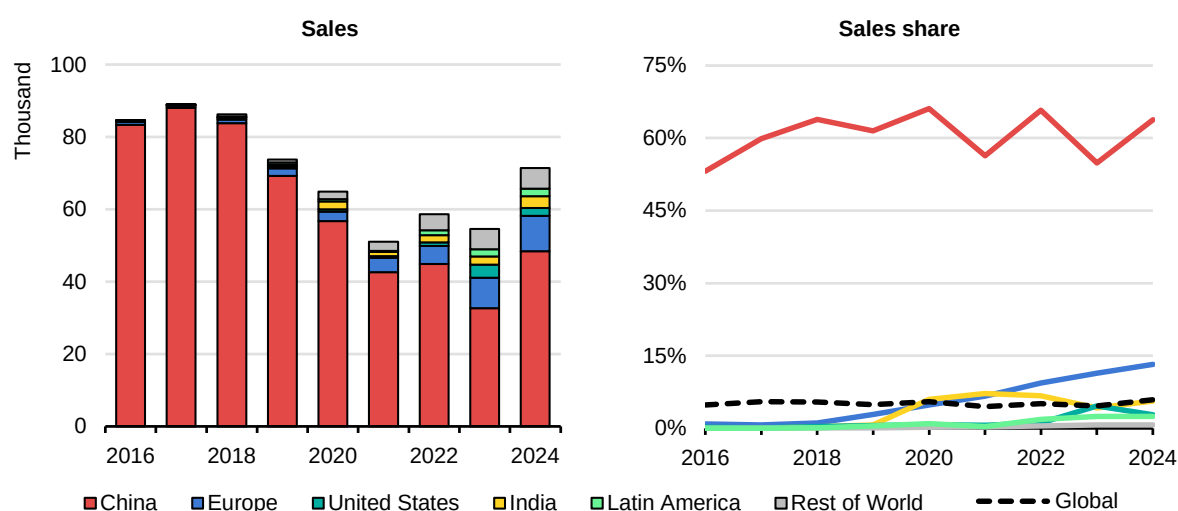
Electric bus and truck sales

The electric bus market continued to expand, backed by increasingly favourable economics

Electric bus sales grew by 30% in 2024

Global sales of electric buses reached more than 70 000 in 2024, driven by renewed growth in China. Sales outside of China increased by just 5% in 2024, although they have almost tripled compared to 2020. As electric bus sales have increased in a range of countries, China's share of global sales has fallen from around 99% in 2017 to less than 70% in 2024. Although electric bus sales in China generally declined from 2017 to 2023, the electric bus sales share has remained relatively stable, hovering around 60%.

Electric bus sales and sales shares by region, 2016-2024



IEA. CC BY 4.0.

Note: Only medium- and large-sized electric buses are included; minibuses and passenger vans are treated as light commercial vehicles.

Source: IEA analysis based on country submissions and data from [EV Volumes](#), [China Commercial Vehicle Dealers Association](#), and [DaaS](#) for sales data for China.

In **Europe**, the world's second-largest market for electric buses, sales increased by almost 15% in 2024, bringing the sales share to more than 13%. Several countries, including Denmark, Finland, the Netherlands and Norway, now have electric bus sales shares of more than 40%. The United Kingdom continues to have the largest number of sales in Europe, accounting for around 20% of the region's sales in 2024, with a year-on-year growth of over 40% and almost 2 000 electric buses sold in 2024. Italy follows, with almost 1 200 sales, and then Germany with almost 900. Sales were [predominantly for city buses](#), for which ten European countries had battery electric sales shares above [80%](#), meaning almost half of all new city buses were battery electric in 2024, up from just over [35%](#) in 2023.

Uptake of electric buses in the **United States** has not been linear. Despite averaging year-on-year growth of more than 70% between 2020 and 2024, electric bus sales declined in 2024 following a peak the previous year. Around 40% fewer electric buses were sold last year, in part due to [supply chain issues](#). As a result, India and Korea overtook the United States to become the second- and third-largest national electric bus markets by sales volume in 2024, with more than 3 200 and 2 800 sales, respectively.

In **Latin America**, electric bus sales have risen from around 600 in 2020 to over 2 000 in 2024, which accounts for almost 40% of sales outside of China, Europe, and the countries mentioned above. [City buses](#) are driving the transition, like in Europe. In Mexico, close to 8% of all bus sales were electric in 2024, up from just above 1% in 2023. There has also been impressive growth in Colombia, Chile, Brazil, and other countries over the past few years.

Another notable trend is the decline in the share of PHEVs among electric buses. In China, the share of PHEVs in total electric bus sales peaked in 2014 at around 60%, but fell to less than 1% in 2017 and close to 0% in 2024. Similarly, in the rest of the world, there was a peak of around 60% of total electric bus sales in 2015, but this fell sharply to 5% in 2017, and around 1% of the share in 2024. Almost all electric bus sales are now battery electric, thanks in large part to declining battery prices, greater model availability and improved charging technology, all of which increase the share of use cases for which they are now practical.

Even as electric bus economics continue to improve, innovative financing and incentives help drive deployment

Innovative financing models, such as those available in the [United Kingdom](#), [Brazil \(São Paulo\)](#), and [Chile \(Santiago\)](#), are also helping to drive up sales. In [Santiago](#), for example, buses have been leased to the operator as opposed to traditional ownership, lowering the upfront cost, which can present a significant barrier to deployment. The scheme benefitted from investment by the International Finance

Corporation (IFC). A similar model is being explored for collaboration between the IFC and [Transvolt](#) in India to help deploy 8 000 battery electric buses.

Italy, which now has the highest number of electric bus sales in the European Union, more than doubled its stock from 2023 to 2024, with growth fuelled by [incentives totalling EUR 50 million](#) made available in July 2022. As in other countries, the majority of electric bus registrations are [intended for urban use](#). In Milan, for example, the municipal public transport operator, [ATM](#), has committed to having a 100% electric fleet by 2030.

In the **United States**, uptake has been greatest for school buses, which represented [around half](#) of the electric bus stock in 2024. As of mid-June, the [Clean School Bus Program](#) had funded approximately [8 100](#) electric school buses, using approximately USD 3 billion of the USD 5 billion allocated for fiscal years 2022-2026 under the Bipartisan Infrastructure Law. Oakland, California, became the first school district in the United States to have a [fully electric fleet](#) in 2024. This contrasts starkly with the experience of New York City, which has a [legally binding target](#) to fully electrify its fleet of [10 000](#) buses by 2035, yet has deployed under 50 to date, partly due to difficulties in [negotiating](#) affordable purchases.

India has seen rapid growth in electric bus deployment since 2020, with stock increasing from less than 3 000 to more than 11 500 at the end of 2024. A combination of increasingly [favourable economics](#), available incentives and additional government support for charging infrastructure has enabled huge year-on-year growth. Demand has been boosted by schemes such as the National Electric Bus Programme, which targets deploying a further [40 000](#) electric buses by 2027, helping to generate [large orderbooks](#) and use [aggregated procurement](#) to drive down costs. This is further strengthened by new schemes such as PM E-DRIVE, which could support sales of a further [14 028](#) electric buses, with preference given to replacements of old public buses. The forthcoming [Bharat Urban Megabus Mission](#) aims to introduce 100 000 electric buses to cities with a population of over 1 million.

China's electric bus sales strengthen, but Chinese OEMs are also focusing on exports

China has the world's highest stock share of electric buses, at 30%, compared to 2% across Europe (the second-largest electric bus fleet), and this share has been steadily growing over the past decade. The country took an early lead in deploying electric buses, with almost 70% of the more than 680 000 electric buses in the country today having been deployed before 2020. The year 2024 saw an increase in electric bus sales following several years of decline, potentially reflecting the replacement of older electric buses in cities such as Shenzhen, which [fully electrified](#) their bus fleets years ago. The introduction of a national-level city bus [scrappage scheme](#) announced in January 2025 looks likely to further support the uptick in sales seen in 2024.

Chinese manufacturers have also been increasingly looking to exports to exploit their available manufacturing capacity. In 2024, more than [15 000](#) electric buses were exported from China, over 25% more than in 2023. BYD and Foton are some of China's leading manufacturers of electric buses, and together with other Chinese manufacturers supplied more than 80% of electric buses in [Latin America's](#) stock. In early 2025, the city of Tashkent, Uzbekistan, signed a purchase agreement for [2 000](#) BYD buses, 1 000 of which are set to be delivered by the end of the year. Chinese OEM Yutong has also seen [success](#) internationally, fulfilling orders in [Greece](#), [Italy](#) and the [United Kingdom](#), and solidifying their position as Europe's [best-selling](#) electric bus brand for the third year in a row. Yutong has already supplied fleets to places as diverse as [Chile](#), [Mexico](#), [Norway](#) and [Uzbekistan](#) since 2020. In Qatar, [70%](#) of the public bus fleet was electrified between 2021 and 2023 through a partnership with Yutong, supporting the government's aim for all of its public transport buses to be electric by 2030. The Qatari government has also made plans for [domestic production](#) of electric buses in partnership with Yutong, with the aim of establishing a production hub for electric buses to serve international markets including Europe, the Middle East and North Africa, as well as meeting growing local demand.

Global electric truck sales grew by almost 80% in 2024

New incentives help China strengthen its lead as overall progress stalls in Europe and the United States

Sales of electric medium- and heavy-duty trucks grew for the third consecutive year in 2024 to exceed 90 000 worldwide. Year-on-year growth was almost 80%, a stark contrast to the decline in sales seen between 2018 and 2021. This spurt was largely a result of Chinese sales more than doubling between 2023 and 2024 – more than 80% of all electric trucks sold globally in 2024 were sold in China.

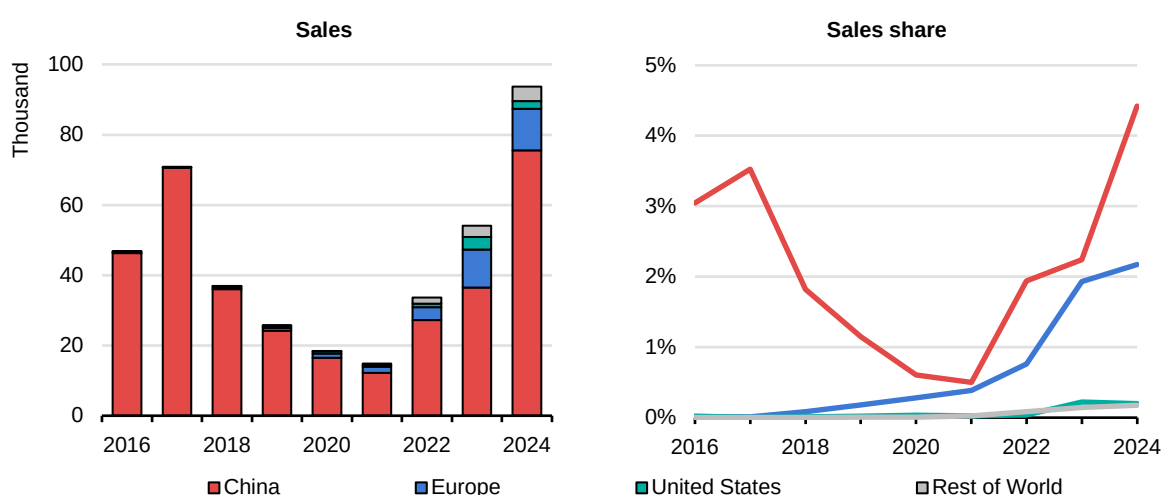
Strong growth in **China** was spurred in part by a vehicle [scrappage scheme](#) including [purchase incentives](#), which is being [renewed in 2025](#). Falling [battery prices](#) and the introduction of [tighter emission standards](#) for trucks issued in July 2023 further accelerated the shift. Pressure on heavy industries to reduce emissions is also translating into deployment of electric trucks, especially in heavily industrialised areas such as Hebei Province, where the fleet of electric trucks reached [30 000 vehicles](#).

In 2024, **Europe** saw more than 10 000 electric trucks sold for the second year in a row, despite a lack of substantial [incentives](#). Denmark, Germany, Italy, the United Kingdom and others saw significant growth, though this was partially offset by drops in electric truck sales in key markets such as France and the Netherlands.

In the **United States**, electric truck sales in 2024 were similar to in 2023. Nevertheless, the number of electric trucks sold in 2024 – over 1 700 – was more than the cumulative number of electric trucks sold in the country between 2015 and 2022. Electric truck sales in the United States were supported by a [tax credit](#) of up to USD 40 000, as well as project grants for vehicle purchases, charging infrastructure and other expenses through the nearly USD 1 billion [Clean Heavy-Duty Vehicles Grant Program](#).

There were positive developments elsewhere in the world, such as in Brazil, where almost 500 electric trucks were sold in 2024, and in Canada, with almost 2 000 sales for the second year in a row. In addition, Japan, South Africa and Thailand saw their collective sales jump from around 130 to almost 900 between 2023 and 2024. India saw a decline in electric truck sales in 2024, but in September the [PM E-DRIVE scheme](#) allocated a budget of USD 58 million for purchase incentives for electric trucks over the next 2 years.

Electric truck sales and sales shares by region, 2016-2024



IEA. CC BY 4.0.

Notes: Trucks refers to medium- and heavy-duty freight trucks. In China, gasoline light-duty trucks and mini trucks are categorised as LCVs, not trucks. Diesel light-duty trucks are classified as medium-duty trucks (defined here as having a gross vehicle weight greater than 3.5 tonnes and less than 15 tonnes).

Sources: IEA analysis based on country submissions and data from [EV Volumes](#), [China EV100](#), [DaaS](#) and [China Commercial Vehicle Dealers Association](#) for sales data for China.

Certain niches are quickly being electrified, including in the heavy freight segment

Deployment of electric trucks varies by application, as some duty cycles are more suited to electrification than others. Cycles with combinations of lower daily mileage, lower speeds, and predictable routes are typically easier to electrify, as seen at [Manhattan Beer](#), which has begun to electrify its fleet. In California, [drayage](#) – the transport of shipping containers over a short distance to their final

destination – has lent itself to the adoption of electric trucks. Across the United States, [yard tractors](#) have also proven to be an early adopter.

Similarly, in India, UltraTech Cement have ordered [100](#) electric trucks to decarbonise a 400 km route between two of their operations, and orders for 180 electric trucks from Billion E-Mobility (including 45 with a gross vehicle weight of 55 tonnes) have spurred [Ashok Leyland](#) to increase their production capacity. In China, successful [battery swapping](#) trials have supported an increase in electric trucks in the concrete industry.

Efforts to switch to electric trucks for delivery services are also spurring uptake and trials of new heavy truck models, where high mileages increase the potential cost benefits of electrification. In California, DHL recently [tested](#) the prototype of the Tesla Semi, which is expected to enter production in 2026, while in Germany, DHL deployed two [Mercedes eActros 300s](#). Similarly, Amazon signed [an order](#) for more than 200 Mercedes eActros-600 electric trucks, which will be deployed in the United Kingdom and Germany with the goal of decarbonising high-mileage predictable routes, on which charging can be planned with a high degree of certainty. These trends indicate that certain niches will become cost-competitive in advance of the segment at large.

Electric heavy-duty models

The number of electric heavy-duty vehicle models reached almost 800 in 2024

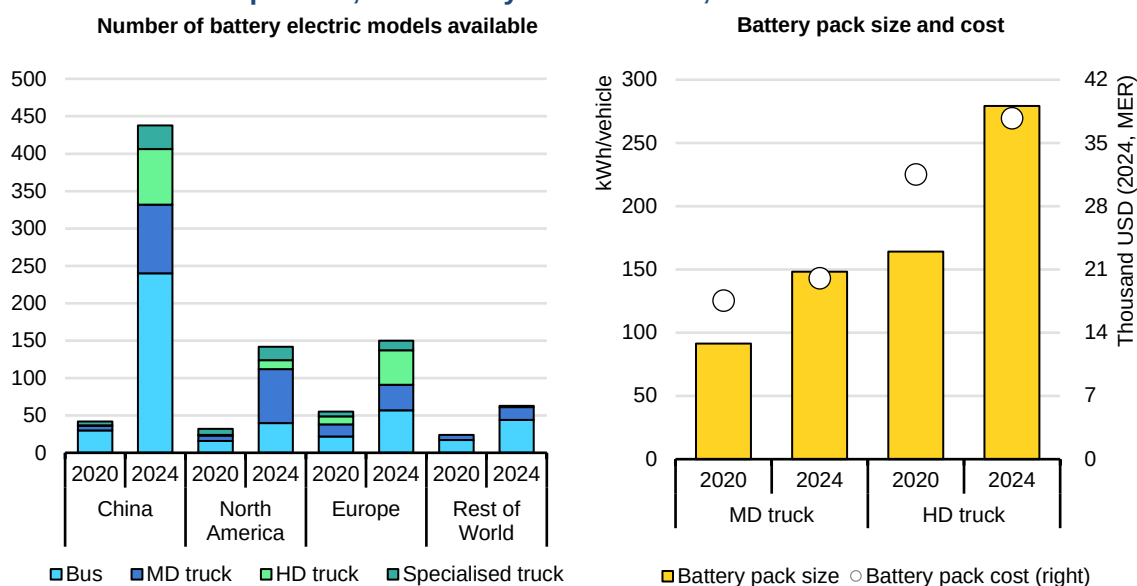
The number of electric heavy-duty models available worldwide has continued to grow steadily, driven by increasing demand as battery costs have declined. The market with the most models available remains China, with almost 450 – more than half of which are electric buses. In the United States, over 140 models are available, around half of which are medium-duty truck models, while buses represent less than 30%. The prevalence of medium-duty models in the US market could suggest that fleet operators are prioritising the electrification of lower-cost vehicles that cover shorter routes before transitioning to long-haul applications. In Europe, there are about 150 electric heavy-duty models available, with a more even distribution across buses, medium-, and heavy-duty trucks.

In Europe, truck OEMs are expanding their electric heavy-duty truck line-ups for regional-haul applications ([<400 km](#)), and improving performances for long-haul trucks amid increasing electric sales. In 2024, Volvo launched its latest electric truck, [FH Electric](#), offering a range of 600 km, similar to the range offered by Scania's [latest](#) electric truck model. On the other hand, OEMs such as [Renault](#) are targeting urban logistics.

Electric heavy-duty models are also becoming available in emerging markets. [BAIC Foton](#) has an electric truck on the market in Argentina, and German truck manufacturer TRATON has been producing their electric “[e-Delivery](#)” truck in Brazil since 2021 under the Volkswagen Caminhões e Ônibus brand. In 2024, BYD licensed [Rêver](#) to build electric buses and trucks based on BYD technologies in Thailand.

Falling [battery prices](#) have been a key driver of growth in electric trucks. Since 2020, battery prices¹ for commercial vehicles have dropped by 30%, enabling manufacturers to either extend vehicle range without increasing costs, or reduce costs to narrow the price gap between diesel and electric trucks. Between 2020 and 2024, the price of medium-duty electric truck battery packs increased only slightly, by almost 15%, despite battery size increasing by more than 60%. For heavy-duty trucks, battery pack size increased by around 70% between 2020 and 2024, but falling battery prices meant the rise in battery pack costs per vehicle was limited to less than 20% over the same period. Strategic partnerships between battery and commercial vehicle manufacturers, such as the agreement between [CATL and FAW](#), seek to deliver even more affordable electric truck models through a more integrated supply chain.

Electric medium- and heavy-duty vehicle model availability by original equipment manufacturer headquarters, and battery size and cost, 2020-2024



IEA. CC BY 4.0.

Notes: MD = medium-duty; HD = heavy-duty. Buses do not include minibuses. Battery pack cost is calculated as the sales-weighted battery pack price per kWh for commercial vehicles multiplied by the sales-weighted battery pack size for the vehicle segment.

Sources: IEA analysis based on the [Drive to Zero ZETI tool](#) (left). IEA analysis based on data from [Bloomberg New Energy Finance](#) and [EV Volumes](#) (right).

¹ Battery price refers to the sales-weighted average battery pack price for commercial vehicles, including light-commercial and heavy-duty vehicles.

Truck total cost of ownership

For electric trucks to reach mass adoption, the total cost of owning an electric truck must be able to compete with the cost of owning a traditional diesel truck. Commercial vehicle owners and operators are typically more sensitive to the total cost of ownership (TCO) than personal car buyers, though higher upfront purchase costs can, of course, still present a hurdle.

The TCO of a vehicle depends on how the vehicle is used, and on the capital, energy and labour costs, all of which vary by region. Long-haul, heavy-duty trucks are often considered one of the [hardest-to-electrify](#) vehicle segments due to the need to balance battery size, range and payload constraints with charging requirements. In this section, we consider battery electric and fuel cell electric heavy-duty (HD) trucks, both of which have zero tailpipe emissions, and compare their TCO to diesel HD trucks in three major markets: China, the European Union and the United States.² A daily driving distance of 500 km is assumed.

The upfront cost of a battery electric truck was two to three times that of a diesel truck in 2024

While the TCO is important for overall business profitability, the upfront costs can be particularly important to small business that may have less access to financing. Small businesses make up the vast majority of hauliers in the [United States](#) (95%) and [Europe](#) (90%), and more than half in [China](#) (less than 70%),³ where the haulage industry has been experiencing increasing consolidation.

Battery electric and fuel cell electric trucks are more expensive to purchase than conventional diesel trucks. This is mostly due to the batteries used in BEVs and the fuel cell stacks and hydrogen storage tanks in FCEVs being more expensive than equivalent diesel ICEV technologies. Today, for a truck with an 800 kWh battery (500 km range), the battery represents almost half of the upfront cost of a battery electric truck, and this is expected to fall to around 35% in 2030. For an FCEV, the battery, fuel cell system and hydrogen storage tank represent around half of the upfront cost today and this is not expected to change in 2030.

The costs of batteries, fuel cells, and hydrogen storage tanks are expected to fall thanks to greater economies of scale and manufacturing learnings, driving down the capital costs of both BEVs and FCEVs. In the next 5 years, the purchase price of a battery electric HD truck could fall by around 15-35%, depending on the

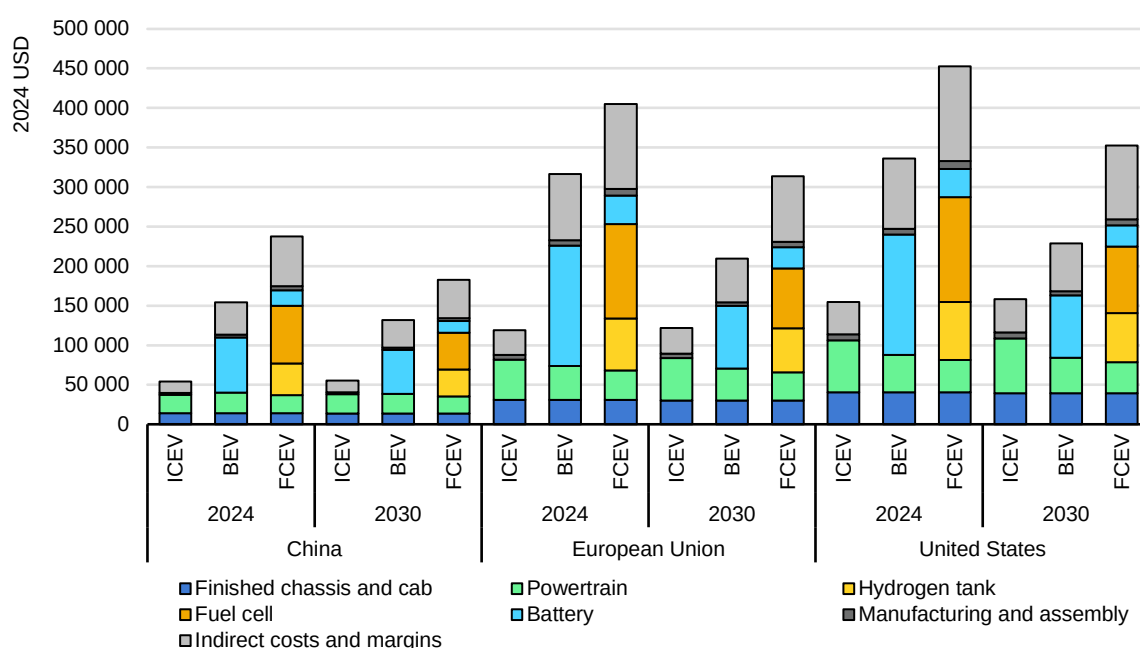
² Please see [Annex A](#) for full assumptions and costs used to calculate TCO in this section.

³ Due to differences in reporting across the sources, in the case of the United States a small business is defined as having up to 10 trucks, in Europe up to 9, whereas in China the equivalent number is 20 or under.

region. That of a fuel cell HD truck could fall 20-25%. However, both are expected to remain more expensive than diesel ICE trucks at the point of purchase.

Purchase prices vary by region, and are lowest in China, primarily due to lower manufacturing and battery costs. Although the absolute price difference between battery electric and fuel cell electric trucks versus diesel equivalents is smallest in China, the low cost of diesel trucks means it has the largest relative price differences, at almost three (for battery electric) and four (for fuel cell electric) times the equivalent diesel price. The United States has the highest prices overall, while Europe enjoys both lower-cost diesel and zero-emissions trucks. Although not a like-for-like comparison, real-world price data shows that the premium for a zero-emissions truck was around [USD 60 000](#) higher in the United States than in Europe in 2024, demonstrating the difficulties the United States is facing in achieving price competitiveness.

Estimated purchase price of hydrogen fuel cell, battery electric, and diesel heavy-duty trucks in 2024 and 2030



IEA. CC BY 4.0.

Notes: ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. The ICEV represents a diesel truck. The powertrain includes the engine for the diesel truck; the electric drive unit, electronics, DC/DC converters, on-board charger, thermal management, and other balance of plant components for both the battery electric truck and the fuel cell electric truck. Please see the Annex for a full list of sources, assumptions, and other inputs.

Increasing the utilisation of charging infrastructure can significantly reduce fuel costs for battery electric trucks

Fuel and infrastructure costs can make up a large share of the TCO for a heavy-duty truck. This is expected to remain the case into the future: over the next 5

years, vehicle efficiencies will likely improve by just 2-5%, meaning the levelised cost of fuel will remain a key component of TCO, especially for trucks with high daily driving distances. However, battery electric trucks are about 55% more energy-efficient than diesel heavy-duty trucks of the same size, while fuel cell electric trucks are about 30% more efficient. As such, based on 2024 fuel prices, the direct fuel costs associated with operating a battery electric heavy-duty truck are almost 70% lower than the diesel equivalent in China, and about one-third lower in the European Union and the United States.

However, unlike diesel, both BEVs and FCEVs require the buildout of new, relatively expensive infrastructure, which adds to the fuel costs. Further, the levelised cost of both EV chargers and hydrogen refuelling stations (HRSs) is highly affected by utilisation rates. Overall, truck charging infrastructure could reach even higher levels of utilisation than LDV chargers, given that logistics operations are typically planned according to a predetermined schedule. Increasing the utilisation rate of an EV charger from 5% to 30% lowers the levelised infrastructure cost per kWh by about 80%, which would cut the overall fuel cost per kilometre by half based on 2024 prices. Increasing utilisation of en route chargers even further is possible, but may require solutions such as [adaptive route planning](#).

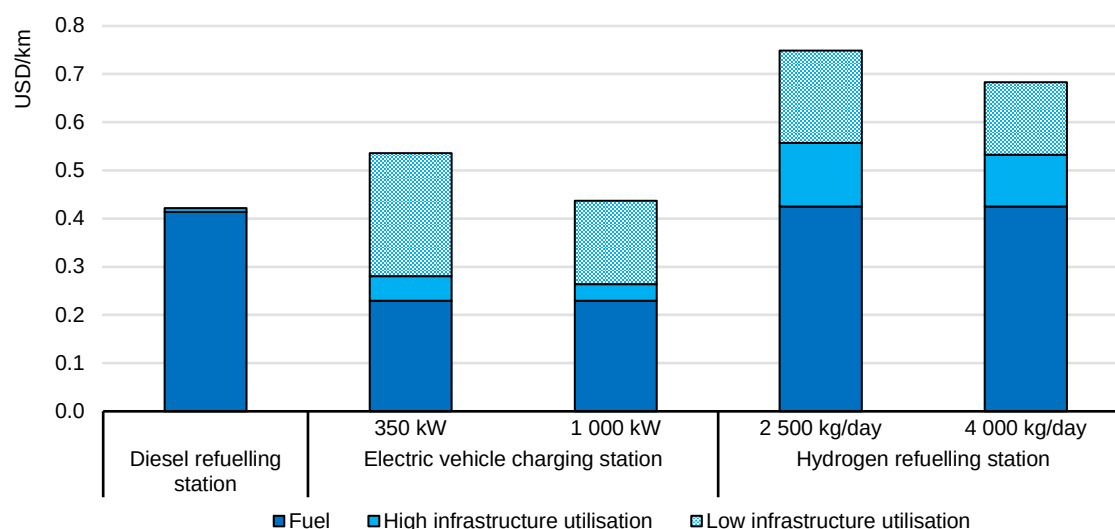
While a single HRS is more costly to build than a charging point, it can serve a large number of trucks daily without the local grid impacts of high-powered chargers. As the utilisation rises from 30% to 80%, the hydrogen cost premium for infrastructure investment payment drops by nearly 60%, resulting in a 25% drop in overall fuel cost per kilometre. However, even at higher utilisation rates, such as for captive fleets (i.e. that are owned by the operators and return to depot) or on busy public routes, the energy plus infrastructure cost per kilometre remains about 5% higher than EV charging at low utilisation rates, and double the cost of EV charging at high utilisation rates.

For every USD 1 million spent on infrastructure, a highly utilised 350 kW charger covers more than twice as many vehicle kilometres as a highly utilised HRS. In addition, HRSs may present a greater barrier to entry, as they cannot be easily phased in gradually: an investment in HRSs must be accompanied by a large investment in FCEVs to avoid prohibitive per-vehicle fuel and infrastructure costs. On the other hand, chargers can be built modularly and more easily scaled as the fleet grows, beginning with depot charging, with en route high-powered charging following later to enable a greater share of journeys to be electrified.

Policies such as the EU [Renewable Energy Directive](#), California's [Low Carbon Fuel Standard](#), or China's multiple cross-cutting [policies](#) promote reductions in emissions associated with electricity and hydrogen production, but can also impact the future fuel costs. A [smaller share](#) of electrolysis projects reached final investment decision between October 2024 and October 2023 when compared to the previous 12 months, potentially constraining the supply of low-emissions

hydrogen, which is [more expensive](#) than the fossil-fuel derived hydrogen predominantly used today. Meanwhile, low-cost solar and wind are driving down electricity grid [emissions](#) and can [reduce](#) electricity prices over time. However, further advances in electricity storage, smart charging and grid integration are needed to compensate for the intermittency of wind and solar and increase the benefits offered by electric trucks, requiring substantial investment.

World average levelised cost of diesel, electricity and hydrogen fuel for trucks, including infrastructure, 2024



IEA. CC BY 4.0.

Notes: "Fuel" represents the average price a truck operator pays, including taxes for each fuel. For hydrogen, the cost is the weighted levelised cost of production from all sources, meaning it is dominated by unabated steam methane reforming, plus the cost of distribution to the refuelling station. For electricity and hydrogen, "Infrastructure cost" is the annualised cost per unit of fuel/energy delivered, assuming a 10-year lifetime and 8% discount rate. For diesel, it is 2% of the fuel price. The "low infrastructure utilisation" factors are 5% for the 350 kW charger and 30% for the hydrogen refuelling station; the "high infrastructure utilisation" case assumes 30% utilisation of EV charger and 80% utilisation of the hydrogen refuelling station, which results in a reduced the cost per unit of energy delivered by serving a greater number of vehicles. Please see the Annex for a full list of sources, assumptions, and other inputs.

Sources: IEA analysis based on studies from the [European Commission](#), the [ICCT](#), and the [US Department of Energy](#).

Battery electric trucks become competitive for long-haul applications this decade in China and Europe

For a diesel HD truck that travels an average 500 km per day, the truck capital cost represents only around 10% of the TCO across China, Europe and the United States. That means that outside of relatively fixed costs such as driver costs, insurance and maintenance, diesel fuel costs dominate the TCO. In comparison, for an 800 kWh battery electric truck, the cost of the truck represents about 20-25% of the TCO, demonstrating the potential trade-off between high upfront costs and lower running costs. For battery electric trucks, energy costs account for around 15-25% of the TCO, and for fuel cell trucks they account for 15-35%, across the three regions examined. For BEVs, more than 10% of the TCO can be attributed to charging infrastructure in Europe and the United States,

while in China, this share is reduced to around 3%, thanks to lower industrial land costs as well as lower capital costs. The refuelling infrastructure for fuel cell trucks has higher costs, representing nearly 10% of the TCO in China and more than 15% in Europe and the United States.

In terms of operations, regulations on truck driver rest periods can play a role in determining the cost of the “dwell” time for recharging electric truck batteries. The time associated with charging is often considered to be a barrier to the adoption of battery electric trucks for long-haul applications as it can potentially disrupt operations, especially in very long-haul applications. This consideration is factored into the TCO calculation by adding the additional labour cost for the truck driver. In the [European Union](#), drivers are required to take a 45-minute break every 4.5 hours. In the [United States](#), a driver is not permitted to drive for more than 8 hours without a 30-minute break. In [China](#), drivers are required to take a break every 4 hours, generally [20 minutes](#). As such, driving regulations can influence the TCO, and [making use of rest periods](#) for charging can make battery electric trucks more or less cost-competitive with diesel trucks. Based on a 500 km daily route and current regulations, an extra 15 (European Union), 30 (United States), and 40 minutes (China) would be needed in addition to the driver rest period in order to charge the battery electric HD truck sufficiently.⁴ The net cost associated with dwell time represents a trade-off between the fuel and labour costs, and as such may make more economic sense in China, where diesel is more expensive than in other regions, and labour and electricity less expensive. In contrast, in the United States, lower costs for diesel and higher labour and electricity costs can make it more difficult to justify.

Charger power is also key in calculating this trade-off. A 350 kW charger, as used in the base case, can provide 200 km of range in around 1 hour, while a [1 MW](#) charger could provide the same in about 20 minutes, potentially eliminating the dwell cost.⁵ Destination charging, particularly where drivers must wait for loading and unloading, could also greatly reduce the dwell time.

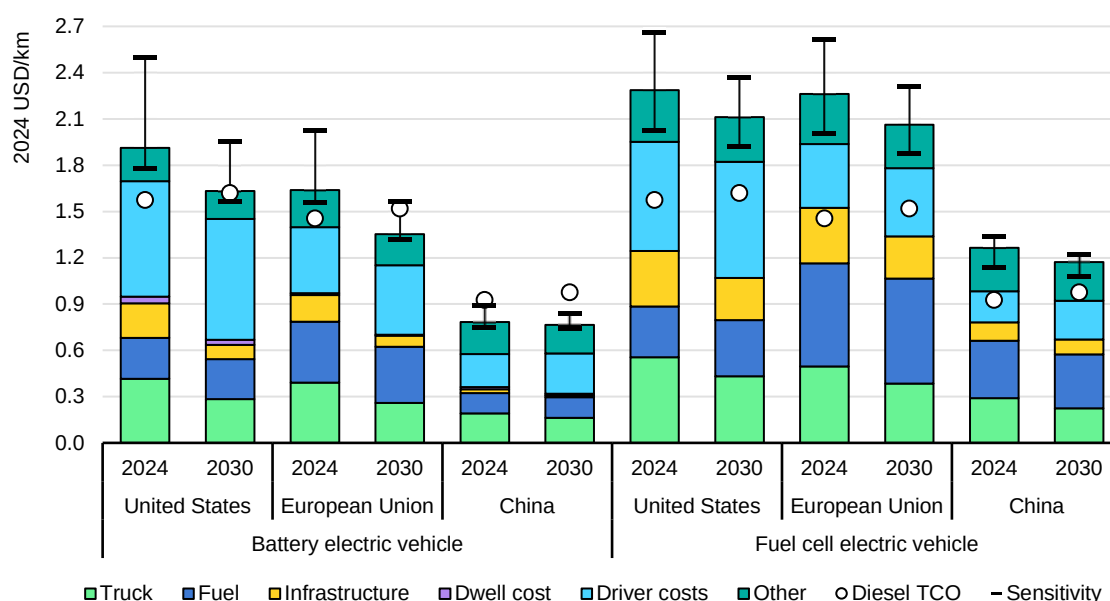
The impact on payload is another consideration for many hauliers. In the [United States](#), 18% of trucks operate close to the general maximum gross vehicle weight, with a further 7% operating above the limit, meaning they could be impacted by the additional weight of either a fuel cell or battery electric truck compared to diesel. Derogations exist in the [United States](#) (907 kg) and the European Union (2 000 kg) to help offset the impact of the additional weight. A [proposal](#) from the European Commission to further increase this to 4 000 kg could eliminate the disadvantage relative to diesel trucks, but could also marginally

⁴ 500 km daily distance is split evenly before and after the minimum rest periods of 20, 30, and 45 minutes in China, the United States, and the European Union, respectively, based on the driver's rest regulations for each country/region, after which drivers, if required, continue to use the 350 kW charger to provide sufficient range to perform the same daily mileage day after day, including for overnight depot charging, based on 2024 fuel economy values and minimum and maximum battery states of charge of 20% and 80%.

⁵ Assuming 1.6 kWh/km fuel economy, and considering that this is below the length of the shortest minimum rest period.

[increase](#) road maintenance costs.⁶ In China, industry stakeholders have also [mooted](#) increasing the weight limits as a means of making alternatively fuelled vehicles more competitive. These potential impacts are considered in the sensitivity case of the TCO.

Total cost of ownership for battery electric and hydrogen fuel cell heavy-duty trucks in 2024 and 2030



IEA. CC BY 4.0.

Notes: TCO = total cost of ownership. "Truck" refers to the cost of the truck including financing over 5 years at 5% interest and the residual value in year 5. "Infrastructure" is the levelised contribution to the cost of the EV charging or hydrogen refuelling station. "Driver costs" is the cost of employing a truck driver during normal working hours and does not include "dwell cost", which is the additional cost incurred when a driver must continue charging beyond their rest period. "Other" costs include insurance and maintenance. Cost projections are based on the 2024 Global Energy and Climate Model Stated Policies Scenario, as published in the [World Energy Outlook 2024](#) report. Please see the Annex for a full list of sources, assumptions, and other inputs.

Sources: IEA analysis based on a studies from [Ricardo](#), [US Department of Energy](#), [ICCT](#), the [European Commission](#).

In China, the TCO of battery electric HD trucks is already lower than that of diesel trucks in a number of applications. This reflects the lower cost of EV batteries in China, as well as the gap in fuel costs, as electricity already costs 65% less than diesel per kilometre. As such, energy costs for battery electric trucks are over 50% lower per kilometre compared to diesel trucks. Fuel cell trucks remained around 35% more expensive than diesel trucks in China in 2024, largely because of the higher infrastructure and fuel costs for hydrogen.

In the United States, higher electricity and infrastructure costs than Europe or China mean that the TCO of a diesel truck is almost 20% cheaper than that of a

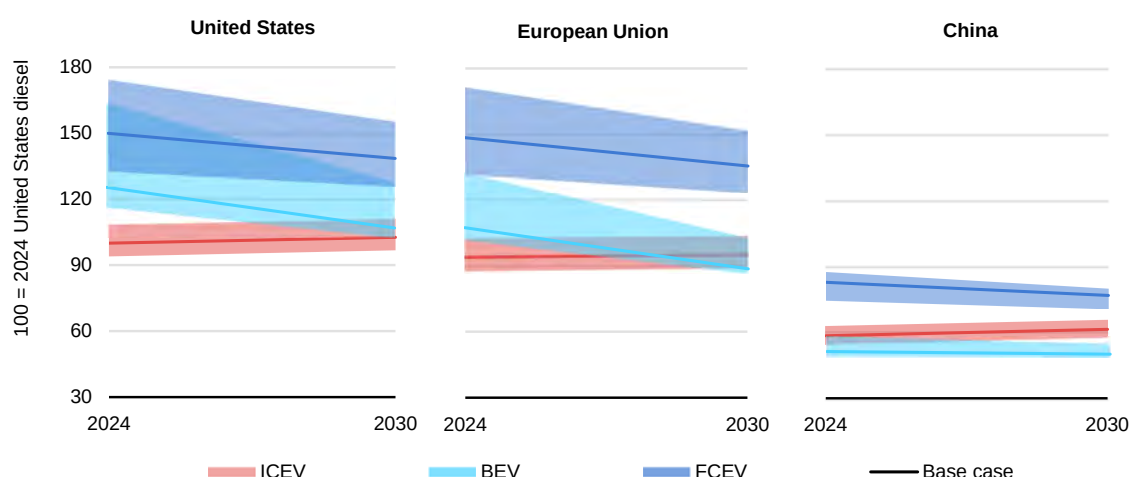
⁶ A full table of maximum gross vehicle weights, estimated unladen vehicle weights, assumptions, and the resulting "payload penalties" is included in the Annex.

battery electric truck, though higher charger utilisation rates could reverse this by 2030. Compared to the European Union, US regulations on driver rest periods and maximum gross vehicle weight further hamper the uptake of zero-emissions trucks. However, in the coming years, the TCO of battery and fuel cell electric trucks is expected to fall due to improvements in infrastructure utilisation and costs, as well as further cost reductions for batteries and fuel cells. In contrast, diesel electric trucks are expected to become more expensive due to more stringent pollutant emissions regulation.

In all three markets, fuel cell trucks remain more expensive than battery electric trucks up to 2030, while continued development of high-powered charging – especially megawatt charging – reduces or eliminates the refuelling time advantage offered by FCEVs compared to BEVs. Increased utilisation of HRSs could result in further reductions to the TCO of fuel cell electric trucks, but battery electric trucks will remain cheaper to operate. For fuel cell electric trucks to become more competitive, substantial reductions in the capital costs of the truck and infrastructure, as well as lower fuel costs, will be necessary.

In 2030, the TCO of battery electric trucks is more competitive than diesel trucks in both China and the European Union. The gap also narrows substantially in the United States, achieving parity around 2030. Incentives such as grants towards the purchase of trucks, chargers, or HRSs, or differentiated taxes and [charges](#) could bring this date even closer, or indeed allow TCO parity to be achieved today in applications particularly suited to electrification.

Total cost of ownership for diesel, battery electric and fuel cell heavy-duty trucks, 2024-2030



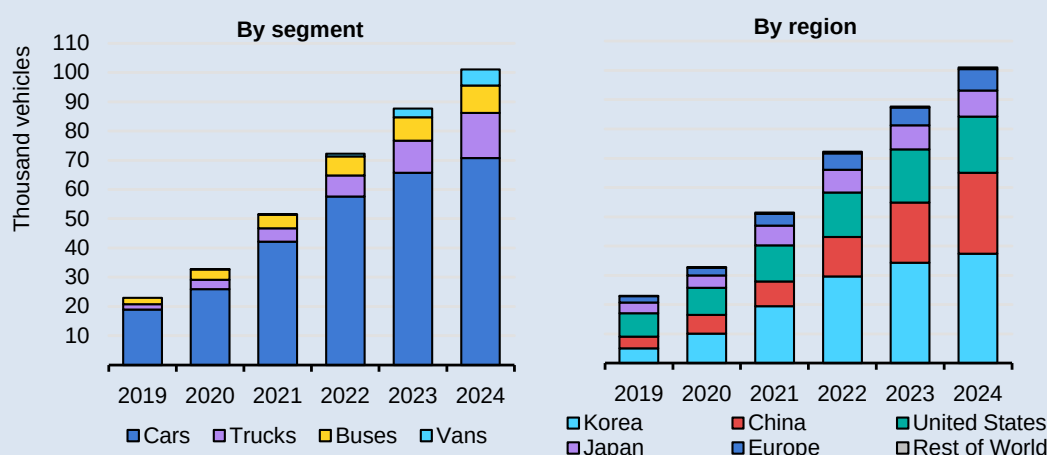
IEA. CC BY 4.0.

Notes: ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. The ICEV is a diesel truck. The total cost of ownership is indexed to the United States 2024 value of diesel heavy-duty trucks. Includes vehicle cost, labour, financing, fuel (including infrastructure costs), maintenance, insurance and residual value. Excludes taxes, charges not included in fuel costs, and any subsidies or incentives. Cost projections are based on the 2024 Global Energy and Climate Model Stated Policies Scenario, as published in the [World Energy Outlook 2024](#) report. Please see the Annex for a full list of inputs and assumptions including the values that define the upper and lower ranges.

Sales of fuel cell trucks and buses outpaced sales of fuel cell cars in 2024

In 2024, the stock of fuel cell vehicles grew to over 100 000, 15% more than the year before. In comparison, the stock of EVs exceeded 60 million (excluding 2/3Ws) at the end of 2024, about 600 times the number of FCEVs. About 70% of the FCEVs on the road are cars, though this share has fallen since the end of 2023 (75%). Fuel cell trucks experienced higher growth in 2024 than fuel cell cars or buses, with the stock increasing by more than 40% compared to 2023.

Fuel cell electric vehicle stock by segment and region, 2019-2024



IEA. CC BY 4.0.

Sources: IEA analysis based on data from the [Advanced Fuel Cells Technology Collaboration Programme](#), EV Volumes, [Toyota](#), [California Fuel Cell Partnership](#).

Growth in fuel cell car sales has slowed in recent years, with just 5 000 sold worldwide in 2024, compared to the peak of more than 16 000 in 2021. This slowdown is particularly acute in the United States and Korea – the two countries with the largest stocks of fuel cell cars. In [California](#), where the majority of US fuel cell cars are sold, only around 600 new fuel cell cars were registered in 2024 – the lowest number since 2015. In Korea, almost 3 000 fuel cell cars were sold in 2024, about 35% less than in 2023 and 70% less than in 2022. Only a handful of OEMs produced fuel cell cars in 2024.

In contrast, the global stock of fuel cell buses grew by almost 20% in 2024. China continues to have the most fuel cell buses, accounting for three-quarters of the global stock. The number of fuel cell buses grew strongly in Korea in 2024 to reach a stock of [1 000](#), about 10% of the global total.

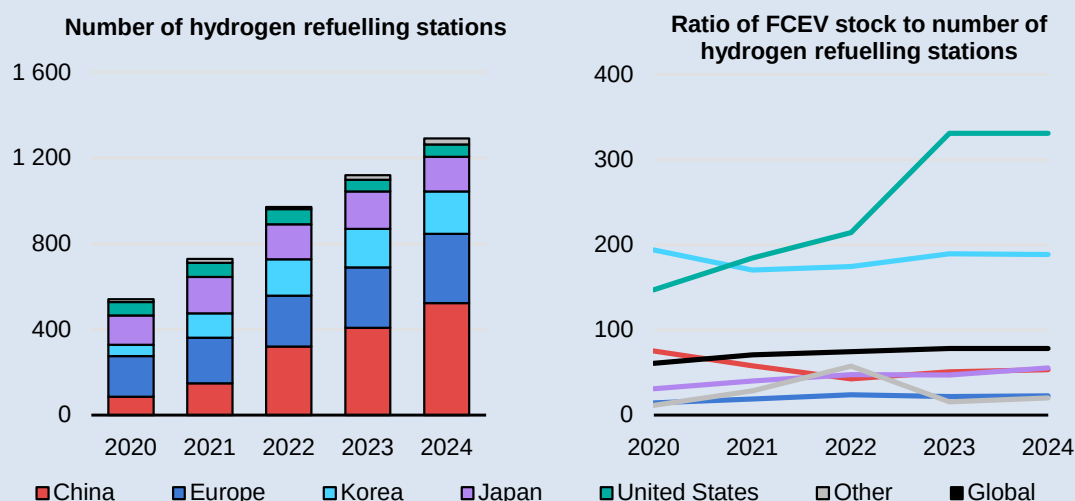
Unlike Korea, the United States and Japan – each of which has traditionally focused more on fuel cell car deployment than on any other segment – over 70% of the FCEV stock in China is commercial vehicles (including LCVs and heavy trucks). In China, cars make up only around 3% of the total fuel cell vehicle fleet, while in the

United States and Korea they account for up to 97%. In 2024, the stock of fuel cell trucks in China increased 40% compared to 2023, reaching almost 15 000 vehicles, about 5 times the amount at the end of 2020. In addition, the stock of fuel cell LCVs in China reached more than 5 000 by the end of 2024, nearly double that of the previous year. Almost 95% of the world's fuel cell commercial vehicles are in China.

Around 50 fuel cell commercial vehicle models were available worldwide in 2024. Over 60% of these were heavy-duty truck models, coming from 20 different manufacturers. However, Nikola, one of the pioneers of heavy-duty fuel cell trucks, [filed for bankruptcy](#) in February 2025, despite [selling 200 vehicles](#) in 2024 and securing orders for [100 more](#) meant to be delivered in 2025.

To support the growing number of FCEVs, countries have supported the buildout of hydrogen refuelling stations (HRSs). The number of operational stations reached around 1 300 worldwide at the end of 2024, 15% more than at the end of 2023. The largest growth occurred in China, where the number of HRSs increased 30% in 2024 to reach more than 500. In Europe, the number of stations increased 15% to over 300 by the end of 2024, despite some [closures](#) in countries such as Denmark and the United Kingdom. The United States and Korea have also seen the number of available HRSs fluctuate over the past year or so, as [hydrogen supply](#) and station reliability issues have led to temporary and permanent closures. The number of [operational HRSs](#) in the United States increased in 2024, but remains below the number available between 2017 and 2022.

Number of hydrogen refuelling stations by region and ratio of fuel cell electric vehicle stock to number of stations, 2020-2024



IEA. CC BY 4.0.

Note: FCEV = fuel cell electric vehicle.

Sources: IEA analysis based on data from the [Advanced Fuel Cells Technology Collaboration Programme](#), [EAFo](#), [US Alternative Fuels Data Center](#).

The number of FCEVs per HRS is significantly higher in the United States and Korea than in other regions. The global average number of FCEVs per HRS has remained at under 80 over the past 5 years, while in the United States this ratio exceeded 300 in 2023 and 2024 and has been close to 200 in Korea since 2020.

For further information on the deployment status of FCEVs and other hydrogen-based technologies, see the IEA [Global Hydrogen Review](#) report series.

5. Outlook for electric mobility

Overview

In this part of the report, we focus on the outlook for electric mobility in road transport over the period to 2030. A scenario-based approach is used to explore the prospects for electric mobility, based on recent market trends, policy drivers and technology developments.

The purpose of scenario projections is to assess a plausible future for global electric vehicle (EV) markets and the potential implications. The scenario projections are not intended as predictions about the future. Rather, they aim to provide insights to inform decision-making by governments, companies and other stakeholders about the future of EVs.

In particular, the [Stated Policies Scenario](#) (STEPS) reflects the current policy landscape, taking into account existing policies and measures, as well as those that are under development. It includes current EV-related policies and announcements, regulations and investments, as well as market trends based on the expected impacts of technology developments, announced deployments and plans from industry stakeholders. The STEPS aims to hold up a mirror to the plans of policy makers and illustrate their consequences.

The projections for EV markets in this year's Global EV Outlook (GEVO-25) are limited to 2030 in the STEPS. As the IEA highlighted in its [2024 edition of Energy Technology Perspectives](#), energy, industrial and trade policies are increasingly interwoven and there are challenges and trade-offs between these key areas of public policy. The way these interactions play out for electric mobility over the longer term will therefore be assessed holistically in the context of the scenarios of the entire global energy system that the IEA will develop later in the year using its Global Energy and Climate Model (GEC-M). Key uncertainties for EV markets for the medium-term – such as those related to the evolution of trade and industrial policy, downside risks to the economic outlook and the impact of different levels of oil prices – are, however, presented in this chapter of the report.

The projections in the STEPS in GEVO-2025 consider historical market data and stated policies up until the end of February 2025. These scenario projections incorporate GDP assumptions from the International Monetary Fund and population assumptions from the United Nations, as described in the [2024 GEC-M documentation](#).

EV deployment is projected by road transport mode and by region. For further details on EV projections and impacts, refer to the IEA's online [Global EV Data Explorer](#), which is updated with each edition of the Global EV Outlook.

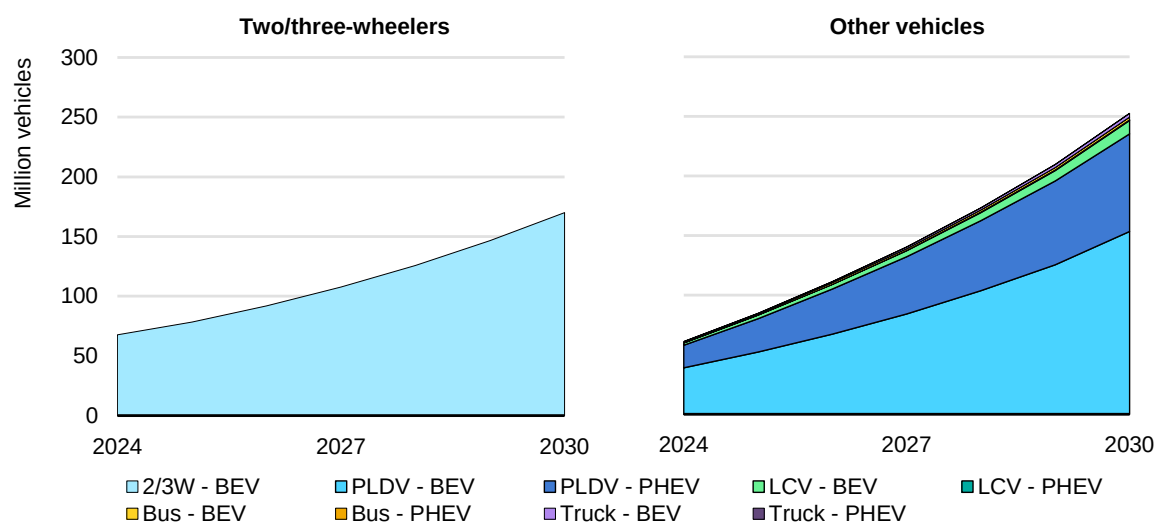
Vehicle outlook by mode

The global electric vehicle fleet grows fourfold to 2030 under stated policies

By 2030, the fleet of EVs across all modes except 2/3Ws reaches 250 million in the STEPS – four times as many EVs as there were at the end of 2024. More than 90% are electric cars, which is similar to the share in 2024. In this scenario, the stock of EVs (excluding 2/3Ws) increases at an average rate of about 25% per year, which is about half the annual growth observed from 2018-2024.

In 2024, the stock of electric 2/3Ws was higher than that of all other EVs combined. By 2030, however, the stock of electric cars overtakes that of electric 2/3Ws, despite the latter more than doubling to reach around 170 million in 2030 in the STEPS. As a result, EVs represent about 15% of all vehicles on the road (including 2/3Ws) in 2030 in this scenario. The share of global EV stock in China decreases from over 70% in 2024 to around 55% in 2030 in the STEPS as adoption in other markets grows.

Electric vehicle stock by mode in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: 2/3W = two/three-wheeler; PLDV = passenger light-duty vehicle; LCV = light commercial vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle. There are no plug-in hybrid electric two/three-wheelers.

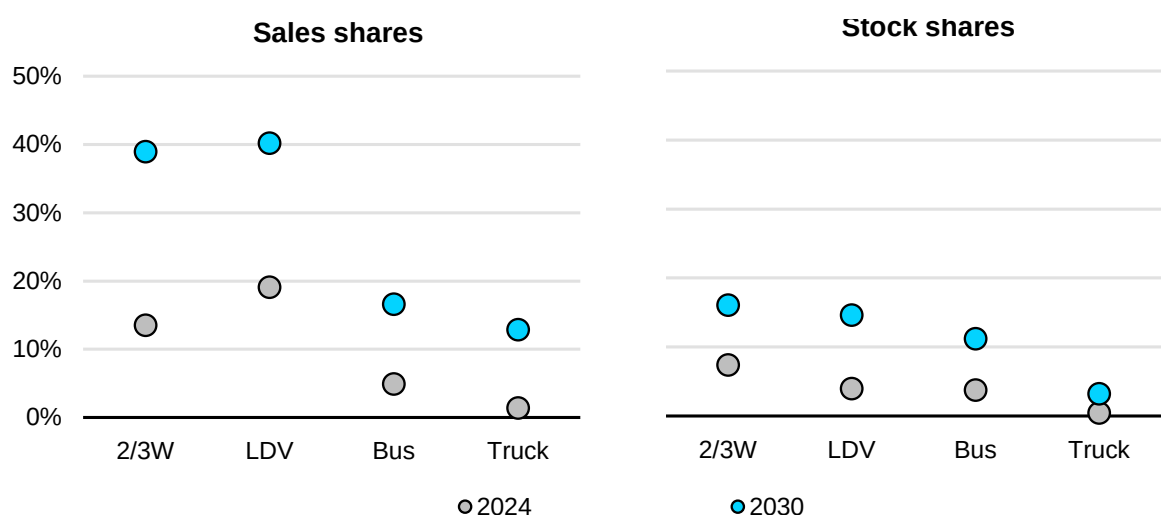
In 2024, the EV sales share was higher for light-duty vehicles (cars and vans) than 2/3Ws, in a change to the trend prior to 2023. In 2030, the EV sales share for both

light-duty vehicles (LDVs) and 2/3Ws reaches around 40% in the STEPS. In terms of stock shares, 2/3Ws remain the most electrified vehicle segment in 2030 in the STEPS, with around one in six 2/3Ws being electric compared to one in seven LDVs.

Despite electric buses and electric LDVs having about the same stock share in 2024, the sales share of electric buses grows more slowly, reaching less than 20% globally in 2030 in the STEPS. As a result, slightly more than 10% of the global bus stock is electric in 2030 in the STEPS.

Trucks remain the slowest mode to electrify but make some progress thanks to HDV emissions standards and improving economics. In 2030, electric truck sales reach around 13% globally in the STEPS, though only 3% of the truck stock is electric at that point.

Electric vehicle sales and stock share by mode in the Stated Policies Scenario, 2024 and 2030



IEA. CC BY 4.0.

Notes: 2/3W = two/three-wheeler; LDV = light-duty vehicle.

Economic and policy uncertainties could impact car markets and the global outlook for EVs

The recent surge in **trade policies and tariffs** may affect the price and resulting sales of EVs – especially electric cars – in several markets over the coming years. In particular, in March 2025 the United States [announced an additional 25% tariff](#) applicable to all automobiles, including electric cars, and to certain components. In 2024, 40% of electric cars sold in the United States (over 600 000) were imported, with over 10% of them coming from Europe and slightly less than 10% each coming from Mexico, Japan and Korea. Conventional car sales are more exposed, with over half of all conventional cars sold in the United States in 2024 having been imported. Conventional car imports generally come from the same

countries as EVs, although there is a much higher reliance on Mexico and lower reliance on Europe. As a result, the impact of tariffs on the sales share of electric cars in the United States may be relatively small compared to the impact of potential changes in demand-side policies (such as fuel economy standards and tax incentives), some of which are already considered as part of the STEPS outlook.

The impact of tariffs might be more pronounced for EV batteries, their components and raw materials, all of which are highly traded across the world because supply is significantly more concentrated than demand. China produces the cheapest EV batteries, and was responsible for nearly 80% of global EV battery cell production in 2024. China's share of production was even higher for battery components, for which the country represented almost 85% of global cathode active material and over 90% of the anode active material production. A global shift towards higher tariffs could put upward pressure on battery prices, counteracting some of the significant battery price declines that have occurred since 2015. For example, a 25% tariff would override the 20% average battery price declines from the past year. However, countries across the world are simultaneously developing and improving the competitiveness of their local battery manufacturing industries, which is expected to contribute to narrowing regional cost gaps.

Emerging trade tensions also have implications for the **economic outlook**, which may create additional uncertainty for the EV outlook. In April 2025, the International Monetary Fund (IMF) released [revised GDP projections](#), which show 2.8% growth globally in 2025 and 3% growth in 2026, as compared to 3.3% in both years in their [January 2025](#) projections. The revisions to GDP growth were most pronounced in North America, with projected 2025 growth for the United States falling from 2.7% previously to 1.8% in the April 2025 update. The IMF now projects in its central scenario that in the United States and China, two of the largest EV markets in the world, GDP growth in 2025 will be one percentage point lower than in 2024. By 2027, the IMF expects global GDP growth to return back to levels previously projected, though for advanced economies as a whole, annual GDP growth projections remain lower through 2029 compared to the IMF's [October 2024](#) publication.

Lower GDP growth could add pressure on already-strained government budgets, which, in turn, could lead to governments downscaling or terminating incentive schemes for EVs ahead of schedule. While direct subsidies are already quite small in most major markets, indirect subsidies, such as those related to company cars, could be affected. Similarly, budgets allocated to the deployment of charging infrastructure at different administrative levels (from national to local levels of government) could be reduced. While all these factors could slow down the uptake of EVs, policy responses can also be developed in a way that supports EV sales, as was done in European countries in the wake of the Covid-19 pandemic.

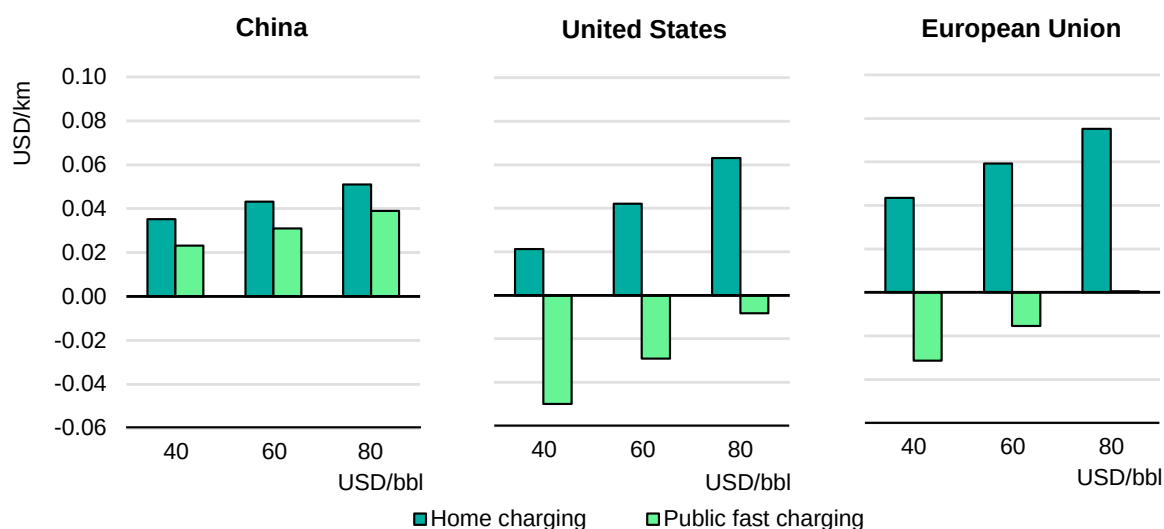
Lower economic growth and the corresponding effects on the purchasing power of consumers could slow down sales of new vehicles across all powertrain types, thereby potentially counterbalancing the impact on EV sales shares. Evidence shows that an economic slowdown can affect car sales. For example, pronounced and abrupt economic crises have led to double digit declines in car sales in the past, for example in the United States between 2007 and 2009 (GDP -2.5%, car sales -37%), and in Italy between 2011 and 2013 (GDP -5%, car sales -25%). More modest and gradual economic slowdowns can also have an effect, such as the slowdown in China between 2017 and 2019 (+6.2 % compared to a ten-year average of over +8%) that led to the first decline in car sales recorded in decades, of -12% over 2 years.

The extent to which car markets – and, as part of that, electric car sales – might be affected by a sluggish economic outlook is still uncertain. The Chinese market will be key to watch: it is the largest single car market in the world, and it drives the outlook for global electric car sales in the medium term, accounting for more than half of global electric car sales through 2030 in the STEPS. In China, electric cars are already price competitive with conventional cars and so there is little reason to believe that electric car sales would be more affected by an economic slowdown than conventional cars. Further, China's extension of its vehicle trade-in policy may also contribute to keeping overall car sales strong. Even if car sales volumes in China are lower than is projected in the STEPS, electric car sales shares are likely to remain relatively robust.

Finally, changes in **energy prices** can also affect the adoption of EVs. Weak demand prospects have led to a drop in global oil prices from an average of around USD 80 per barrel in 2024 to [below USD 60](#) per barrel at one point in April 2025. Lower oil prices, if sustained, could translate into lower retail prices for gasoline and diesel, thus reducing the economic incentive to purchase EVs, all else being equal. The impact of such a drop is likely to vary across regions: it will be more moderate in regions with high fuel taxation (such as the European Union), and more pronounced in regions with lower fuel taxation, such as the United States and China. Nonetheless, oil prices would need to be extremely low to completely offset the savings offered by the lower running costs of EVs.

Taking oil prices around USD 40 per barrel as an illustrative example, there are significant savings to be made in all major markets from running a battery electric car if it is charged at home. In China, even at such a low oil price, battery electric cars remain cheaper to run when charged at public fast chargers due to a combination of low electricity prices and high charging infrastructure utilisation rates. In the United States, the vast majority of electric car owners have access to home charging, but public fast charging can be expensive compared to gasoline. In the European Union, most EV owners also have access to home chargers, though to a lesser extent. Low oil prices could therefore undermine the economic case for EVs for drivers without access to home charging depending on the speed and thus cost of public charging.

Electric car running cost savings compared to an internal combustion engine car for a range of illustrative oil prices, 2024

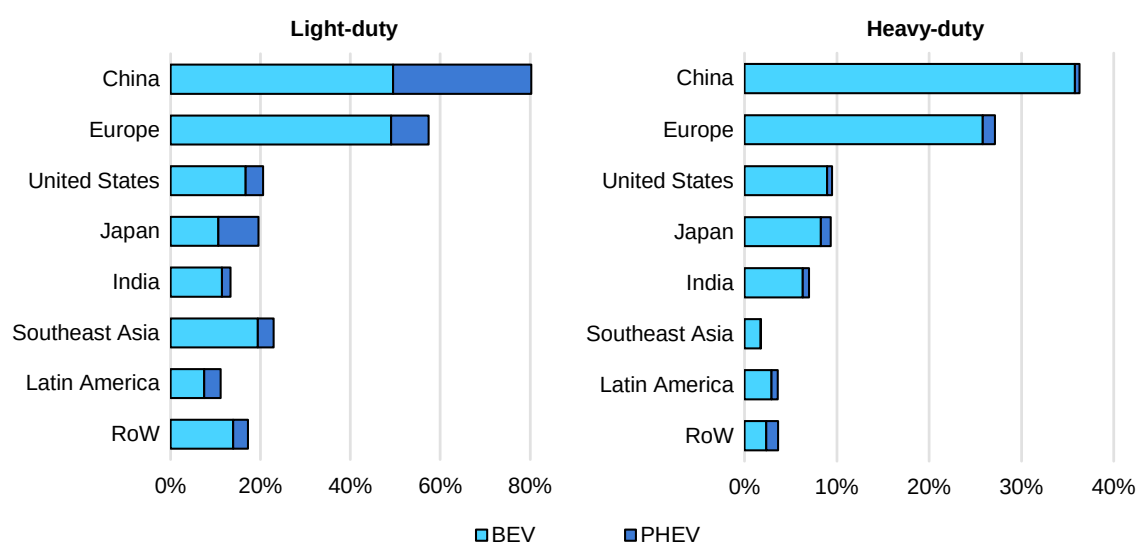


IEA. CC BY 4.0.

Notes: bbl = barrel. Negative savings indicate it costs more to run a battery electric car than an internal combustion engine car. Average on-road fuel consumption values in each region is assumed.

Vehicle outlook by region

Electric vehicle sales share by mode and region in the Stated Policies Scenario, 2030



IEA. CC BY 4.0.

Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; RoW = Rest of World. Light-duty refers to passenger light-duty vehicles and light commercial vehicles. Heavy-duty refers to buses, medium-duty and heavy-duty trucks. Regional projected EV sales and sales shares data can be explored in the interactive [Global EV Data Explorer](#).

Market momentum in China sees electric cars reach a sales share of around 80% by the end of the decade

In the second half of 2024, China achieved the milestone of an electric car sales share of more than 50%, partly thanks to the cost competitiveness of EVs. For the past few years, over half of the electric cars sold in China have been cheaper than ICE cars of the same size, and as battery prices continue to fall, this trend is likely to continue.

Based on stated policies, the share of electric cars and vans in China is expected to reach around 80% of total sales in 2030, backed by continuing policy support and progress on affordability. China has already exceeded the official government target of reaching a sales share of [45% of new energy vehicles](#) (NEV) among new cars by 2027, underscoring the strong market dynamics behind the shift to electromobility. [Trade-in grants](#) that were due to expire at the end of 2024 have been extended to 2025, and the NEV exemption from vehicle purchase tax has also been extended until the end of 2027, further supporting uptake of EVs in the short term. In addition, government plans to [enhance charging infrastructure](#) over the period to 2030 aim to keep pace with EV uptake by promoting the construction of charging stations in residential areas, as well as in parking spaces in enterprises, industrial parks and government buildings.

Policy action to restrict ICE 2/3Ws in several cities over the past decade has driven high adoption rates of electric [2/3Ws](#), with more than 30% of 2/3Ws now electric. In the STEPS, the share of electric 2/3Ws on the road reaches nearly 50% by 2030, driven by the continued momentum of electromobility in China and a further decline in battery costs.

This growing trend also extends to buses, especially in cities, where nearly [all new buses](#) are now electric. However, the electric market share of coaches for intercity transport was below 10% in 2024. By 2030 in the STEPS, the sales share of electric buses reaches almost 75% across all bus segments, up from less than two-thirds today.

China currently accounts for more than 80% of electric medium- and heavy-duty truck sales worldwide, and the sales share in the country increased to more than 4% in 2024, from 2% in 2023. In some months, the sales share of battery-electric heavy trucks reached a new high of [almost 15%](#), as seen in late June. Truck manufacturers are making efforts to reduce costs, such as by adopting the less costly lithium iron phosphate (LFP) battery chemistry. In addition, policy support for HDV charging infrastructure and the increasing availability of battery-swap-capable vehicles could further accelerate electrification in this segment. Although the upfront cost is higher today compared to diesel powertrains, the annual savings from significantly lower fuel costs mean that electric medium- and heavy-

freight trucks become a cost-competitive option in many applications in the short-term (see Truck total cost of ownership in Section 4). By 2030, the sales share of electric trucks exceeds 30% in the STEPS.

Given China's strong position in the shift towards electromobility, the sales share of EVs across all vehicle types (excluding 2/3Ws) reaches close to 80% by 2030 in the STEPS, well on track with what is needed for its target of reaching climate neutrality in 2060 and supporting efforts to [reduce air pollution](#).

European policy environment continues to promote EVs while offering some flexibility in the short term

Electric car sales stagnated in Europe in 2024, due to a mix of factors including reduced availability of purchase subsidies and a lack of affordable mass-market EV models in OEMs line-ups, as well as sluggish car markets in general. Nonetheless, the policy environment in Europe is one of the strongest in terms of support for EVs, which could encourage strong growth in electric LDV sales over the remainder of this decade. OEMs are beginning to introduce more competitively priced models to comply with the new phase of EU CO₂ standards, which entered into force in 2025.

The 2025-2029 EU fleet-wide CO₂ [targets](#) that were originally proposed represent a 15% emissions reduction compared to a 2021 baseline. The stringency of the standard is further bolstered by two [changes](#) in the way CO₂ emissions are calculated starting from 2025. First, the utility factor (the share of distance driven in electric mode only) of new PHEV models, which is used to calculate their official CO₂ emission values, [decreases](#), meaning PHEV sales are now less effective in helping OEMs reach target compliance. Second, the revised [calculation](#) of CO₂ emission targets will be more favourable to smaller, lighter OEM fleets, potentially increasing the challenge for manufacturers of heavier models.

As a response to concerns that compliance would be difficult for some European manufacturers, the European Commission recently published an [Industrial Action Plan](#) for the European automotive sector, which announced a [proposal](#) to offer flexibilities in meeting the 2025 CO₂ standards for cars and vans. This allows OEMs to reach target compliance by averaging their emissions over the period 2025-27, rather than needing to reach the target by the end of 2025. Despite giving more leeway to carmakers to fall in line with their CO₂ targets, the Action Plan has reaffirmed the overall impetus towards the 2030 and 2035 targets. It was also [announced](#) that the review of the 2035 targets would be sped up, with full technology neutrality as a core principle, though the outcome and thus impact on EV shares remains to be seen.

The European Union is also exploring measures to accelerate the adoption of zero-emission vehicles in [corporate fleets](#), which currently account for [around 60%](#) of new car sales. Policies to support EV uptake in EU member states include national-level measures such as tax credits for EV company cars in countries including [Belgium](#), or France's ["social leasing" schemes](#) for low-income households, which will be rerun in 2025. When considered alongside the [zero emission vehicle mandate](#) in the United Kingdom, stated policies drive the sales share of electric cars and vans in Europe to nearly 60% by 2030 in the STEPS, up from less than 20% today.

For buses and medium- and heavy-duty trucks, the EU HDV CO₂ standards serve as the key lever for further electrification. Policy momentum is particularly strong for electric buses in the European Union, and their share in total bus sales reaches around two-thirds by 2030 in the STEPS. For medium- and heavy-freight trucks, policies already in place towards meeting the EU CO₂ standards result in around one-third of new registrations in the European Union being electric by 2030 in the STEPS. The European Commission's proposal to [exempt zero-emission trucks](#) from road tolls could further support this trend. Toll charges for a long-haul diesel truck can amount to [EUR 25 000](#) annually. Across Europe as a whole, the share of electric medium- and heavy-duty trucks in this scenario is around 25% in 2030, reflecting the varying levels of policy support across different countries.

In Europe, EV sales across all vehicle types (excluding 2/3Ws) are projected to exceed 55% by 2030 in the STEPS, with lighter vehicles such as passenger cars and light commercial vehicles making up the majority of sales.

Recent US policy directs the government to reduce support for EVs

On 20 January 2025, [Executive Order 14154](#) declared that it was US policy to, among other things, eliminate subsidies and other policy measures influencing markets in favour of EVs. Following this, a [bill](#) was introduced to the US Senate that proposes to repeal the Clean Vehicle Tax Credit for both electric cars and commercial vehicles. In addition, the US Secretary of Transportation has [directed](#) the National Highway Traffic Safety Administration to review existing fuel economy standards for LDVs. The [fuel economy standards](#) that were finalised in 2024 require the fuel economy of passenger cars to improve around 2% per year for model years 2027-2031.

While emissions from vehicles are typically regulated at the federal level under the [Clean Air Act](#), in December 2024, the US Environmental Protection Agency (EPA) granted California's request for a [waiver](#) from federal pre-emption (by which federal law supersedes conflicting state law) for their [Advanced Clean Cars II](#)

(ACC-II) regulation. The ACC-II regulation requires an increasing number of electric and fuel cell electric new car sales, from 35% in 2026 to 100% in 2035 and beyond. In 2024, California represented almost 30% of US electric car sales, but only around 10% of total US car sales. In addition to California, 11 other states and Washington DC have [adopted](#) the ACC-II regulation under Section 177 of the Clean Air Act. All together, the states that have adopted the ACC-II regulation represent about 30% of all US LDV sales. However, [Executive Order 14154](#) also directed US policy to terminate, “where appropriate, state emissions waivers that function to limit sales of gasoline-powered automobiles.” Based on stated policy intentions, electric LDV sales in the United States increase from about 10% today to about 20% in 2030 in the STEPS. To put this in context, in the STEPS of [GEVO-24](#), US electric car sales reached more than 50% in 2030, on the back of policies in support of EVs.

The availability and stringency of fuel economy and emissions standards also has significant implications for HDV electrification prospects in the United States. In April 2023, the US EPA granted a [waiver](#) of pre-emption for California’s [Advanced Clean Trucks \(ACT\) Regulation](#), which requires that manufacturers produce and sell increasing quantities of medium- and heavy-duty near-zero and zero-emission vehicles. Ten states have since adopted the ACT regulation. On the other hand, California [withdrew](#) its request for a waiver of pre-emption for the [Advanced Clean Fleets \(ACF\) Regulation](#), which would have required certain fleet owners to purchase increasing shares of near-zero and zero-emission trucks. Some elements of the ACF Regulation would not have been affected by the waiver and so state and local government fleets will still be required to comply with the regulation. At the federal level, in March 2024, the US EPA released final [emissions standards for HDVs](#), which require CO₂ emissions reductions (per ton-mile) of about 25-60% for model year 2032 trucks compared to model year 2027, depending on truck type.

Given uncertainty in the longevity of the existing emissions standards and state waivers, the sales share of electric medium- and heavy-duty trucks in the United States reaches around 8% in 2030 in the STEPS, up from less than half a percent in 2024. This compares to 20% electric truck sales projected in 2030 in the STEPS of GEVO-24.

Electric bus deployment has historically been supported at the federal level through funding opportunities such as the [Clean School Bus Program](#), but city and state policy also play a role in driving uptake, meaning that electric buses may be relatively insulated from changes to federal policies. For example, the Illinois State Legislature passed [law](#) that transit agencies in the state can purchase only zero-emission buses from 2026. The [California](#) state government also offers incentives for the purchase of buses and dedicated charging infrastructure, such as the

[USD 500 million](#) allocated to school buses during the 2023-2024 fiscal year. In the STEPS, EVs represent close to 15% of bus sales in 2030, up from about 3% in 2024.

Across all vehicle types, excluding 2/3Ws, EVs represent one in five vehicles sold in the United States in 2030 in the STEPS, meaning one in thirteen vehicles on the road in 2030 is electric. This is about half the sales share across the rest of the world, where around 40% of vehicle sales (excluding 2/3Ws) are electric in 2030 in the STEPS.

Strong domestic industry, fuel economy standards and targeted subsidies support EV growth in Japan

The policy framework in Japan has remained fairly stable over the past year. In 2019, the country published [LDV fuel economy](#) targets for 2030, aiming to achieve an improvement of 32% in fuel economy by 2030 compared to 2016. This 11-year lead time has given automakers time to incorporate the fuel economy standards in their company strategies, and the seven largest Japanese automakers now all have electrification targets in place.

In addition, purchase [subsidies](#) are available for electric and fuel cell cars to help achieve the country's net zero and [Green Transformation](#) target of 100% electrified (including fuel cell and hybrid) car sales by 2035. In the STEPS, Japan's electric LDV sales increase from 3% of total LDV sales in 2024 to 20% by 2030. This is in line with the low end of the range described in Japan's [Next-Generation Vehicle Strategy](#), which aims for a 20-30% sales share of electric LDVs by 2030, with another 30-40% sales being hybrids, and 3% being fuel cell LDVs.

Fuel economy [standards](#) for HDVs, including buses and trucks, require a reduction in fuel consumption of more than 13% in 2025 compared to the 2015 baseline. Japan also has purchase [subsidies](#) in place for buses and trucks to support EV and FCEV uptake. Electric bus sales reach about 12% in 2030 in the STEPS, up from 2% in 2024. Electric medium and heavy freight truck sales are slow but rise from less than 0.5% today to around 10% by the end of the decade.

Japan is steadily moving towards the electrification of 2/3Ws, with electric 2/3Ws already accounting for 7% of sales in 2024. This is further supported by city-level policies, such as Tokyo's [subsidies](#) for eligible 2/3Ws, which have been introduced with the aim of all new sales being electric by 2035. The share of electric 2/3Ws continues to rise in the STEPS, reaching more than 45% by 2030.

Japan's EV sales share across all modes (excluding 2/3Ws) was at 3% in 2024 and increases to nearly 20% by 2030 in the STEPS, and just slightly over 20% when including 2/3Ws. As a result, about 1 in 20 vehicles in Japan is electric in 2030 based on stated policies.

Policy support in India focuses on the electrification of vehicles other than cars

Following years of support under the Faster Adoption and Manufacturing of Electric Vehicles ([FAME](#)) scheme, which was introduced in 2015, implementation of the new PM Electric Drive Revolution in Innovative Vehicle Enhancement ([PM E-DRIVE](#)) scheme began on 1 October 2024. The new scheme focuses on electric 2/3Ws, buses, trucks and charging infrastructure, while specifically excluding electric cars, and has a budget envelope of USD 1.3 billion to 31 March 2026.

The 2/3W segment is already the most electrified segment in India, with close to 10% of sales in 2024 being electric. This high electrification rate has been driven by the significant savings on total cost of ownership (TCO) offered by existing electric 2/3W models in India. As early as 2023, we estimated that, with subsidies in place, the [TCO](#) of an average electric 2W would be 40% less than its ICE equivalent after 5 years of ownership. The combination of policy support and advantageous economics mean that momentum in electric 2/3W sales is set to continue, and electric models are expected to account for more than one-third of 2/3W sales by 2030 in the STEPS.

Although there are no purchase subsidies for electric cars in India, other mechanisms may support adoption. These include the national vehicle scrapping policy ([V-VMP](#)), along with a number of federal and state-level [policies](#), such as a reduction in the rate of the federal [Good and Services Tax](#) and in the [Regional Transport Office](#) state-level tax, as well as other registration and road tax waivers. In addition, the government's Production Linked Incentive scheme for [Automobile and Auto Components](#) and for manufacturing of [Advanced Chemistry Cell Battery Storage](#) aims to attract investments in domestic EV and battery manufacturing. In March 2024, the government approved the [Scheme to Promote Manufacturing of Electric Passenger Cars in India](#) to attract investment from global EV manufacturers. This allows EV manufacturers committing to invest in India to import electric cars with import duties reduced from 70% (or 100% if the purchase price [exceeds](#) USD 50 000) to 15%. These policies in support of domestic manufacturing are well-poised to help drive EV uptake.

The Indian Government is currently drafting new CO₂ emissions [standards](#) for cars, CAFE III (2027-2032) and CAFE IV (2033-2037), which have proposed WLTP CO₂ emission targets of 91.7 g CO₂/km and 70 g CO₂/km, respectively. This standard will be implemented with a super-credit mechanism, making it easier for OEMs to reach compliance through electric car sales rather than through sales of conventional cars and non-plug-in hybrids. Based on existing policy support

(excluding the latest CAFE III and IV proposals which are still at the consultation stage), sales of electric cars increase from 2% in 2024 to almost 15% in 2030 in the STEPS.

In October 2024, the government of India also adopted the [PM e-Bus Sewa-PSM Scheme](#) to support the roll-out of 38 000 electric buses across the country, with a budget of INR 34.4 billion (USD 394 million). When considered alongside the support from the PM E-DRIVE scheme, electric bus sales reach 25% in 2030 in the STEPS, up from less than 6% in 2024. Electrification of other heavy vehicles, namely freight trucks, is expected to proceed less quickly, due to greater price barriers. Electric truck sales reach around 2% in 2030 in the STEPS, which is similar to India's 2024 EV sales share for cars.

Across all vehicle modes, excluding 2/3Ws, EVs represent 1 in 8 vehicles sold in India in 2030 in the STEPS, up from less than 1 in 50 in 2024. When 2/3Ws are included, stated policies imply that the electrification rate increases to one in three vehicles sold by 2030.

EV sales in Southeast Asia approach 30% of all vehicle sales in 2030 under today's policy settings

Indonesia, Southeast Asia's second-largest car market, has introduced a range of policies to meet its ambitious EV [targets](#). One of the key incentives was the introduction in April 2023 of a VAT [discount](#) on EV sales, which is [continuing](#) in 2025. In addition, EV manufacturing and trade [policies](#) currently provide import duty exemptions for EVs made by manufacturers committing to establish domestic manufacturing facilities by 2026. Under stated policies, the electric car sales share reaches 25% by 2030, up from 9% in 2024. This translates into a stock of almost 1 million electric cars in 2030 in the STEPS, which is still less than half of the [government's target of 2 million](#). The country has also set the target of [13 million electric motorcycles](#) by 2030. Based on recent market trends, the EV share of 2/3W sales in Indonesia increases from less than 2% in 2024 to 30% in 2030. Despite this strong growth, the total stock of electric 2/3Ws is less than the government target for electric motorcycles.

Several other Southeast Asian countries have recently adopted manufacturing and trade policies to facilitate EV imports while also developing domestic EV manufacturing. In most of these countries, such policy developments are accompanied by measures to support EV uptake. In **Malaysia**, for example, the largest car market in the region in 2024, electric cars are exempt from import duties, registration and road taxes until the end of 2025, and until 2027 if locally built. **Thailand**, Southeast Asia's third-largest car market in 2024, implemented a set of measures called the [EV 3.5 Policy](#) to support the roll-out of electric passenger cars, pick-up trucks and motorcycles. This new scheme, adopted in

2024, is designed as the continuation of the previous EV 3.0 Policy, while at the same time giving BEV manufacturers more time to meet their production commitments under the 3.0 version to help avoid oversupply. The Thai government will establish new purchase subsidies and road tax exemptions until 2027 under the new framework, including some incentives also for hybrid vehicles, along with waivers on import duties for OEMs committing to produce EVs domestically. The **Philippines**, **Viet Nam** and **Singapore** have also adopted policies to reduce import [duties](#), exempt EVs from excise [taxes](#), or set up EV [mandates](#) to further support the adoption of EVs in the region.

The outlook for EV sales in Southeast Asia is bright, thanks to its emerging role as a manufacturing hub, and the existing set of manufacturing, trade and demand-side policies supporting the electrification of road transport. Under stated policies, electric car sales in Southeast Asia are likely to reach 25% of total car sales by 2030. Other vehicle modes are also expected to make significant strides in electrification, with electric 2/3Ws surpassing a 30% sales share and electric buses nearing 15%. Overall, across all vehicle segments, the EV sales share in Southeast Asia approaches 30% in 2030 in the STEPS.

Policy support in Latin America means electric bus sales could increase more than tenfold by 2030

Countries in Latin America have been increasing their policy support for EVs, especially since 2020. In particular, Brazil, Colombia and Chile stand out for passing legislation to promote EVs. This is important for the EV outlook in the region as together, these three countries represent almost half of Latin America's car and bus sales.

In 2024, **Brazil** approved the [MOVER programme](#), which incentivises private sector investment in the R&D and manufacturing of sustainable vehicle technologies including EVs. **Colombia** also has relevant legislation, particularly to encourage the electrification of public buses, including a [law](#) that requires cities with mass transportation systems to ensure that electric or zero-emission vehicle sales increase from 10% in 2025 to 100% in 2035. In 2024, the government also created the [Fund for the Promotion of Technological Advancement](#), which among other things will support electric LDV sales by covering the price differential with ICEVs. In 2024, new LDV [fuel economy standards](#) came into effect in **Chile**. These promote zero-emission vehicles by offering credit multipliers. Other countries in Latin America also offer policy support for EVs, mainly in the form of tax incentives.

Electric car sales in Latin America increased from 0.3% in 2020 to around 4% in 2024, and reach around 13% in 2030 in the STEPS. Latin America has also seen success in deploying electric buses, which is expected to continue: in 2030 in the STEPS, electric bus sales reach almost 14%, up from 2% in 2024.

Automakers' electrification announcements

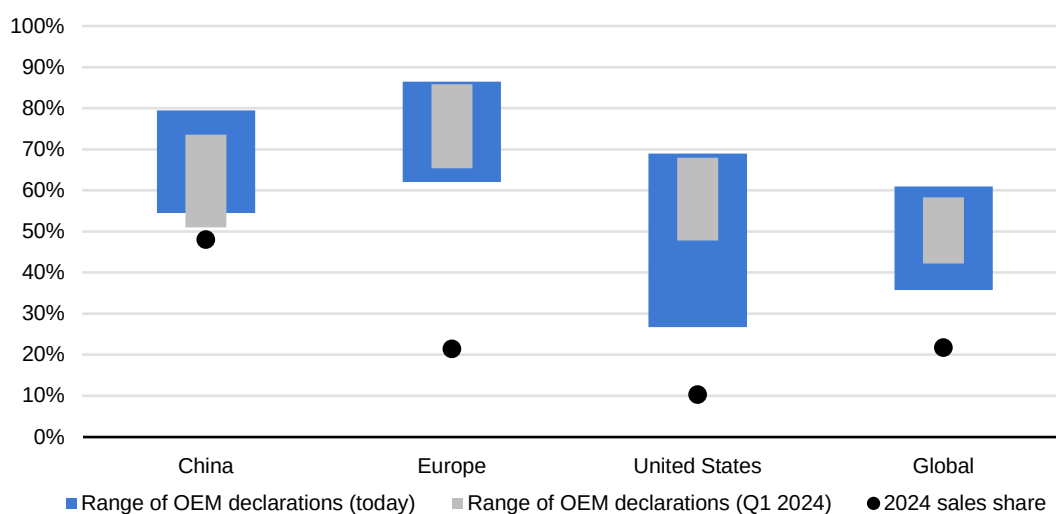
Near- and mid-term automaker electrification targets are increasingly uncertain

A number of automakers have scaled back their near-term targets for EVs over the past year, [citing](#) lower-than-expected consumer demand, and in the context of difficulties in [achieving profitability](#) with BEVs for many non-Chinese OEMs. Many, if not all, had previously set those targets with a degree of flexibility dependent on market conditions. The shifting policy landscape in some markets further increases uncertainty in automaker electrification targets out to 2030, though the outlook for electric car sales remains robust.

General Motors (GM) – the best-selling carmaker in the United States – missed its goal of producing and wholesaling 200 000 EVs in North America in 2024 by [about 5%](#). The company expects to produce up to 300 000 EVs in 2025, and is [no longer reiterating](#) its previous target of reaching an annual production capacity of 1 million EVs by the end of 2025. Similarly, Tesla – the best-selling electric carmaker in the United States – [dropped](#) the goal of selling 20 million cars per year by 2030 from its 2023 annual impact report, despite this target having been included in consecutive previous reports. The uncertainty around whether Tesla will still aim to sell 20 million electric cars worldwide in 2030 has a significant impact on the range of OEM electrification targets in all of the major markets.

In 2021, Ford, GM and Stellantis released a [joint statement](#) announcing their aspiration to achieve sales of 40-50% electric or fuel cell electric cars in the United States by 2030, in line with the Biden administration's target. Given the change of administration in the United States, the future commitment to these targets is unclear. As such, the range of OEM declarations for electric car sales in the United States in 2030 now stretches from 70% electric car sales in 2030 to less than 30%; a year ago the lower end of the range of OEM declarations in the United States was around 50%. In spite of this, even if only the lower end of the OEM target range were to be achieved, the electric car sales share in the United States would almost triple by 2030.

Range of electric car sales shares based on automaker electrification targets, 2030



IEA. CC BY 4.0.

Notes: OEM = original equipment manufacturer. Q1 2024 OEM declarations reflect the interpretation of automaker targets as presented in the [Global EV Outlook 2024](#). The range today reflects OEM announcements as of the end of Q1 2025. The relative market share of OEMs is held constant unless the OEM has EV volume targets rather than sales share targets.

Sources: IEA analysis based on company announcements and data from EV Volumes and Marklines.

With regards to the European market, Ford has [abandoned](#) its goal to shift entirely to electric sales in Europe by 2030, though in 2024 Ford was responsible for less than 5% of car sales in the region. Volvo Cars, also representing less than 5% of car sales in Europe, has also [scaled down](#) its 2030 all-electric target, allowing for up to 10% of its sales to be hybrids. Similarly, Renault had previously aimed for 100% of its car sales to be electric in Europe by 2030, but in 2024 its CEO announced that a [two-pronged approach](#) of selling both ICE and electric cars will continue for the next decade. Nevertheless, the range of OEM electrification targets for Europe remains the highest of the major EV markets, reaching from over 60% to around 85% of car sales in 2030.

In contrast, as Chinese EV sales remained strong over 2024, BYD [surpassed](#) its 2024 sales target, which had already been increased from 3.6 million new energy vehicles (i.e. EVs and FCEVs) to 4 million. In total, BYD represented about 15% of car sales in China; all-electric car brands (including Tesla, Li Auto, NIO and others) together represented one-quarter of car sales in China in 2024. As a result of the growing success of all-electric car brands, the EV sales shares in China in 2030 based on OEM targets has increased, despite there being no new targets for 2030. The range of OEM declarations for 2030 would imply a 55-80% electric car sales share.

While Honda has not scaled back its long-term zero-emission vehicle targets (100% of sales by 2040), it has announced the aim to double hybrid car sales by 2030. Indian OEM [Tata](#) has reduced its 2030 BEV sales target from 50% to 30%.

At the global level, the range of uncertainty in electric car sales in 2030 projected in automakers' declarations has grown over the past year, meaning that the increase in global sales as envisaged by their targets now ranges from 35-60%. However, achieving even the lower end of this range would mean that the number of electric car sales in 2030 would be approximately double that of 2024.

6. Electric vehicle charging

Charging electric light-duty vehicles

Public chargers have doubled since 2022 to reach more than 5 million

Access to public charging points is key to supporting mass adoption

Home charging remains the most popular way to charge for EV owners. However, more public chargers are needed to support mass adoption of EVs among segments of the population without access to home chargers.

In 2024, more than 1.3 million public charging points were added to the global stock, representing an increase of more than 30% compared to the previous year. Just the charging points added in 2024 were approximately equal to the total number of points available in 2020. About two-thirds of the growth in public chargers since 2020 has occurred in **China**, which now has about 65% of the charging and 60% of the electric light-duty vehicle stock globally.

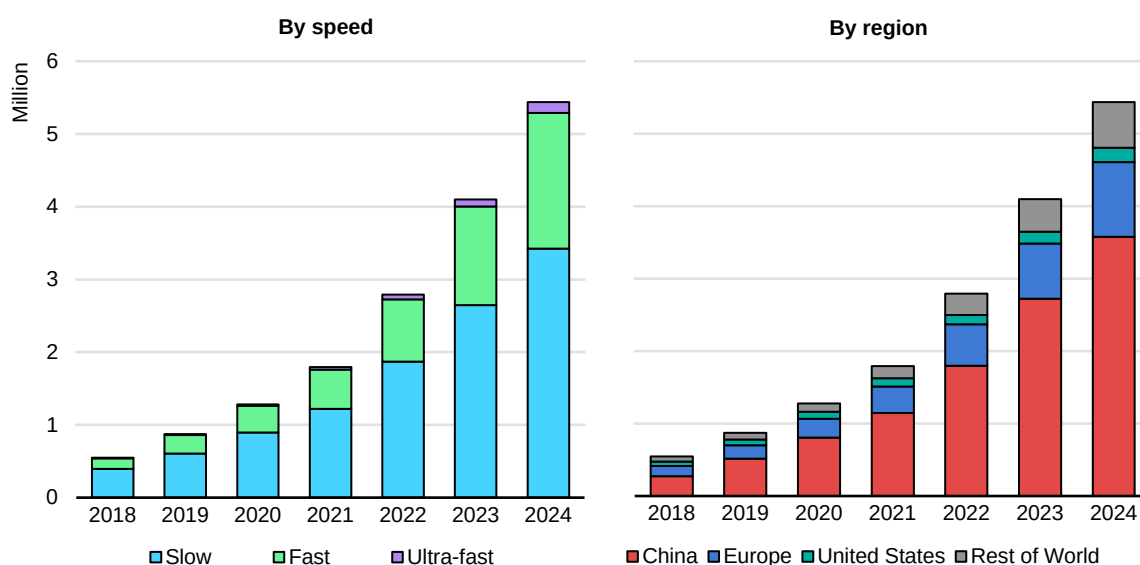
In **Europe**, the number of public charging points grew more than 35% in 2024 compared to 2023, to reach just over 1 million. However, there are significant variations across countries due to differing rates of EV adoption and charging infrastructure development. Within the **European Union**, 11 out of 27 countries saw their public stock of charging points increase by more than 50% in 2024 compared to the previous year. At the end of 2024, the **Netherlands** had the largest national charging network in Europe, with over 180 000 public charging points, followed by Germany (160 000) and France (155 000). In **Austria**, 8 000 public charging points were added in 2024, most of which were supported by a [subsidy](#) that ended at the beginning of 2025.

Installation of public charging points across the European Union is expected to increase as a result of the [Alternative Fuels Infrastructure Regulation](#) (AFIR), which mandates the installation of fast-charging stations for cars and vans of at least 150 kW every 60 km along the TEN-T core road network by 2025. Each station must offer a minimum total power output of 400 kW, increasing to 600 kW by the end of 2027. In addition, roll-out of private charging at residential and commercial buildings is covered under the revised [EU Energy Performance in Buildings Directive](#), which establishes criteria for pre-cabling to prevent the future need to retrofit parking infrastructure, which can be [costly](#).

The **United States** increased its charging stock by 20% in 2024 to just under 200 000 public charging points. The [National EV Infrastructure Program](#), part of the Bipartisan Infrastructure Law that was passed in 2021, allocated USD 5 billion to fund fast chargers along corridors, although by the end of 2024 only around [USD 30 million](#) had been spent on charging points that are now in operation. In January 2025, [Executive Order 14154](#) paused the disbursement of these funds for a review of the processes, policies and programmes associated with grant selections, making future disbursements of the remaining unspent funds uncertain.

Policy efforts in **India** continue to support charging accessibility, with about 40 000 new public chargers installed in 2024. In October 2024, [INR 20 billion](#) (USD 240 million) was allocated to charging infrastructure through the PM E-DRIVE scheme, with a focus on urban centres and heavily-used transport corridors. However, the Indian government has also introduced an EV policy that [caps the investment in charging infrastructure eligible](#) for tariff relief, potentially impacting automakers' plans to invest in EV charging networks.

Global stock of public charging points by speed and region, 2018-2024



IEA. CC BY 4.0.

Notes: Chargers less than or equal to 22 kW are classified as slow, chargers greater than 22 kW and up to 150 kW as fast, and 150 kW and above as ultra-fast.

Sources: IEA analysis based on country submissions and data from EV Volumes and [EAFO](#).

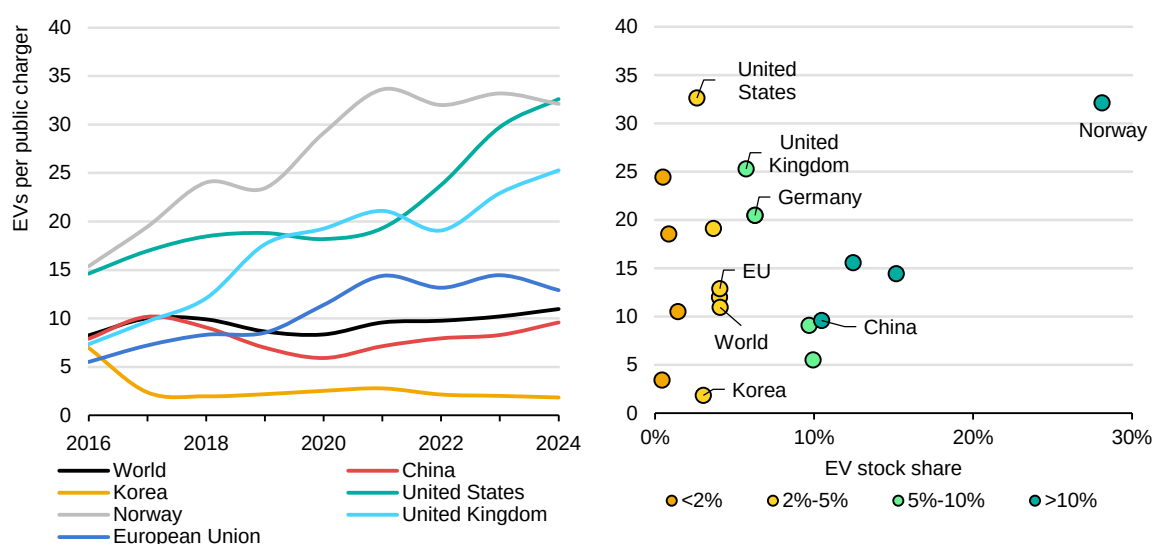
Brazil's charging infrastructure has expanded at speed. By early December 2024, there were over [12 000](#) public charging points across the country. Public charging networks have also experienced rapid expansion in other key emerging markets, reflecting strong policy support and investment in infrastructure. Public charging points have increased by 60% in **Colombia** and by 20% in **Mexico** since 2022.

Similarly, thanks to a mix of government initiatives and private sector collaboration, there are now over 24 000 chargers installed across **Indonesia, Thailand, Malaysia** and **Viet Nam**, 9 times more than in 2022.

Variation in ratio of EVs per public charger reflects differences in market maturity and population demographics

One way to think about public charging coverage is in terms of the number of public charging points compared to the stock of electric light-duty vehicles those points are meant to serve. **China** and the **European Union** have maintained a steady pace of charger deployment compared to the number of EVs on the road, though at different levels. There is now more than 1 public charger for every 10 electric cars in China. On average, the European Union has 1 charger for every 13 electric cars – a decrease of more than 10% compared to 2023.

Electric light-duty vehicles per public charging point in selected regions, 2016-2024 (left) and ratio compared to electric vehicle stock share in selected regions, 2024 (right)



IEA. CC BY 4.0.

Notes: EU = European Union; EV = electric vehicle. Historic trends in electric light-duty vehicle stock and public charging infrastructure by country can be interactively explored using the [Global EV Data Explorer](#). The figure on the right-hand side shows selected regions as dots, with the over 10% group comprising China, Denmark, Norway and Sweden, the 5-10% group Belgium, Germany, the Netherlands, and the United Kingdom; the 2-5% group: European Union (average), France, Korea, the United States and the World average; and the group below 2%: India, Indonesia, Italy and Japan.

Sources: IEA analysis based on country submissions, EV Volumes, BNEF, [EAFO](#), and [US AFDC](#).

However, demand for public charging points also differs based on driver location and behaviour. In China's densely populated cities, many drivers rely on public charging points, whereas in Europe, access to home chargers is far higher. The combined stock of the top [15 cities](#) by public charger stock in China covers more than 50% of the national stock, compared to a share of 25% in Europe. The types of housing typically available (apartment, terrace, detached, etc.) can also play an

important role in shaping the need for public charging access. For example, Germany and the United Kingdom both have a similar electric car stock share, but the United Kingdom has 60% more electric cars per public charger. In Germany, [more than 60% of people live in](#) apartments or flats; whereas in England and Wales, [fewer than 25%](#) of people do, meaning it may be easier to install private charging.

In the early stages of electrification, greater availability of public EV charging points can encourage adoption. However, as EV adoption increases, and as charging speeds become faster and battery ranges improve, the number of charger points per vehicle can decrease as the system is optimised.

Fast charging continues to expand, with ultra-fast charging having more than doubled in Europe since 2022

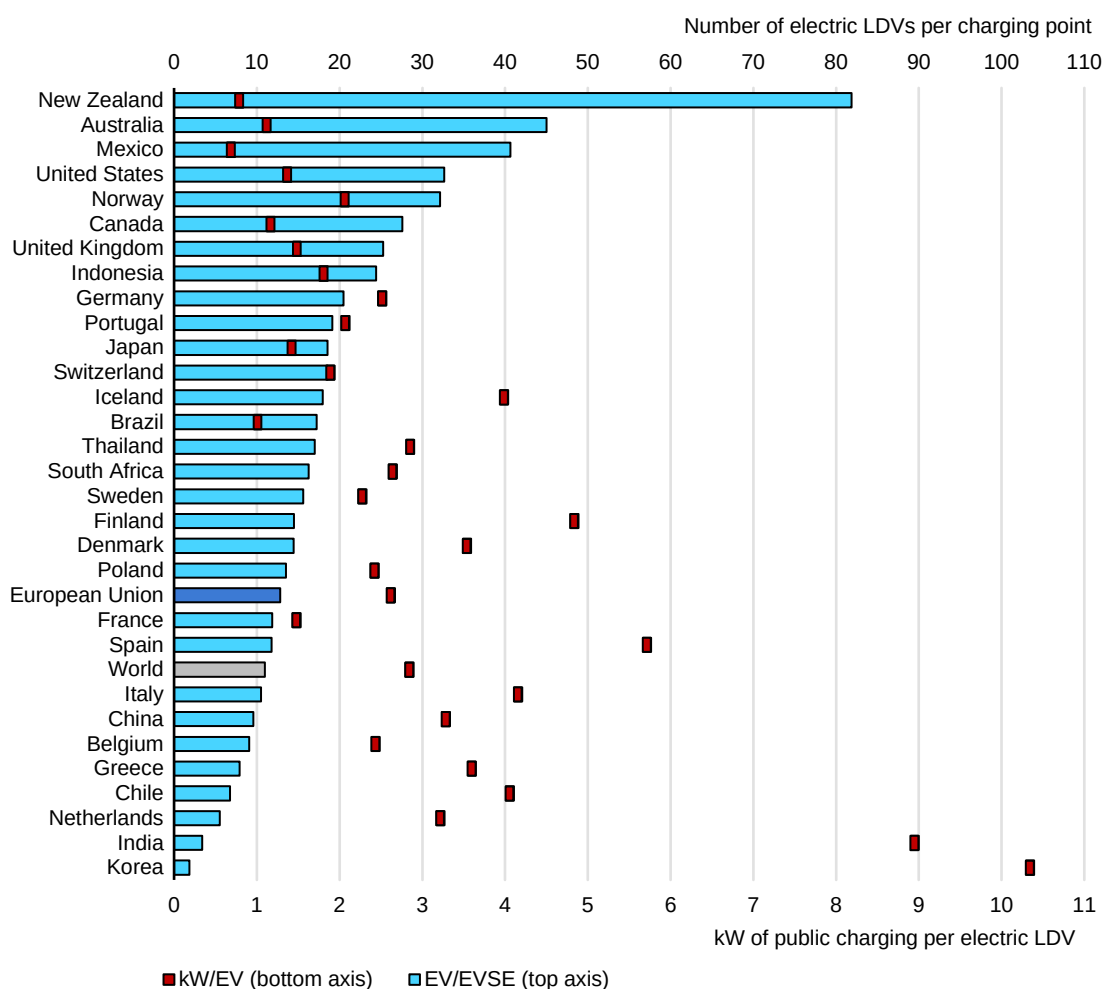
In addition to coverage, the capacity of public chargers can serve as an indication of sufficiency. Fast and ultra-fast public charging points can deliver more energy per day than slow chargers and thus serve a higher number of vehicles. In 2024, the global stock of fast chargers (with a power output higher than 22 kW and lower than 150 kW) reached 2 million, and ultra-fast chargers – capable of delivering 150 kW or above – growing by over 50% in 2024 and now accounting for nearly 10% of all fast chargers. Falling costs have played a role in this shift, with the price of ultra-fast chargers falling by [20%](#) between 2022 and 2024.

China remained the largest player in fast charging deployment last year, responsible for 80% of the global growth, with the number of fast chargers surging from 1.2 million in 2023 to 1.6 million in 2024. Today, the estimated public charging capacity per electric LDV in China is over 3 kW. In comparison, the **United States** expanded its total fast charger stock (including ultra-fast) from 40 000 in 2023 to over 50 000 in 2024, growing at a similar rate to in China. At the end of 2024, there was less than 1.5 kW of public charging capacity available in the United States per electric LDV.

Meanwhile, the **European Union** expanded its network of fast chargers (excluding ultra-fast) nearly 50% from 2023 to reach 71 000 in 2024, and has an average public charging capacity of 2.6 kW per electric LDV. It also saw strong deployment of ultra-fast charging points in 2024, increasing by 60% compared to 2023 to reach over 77 000 chargers. Denmark saw its stock of ultra-fast chargers more than double in 2024, and in France, Finland and Germany the stock increased by between 70-95%. Further expansions are also being planned, for example in France, where ["Charge France"](#), a charge point operator association established in 2025, committed to investing EUR 4 billion to expand the national stock of ultra-fast charging points from over 17 000 today to 40 000 by 2028.

Of the ultra-fast chargers in the European Union, about 20% deliver a power of 350 kW and above. Today, [only a few](#) high-end electric cars are capable of charging at this speed, but charging point operators such as [FastNed](#) and [Iberdrola and BP Pulse](#) are deploying these stations in anticipation of future demand. In 2024 this higher segment of ultra-fast chargers almost doubled compared to 2023.

Number of electric light-duty vehicles per public charging point and kilowatt per electric light-duty vehicle, 2024



IEA. CC BY 4.0.

Notes: EV = electric vehicle; EVSE = electric vehicle supply equipment; LDV = light-duty vehicle. Kilowatts per EV are estimated assuming 15 kW for slow and 50 kW for fast chargers and 150 kW for ultra-fast chargers. For countries in Europe, average power per EVSE was used per power group: slow (lower than 22 kW), fast (between 22 kW and 150 kW) and ultra-fast (higher than 150 kW) and multiplied with reported stock of chargers. Official national statistics, which rely on more granular data, might differ from these values.

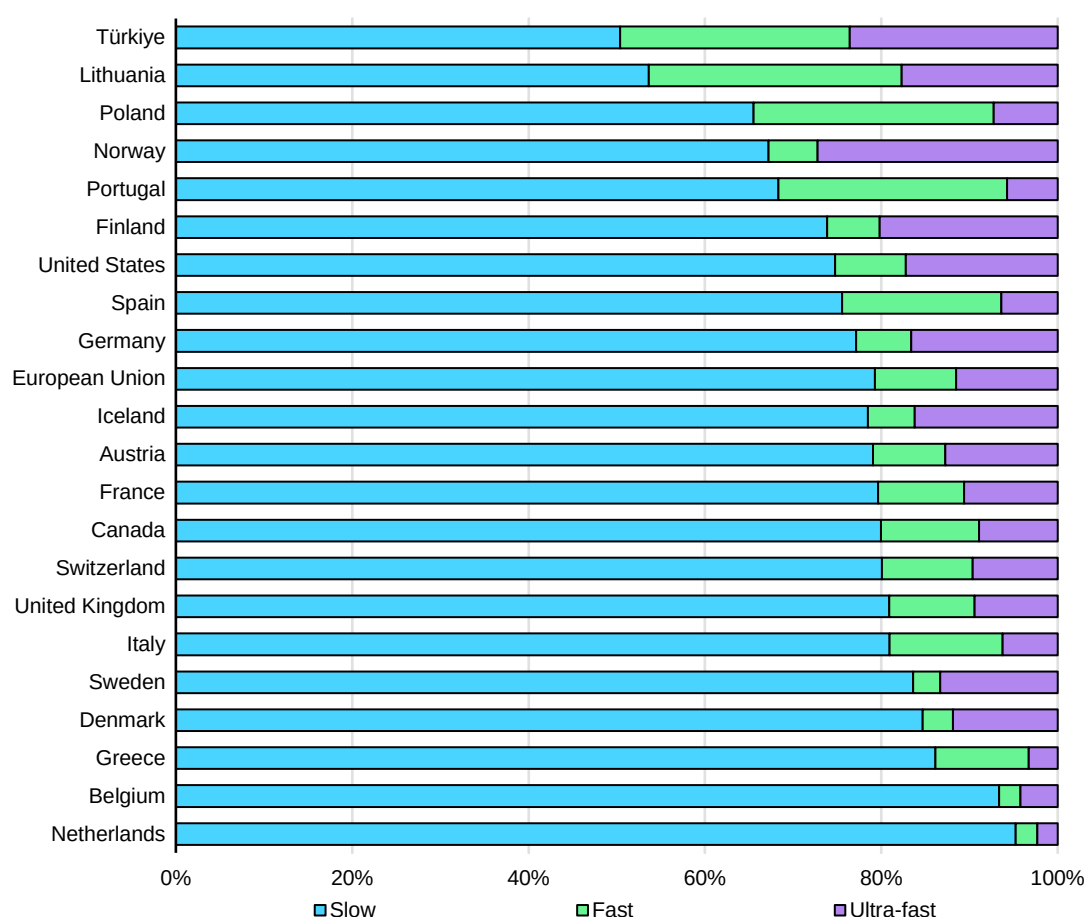
Sources: IEA analysis based on BNEF, EV Volumes, [EAFU](#) and Eco-Movement, [US AFDC](#).

Ultra-fast charging infrastructure projects are also underway in **Chinese** cities. Beijing aims to build [1 000 ultra-fast charging stations](#) by the end of 2025, and Chongqing to deploy [4 000](#) additional ultra-fast chargers by the end of 2025.

These regional plans also align with XPeng and Volkswagen's plans to roll out [20 000 ultra-fast chargers](#) across more than 400 Chinese cities.

Elsewhere, **Korea** has seen rapid growth in its fast charger stock (including ultra-fast), rising from 34 000 in 2023 to 47 000 in 2024. In 2025, authorities plan to deploy [4 400](#) new fast chargers in high demand areas. Korea's [total budget](#) for enhancing charging infrastructure was raised by 40% compared to 2024 to KRW 620 billion (Korean won) (USD 425 million), with 60% of the assigned budget targeting fast chargers, and the remainder dedicated to slow smart-charging installations. In **India**, three major government-owned oil marketing companies built nearly 8 000 fast-charging points over the course of 2023 and 2024, funded by the FAME Phase II [scheme](#).

Proportion of slow, fast and ultra-fast public chargers in selected countries, 2024



IEA. CC BY 4.0.

Notes: Chargers less than or equal to 22 kW are defined as slow, chargers between 22 kW and 150 kW are fast, and ultra-fast chargers are those of 150 kW or more.

Sources: IEA analysis based on EAFO and US AFDC.

Advances in battery technology for electric cars can make charging competitive with refuelling time, if charging infrastructure can keep up

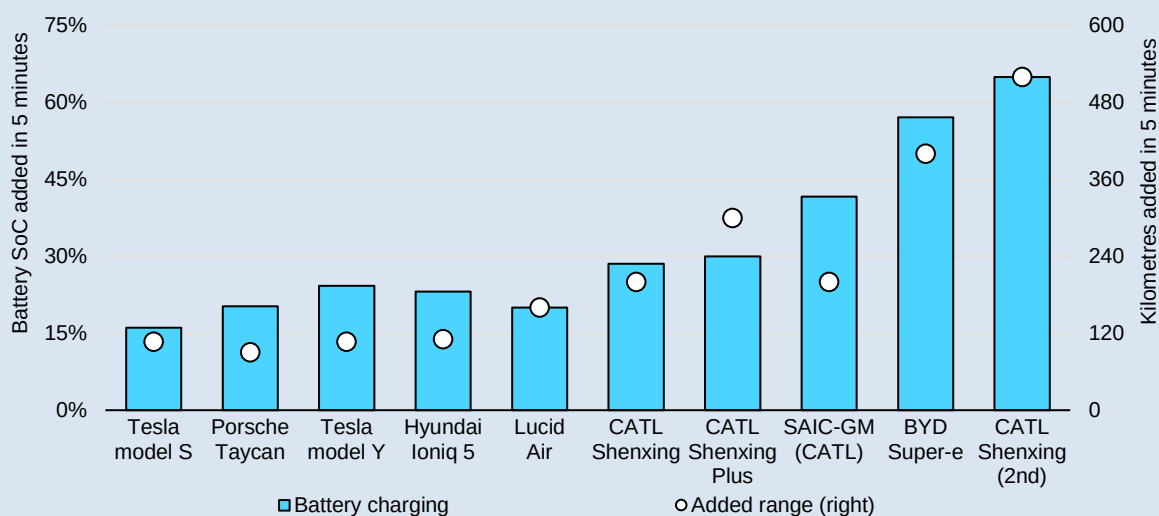
EV owners report that [charging speed](#) is their most important consideration when using public chargers. Safety concerns relating to EV battery technology have long been a limiting factor in reaching faster charging, but recent innovations are now reshaping the fast-charging landscape.

During charging, lithium ions are released from the cathode to the anode. If the process is too slow compared to the desired charging speed, lithium can accumulate on the anode surface, forming dendrites – needle-like structures that can pierce the battery, potentially causing short circuits and uncontrolled fires. Recently, however, some battery manufacturers have largely succeeded in addressing this through advanced anode designs, such as [multi-gradient layered structures](#), which accelerate lithium uptake.

In 2023, CATL launched the [Shenxing](#) battery, which is able to charge about 30% of the battery in just 5 minutes, providing 200 km of additional range. This was further improved in 2024, when they released a battery offering similar energy density but [faster](#) charging speeds in collaboration with SAIC-GM – allowing to recharge over 40% of the battery capacity in 5 minutes – as well as a battery with the same charging speed (30% in 5 minutes) but increased [energy](#) density, providing 300 km of additional range in 5 minutes. For comparison, a typical [Tesla supercharger](#) can offer about 100 km of additional range during the same time.

In March 2025, BYD set a [new benchmark](#) with its [Super-e platform](#), which is claimed to deliver around 400 km of range in 5 minutes. This leap was [made possible](#) by next-generation silicon carbide power chips, all-liquid-cooling, and a 1 000 V architecture, which allows for coupling with 1 MW charging. Just one month later, CATL announced the second generation of its Shenxing battery, offering even higher charging speeds. Megawatt charging was previously limited to heavy-duty vehicles, where the energy was distributed across battery packs roughly ten times larger than those in passenger cars. Now, advances in battery technology and charging platforms are bringing this capability to the passenger car market, with the [first models](#) already on sale in China.

Maximum share of battery capacity charged and electric range added in 5 minutes by electric car model or battery technology



IEA. CC BY 4.0.

Notes: SoC = state of charge. Battery SoC added indicates how much the battery is recharged starting from a low SoC (20%). For example, adding 30% SoC means charging the battery from 20% to 50%. The additional range is calculated by multiplying the manufacturer's stated electric range by the proportion of the battery that can be recharged in 5 minutes under optimal conditions. Tesla model Y and S are assumed to be charged through a [third generation](#) supercharger.

Sources: IEA analysis based on data from [EV Volumes](#), [Tesla](#), [Porsche](#), [Hyundai](#), [Lucid](#), [CATL](#), [GM authority](#), and [BYD](#).

The full realisation of these advantages, however, [hinges](#) on deploying ultra-high-power charging infrastructure. [Megawatt chargers](#) impose significant loads on grids, often requiring [upgrades](#) that could significantly slow down or limit deployment, and are more expensive than fast chargers, which could result in higher charging prices for consumers. Pairing these chargers with battery storage to alleviate peak demand and optimise grid usage might offer a pathway to accelerate their roll-out. In recognition of the infrastructural challenge, BYD – together with its Super-e platform – has announced plans to deploy 4 000 megawatt chargers supported by battery storage in China. This evolution would also strengthen the interdependencies between the two biggest battery markets – EV batteries and battery storage – potentially increasing the competitive advantage of producers manufacturing both, such as BYD and CATL.

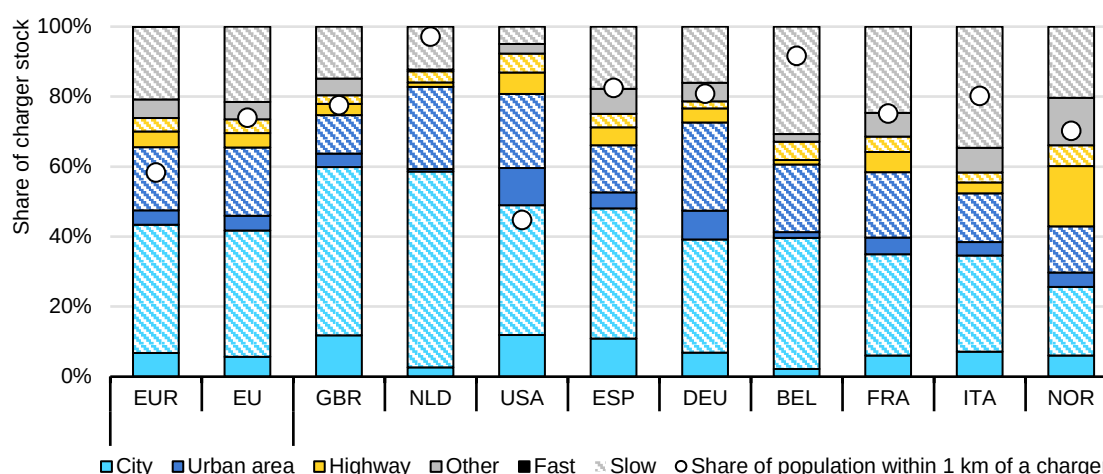
For most consumers, reliable [fast charger networks](#) capable of recharging a vehicle in 15-20 minutes may be sufficient for long-distance travel. However, the ability to charge EVs in a timeframe comparable to refuelling conventional cars could further accelerate consumer adoption.

The location and speed of public charging stations reflect typical usage

Most public chargers are slow chargers in urban areas but highway chargers account for a larger share of capacity

Individual countries and cities have taken different approaches to public charging station deployment, based on the distribution of population, availability of home charging, and road networks, although there are some commonalities. Currently, in Europe and the United States, more than two-thirds of chargers are located in urban areas. In the European Union, deployment has broadly followed housing patterns, and over 70% of the population now lives within 1 kilometre of a charging point. In the United States, which has a lower population density, less than half of the population lives within 1 kilometre of a charger.

Type and location of public charging in selected regions and countries and the share of population living within 1 kilometre of a charger, 2024



IEA. CC BY 4.0.

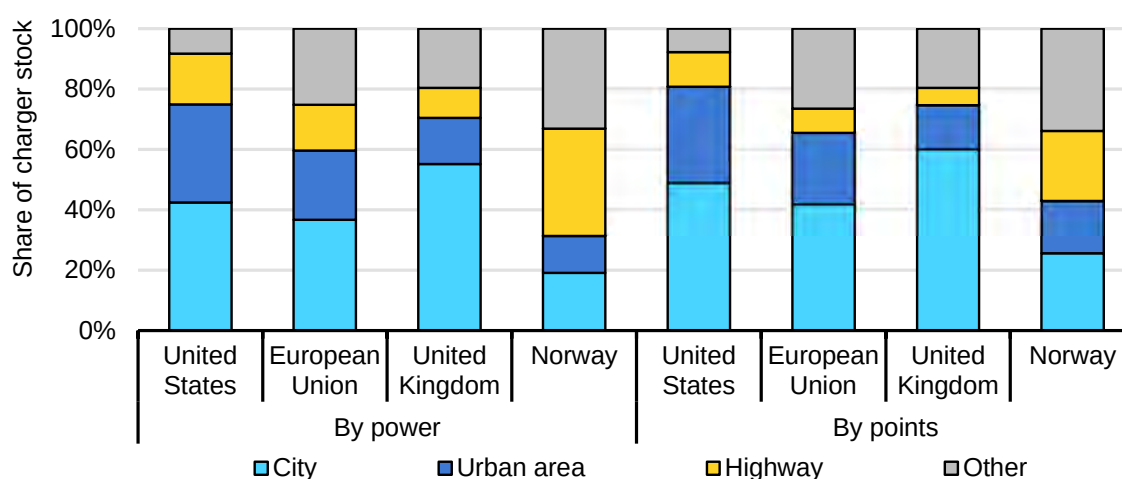
Notes: EUR = Europe; EU = European Union; GBR = United Kingdom; NLD = Netherlands; USA = United States; ESP = Spain; DEU = Germany; BEL = Belgium; FRA = France; ITA = Italy; NOR: Norway. Solid colours represent fast chargers and hatched colours slow chargers. Chargers less than or equal to 22 kW are defined as slow; fast chargers are over 22 kW.

Sources: IEA analysis based on US AFDC, EAFO, Eco-Movement. Urban areas for Europe are taken from the [Functional Urban Areas](#) of 2020 and consists of the [city and the commuting zone](#), urban areas for the United States are the [Census Populated Place Areas](#) from the US Energy Atlas.

The public charging infrastructure in cities and urban areas consists mainly of slow chargers (less than or equal to 22 kW), which was the most widely adopted technology until relatively recently. Only 15% of the urban public chargers in Europe are rated over 22 kW. This share is slightly higher in the United States, where nearly 30% of urban public chargers are fast. While deploying fast chargers can help to serve more EVs per charging point each day, limited available network capacity in city centres or urban areas can present a hurdle.

On average, in the United States and Europe, between 4% and 6% of public charging points are positioned along highways and have at least 22 kW rate power. Norway is an exception, with nearly 20% of its charger stock being fast chargers positioned next to highways, as a result of a 2016 target to install [fast-charging stations at least every 50 km](#) on major roads to support long-distance trips. When considering charging power rather than points, the share becomes even larger, with 35% of public charging capacity being located along the highway in Norway. Across all countries considered, the share of highway chargers in terms of total power is higher than by charging point stock, as highway chargers tend to be the fastest.

Location of public charging stock by capacity and number of charging points in selected regions and countries, 2024



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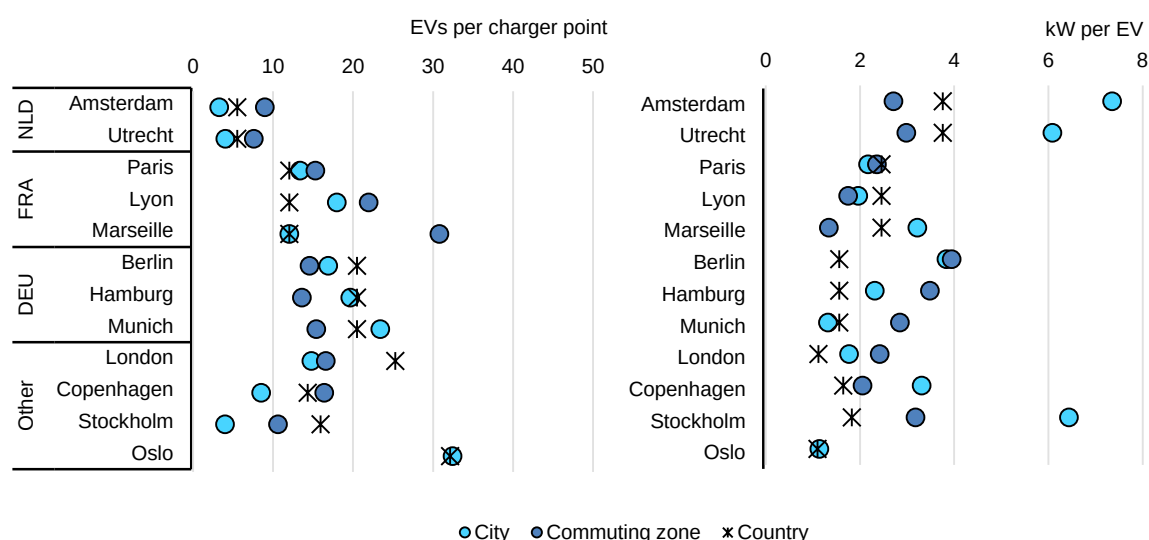
Sources: IEA analysis based on US AFDC, EAFO and Eco-Movement. Urban areas for Europe are taken from the [Functional Urban Areas](#) of 2020 and consists of the [city and the commuting zone](#). Urban areas for the United States are the Census [Populated Place Areas](#) from the US Energy Atlas.

Major European cities typically have more chargers per EV than surrounding areas

The different characteristics of roads, buildings and parking spaces in different cities can affect the strategy for deploying public chargers. In cities such as Amsterdam, where residential and office buildings often have less private parking, more public chargers need to be available. Public chargers in cities must also serve taxis and delivery vehicles, for which overnight charging is not sufficient, as well as other visitors to the city that may need to charge during the day. The split between overnight charging by residents and opportunity charging for other vehicles will affect the speed and distribution of public charges, as reflected by the charging capacity per EV in the stock.

European cities have different levels of electric car adoption. Scandinavian cities such as Oslo, Stockholm and Copenhagen have the highest share of electric cars in their fleet, with 55%, 35% and 20% of the cars being electric. As the most mature market, Oslo also has one of the highest ratios of EVs per charger (over 30) and the lowest capacity available per EV (around 1 kW). Both Copenhagen and Stockholm have less than 10 EVs per public charging point in the city – lower than their national average, which indicates that expanding coverage in cities has been prioritised ahead of rural areas around highways.

Charger to electric vehicle ratio and kW per electric vehicle for selected cities and their commuting zones, and country averages, 2024



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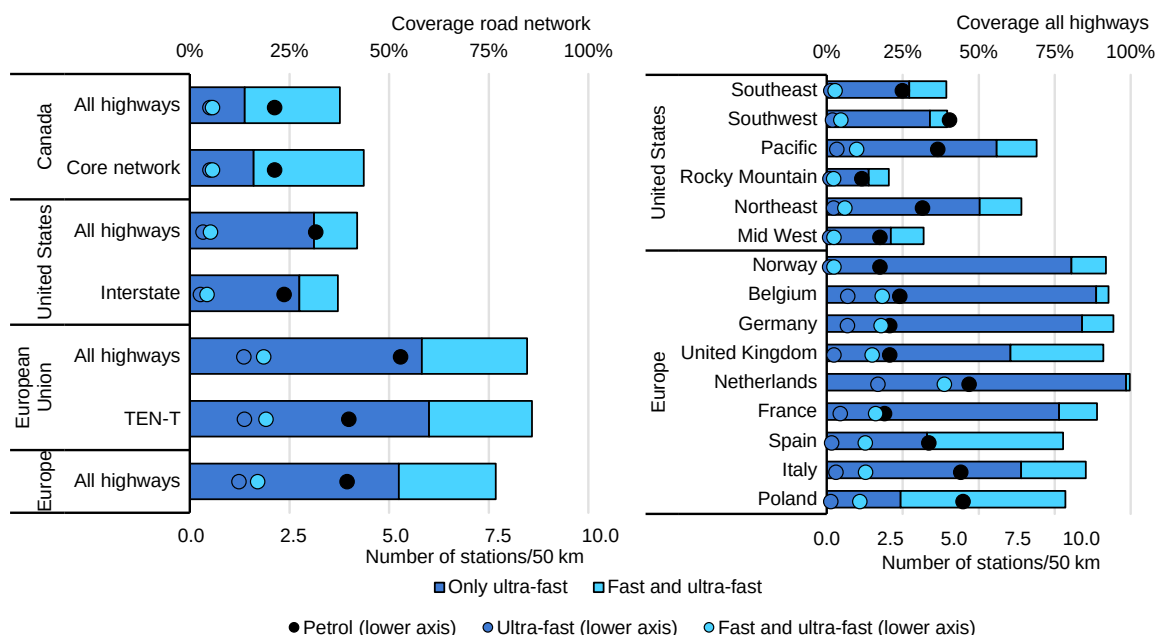
Notes: NLD: Netherlands; DEU: Germany; FRA: France. Data on chargers in Oslo's commuting zone are not available.
 Sources: IEA analysis based on national statistics, EAFO and Eco-Movement. City EV stock: NLD: [Atlas van de auto](#); FRA: [AAA Data](#); DEU: [KBA](#); London: [Department for Transport and Driver and Vehicle Licensing Agency](#); Stockholm: [TRAFA](#); Oslo: [SSB](#); Copenhagen: [SDG Statistikbank](#); number and capacity per city and commuting zone was determined using point location of charger database of Eco-Movement, consulted February 2025.

Cities in the Netherlands, Germany and France have a lower share of electric cars in the fleet; across Amsterdam, Utrecht, Paris, Berlin and Munich, between 6% and 13% of cars are electric. In terms of both coverage and capacity, the Dutch cities perform better compared to the national and urban averages. In particular, the gap between the city capacity per EV and the national average indicate that these cities have placed greater emphasis on faster chargers and installing them in a higher density compared to other areas outside the city.

European highways have more charger coverage than highways in the United States

At the end of 2024, over 75% of the European highway network had chargers at most 50 km apart, whereas only 35% of the US interstate highway system had the same level of coverage. Within Europe, coverage is varied: For example, in the Netherlands, Belgium, Norway, Germany and France, over 90% of the highway network has a charging point every 50 km, while in Spain and Poland the share is below 80%. Similarly, deployment in the United States varies across regions. In the Pacific region (e.g. California, Oregon and Washington), which has the largest share of EV stock, 70% of the highways have charging infrastructure every 50 km, but in the centre of the country that share is between 20% and 30%.

Percentage of highways that are covered by a fast or ultra-fast charger in selected markets and road networks and number of chargers and petrol stations per 50 km of highway, 2024



IEA. CC BY 4.0.

Notes: TEN-T = [Trans-European Transport Network](#). Chargers between 22 kW and 150 kW are classified as fast, and ultra-fast chargers are those of 150 kW or more. For regional groupings for the United States see [Annex B](#). Only chargers within a radius of 150 metres of the highway are included; stations with less than 4 charging points are excluded. Coverage is calculated by setting a radius of 25 km around each charging point, so actual driving distance between two charging points likely exceeds 50 km based on the curvature of the road and the routing. To determine the number of stations on the bottom axis all charging points within 500 metres of each other are considered as one station.

Sources: IEA analysis based on [US AFDC](#), EAFO and Eco-Movement. Existing and planned TEN-T highways roads were taken as depicted in [TENtec viewer](#), other highways for Europe are taken from [Esri](#) filtered on attribute "Highway". The Interstate highway network can be found on the [National Highway System Map](#) provided by the Federal Highway Administration. North American highways other than the interstate network are taken from the [National Transportation Atlas Databases](#) for the United States, whereas the highway system of Canada is taken from [Transport Canada](#). Location of petrol stations was taken from [Open Street Maps](#) using amenity "fuel"; points within 150 metres of each other were considered as one petrol station.

Ultra-fast charging (150 kW and above) allows the most direct comparison with a conventional highway pit stop, where charging times of 15 minutes can provide an additional 150 km of driving range.¹ For long trips on interstate or international corridors, EV drivers may prefer a longer break, meaning fast charging at rates between 22 kW and 150 kW may also be an attractive option. If fast chargers are also taken into account, the charging coverage in the European Union increases, with an additional 25% of the roads having a fast charger at least every 50 km. In the United States, the share of the interstate road network covered by a charging station also increases from nearly 30%, when considering ultra-fast charging exclusively, to nearly 40% when also including fast charging.

Despite the high charging infrastructure coverage along European roads, the number of fast-charging stations along highways remains significantly lower than that of petrol stations. Ensuring a denser charging network would help to address range anxiety and help instil confidence in EV adoption by making charging as convenient and reassuring as conventional refuelling. This would allow for more flexibility in planning routes around charging stops and help address worst-case scenarios, such as unexpected detours, traffic delays, or extreme weather conditions.

Public charging does not always equal accessible charging

About 20% of public chargers in Europe are in fact “semi-public”, meaning that access is limited to part of the population, such as chargers provided by hotels or supermarkets that are only accessible to customers. Such chargers may also have physical barriers and more limited hours, which degrades charging access and experience.

Technical barriers can also hinder ease of use, even for fully public charging stations, as can occur with incompatible plug types (e.g. Type 2, Combined Charging System, CHAdeMO). Other factors, such as the payment system or (in the case of Tesla chargers), the brand of the vehicle, can also limit the usability of charging infrastructure, reducing overall accessibility. Standardisation, in combination with access to reliable data on the availability and pricing of charging stations, will therefore be important for making public charging infrastructure more accessible.

¹ This estimate assumes a fuel economy of 20 kWh/100 km and a minimum charging level of 20%. For reference, the fuel economy of the Tesla Model X is rated at [22.5 kWh/100 km](#)

Light-duty vehicle charging outlook

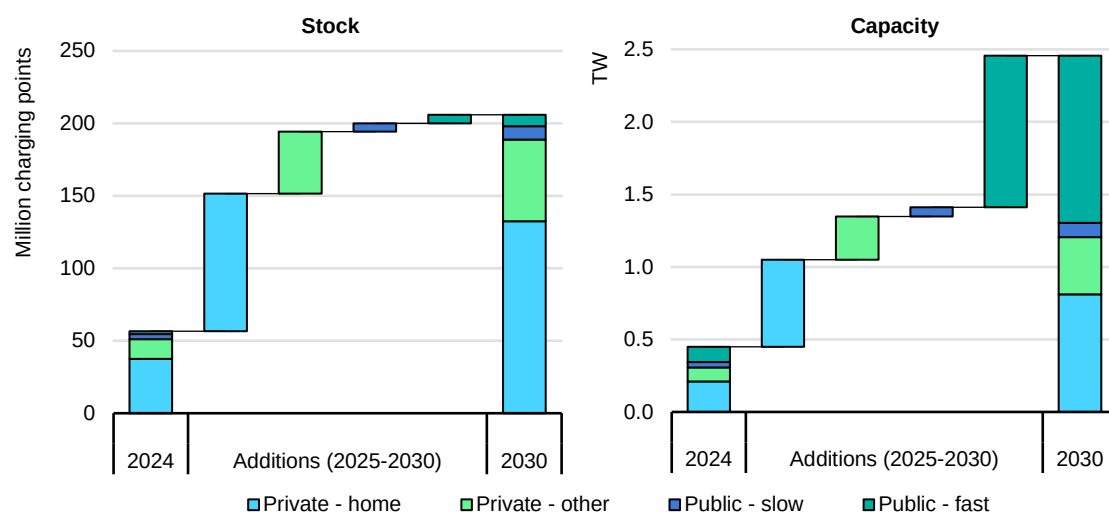
Public charging capacity for light-duty EVs grows almost ninefold to 2030

In general, early adopters of electric cars have tended to have higher rates of access to home charging than the broader population. Even though electric LDVs represent 15% of the global stock in 2030 in the STEPS – which could be considered as moving past the early-adopter phase – home charging is expected to remain the [preferred way](#) to charge an EV when available, given the affordability and convenience. Charging availability at other private locations, such as at workplaces, and public charging, will also support more widespread adoption of EVs, especially among populations without access to home charging, or for travelling long distances. In the STEPS, around 150 million charging points are added from 2025 to the end of 2030, with almost two-thirds of those being home chargers, 30% other private chargers, and the remaining 8% public charging points.

The build-out of public charging points in the STEPS is intended to reflect the number required to serve the stock of electric LDVs projected in the scenario. As such, the charging projections are based on the policies and market trends driving the vehicle projections as opposed to simply matching charging-related policies and regulations. The charging point projections do, however, account for regional trends, such as the historical evolution of the number of charging points per EV, the share and capacity of public fast chargers, and access to home and other private charging. Generally, as EV markets mature, optimisation of the public charging network is expected to improve, meaning that utilisation can increase with no negative effect on user experience. In line with this, in the STEPS, the number of electric LDVs per public charging point worldwide increases from about 11 in 2024 to around 14 in 2030.

The number of charging points available constitutes just one metric of coverage; the installed charging capacity is also important. Public fast chargers, with their higher charging capacity, are able to provide more energy and thus serve more EVs per day than slow chargers. Over half of the charging capacity installed to serve electric LDVs between 2025 and the end of 2030 in the STEPS takes the form of fast public chargers. That means that the public fast charging capacity increases more than tenfold by 2030, while private charging capacity increases less than fourfold.

Global light-duty vehicle charger stock and capacity in the Stated Policies Scenario, 2024-2030

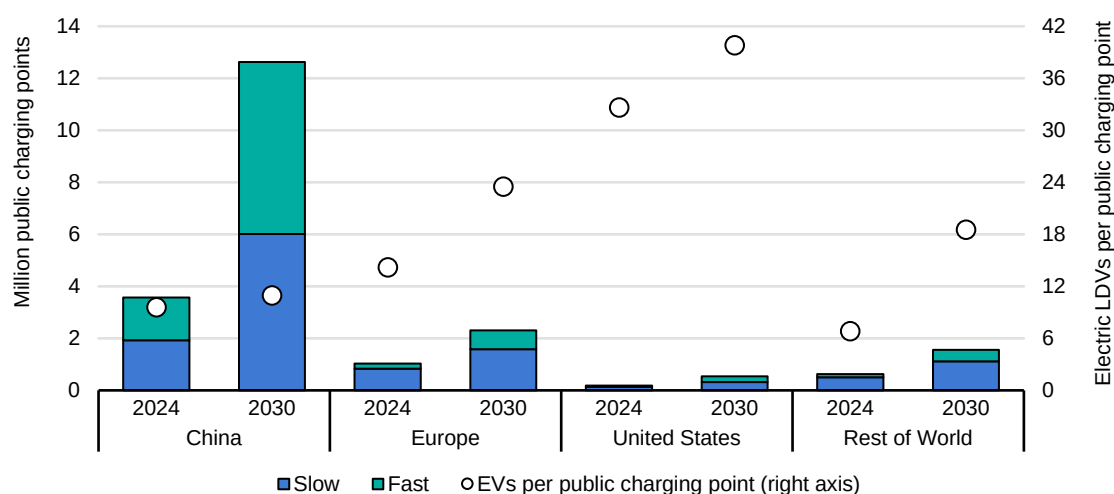


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Notes: "Private – other" refers to charging points that are neither publicly accessible nor at private residences. Home charging stock in 2024 is estimated based on electric light-duty vehicle stock and regional assumptions regarding the ratio of home chargers to vehicles. Regional projected electric vehicle supply equipment (EVSE) stock data can be explored via the interactive [Global EV Data Explorer](#).

In **China**, the relatively low ratio of electric LDVs to public charging points that has been maintained over the past decade is partly because Chinese EV owners have tended to be concentrated in dense cities with limited access to home charging. In the STEPS, the ratio of electric LDVs per public charging point remains relatively low but still grows to around 11. The stock of public charging points in China grows more than threefold by 2030 in the STEPS, reaching over 12 million charging points. The share of public fast chargers continues to grow, as it has during the first half of this decade, increasing from around 45% in 2024 to over 50% in 2030. In 2024, China added about 850 000 public charging points. The average annual additions needed to reach the public charging stock projected in the STEPS in 2030 are about 75% higher than was observed in 2024, and 60% higher than the additions in 2023. For China to reach an electric LDV stock of around 140 million in 2030, as in the STEPS, maintaining a ratio of 11 EVs per public charging point would require, on average, net additions of 1.5 million charging points each year. The public charging capacity in China increases by about 900 GW to 2030 in the STEPS. To limit the stress that EV charging puts on the grid, the Chinese government has published a [policy](#) for standardising vehicle-to-grid technologies, through which EVs are [expected](#) to provide 10 GW of flexible capacity by 2030 (see [Smart charging and vehicle-grid integration](#) below).

Number of public light-duty vehicle charging points by region in the Stated Policies Scenario, 2024-2030



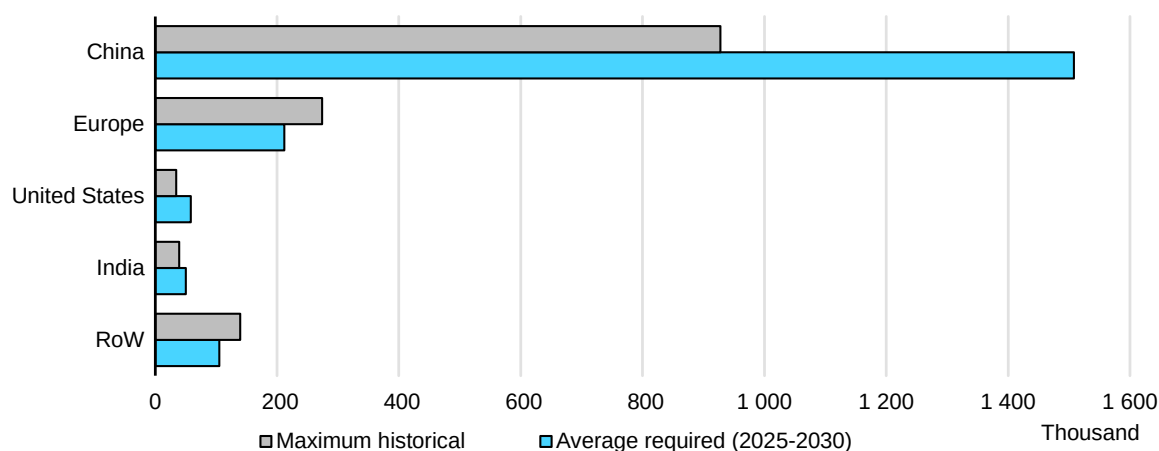
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Notes: EV = electric vehicle; LDV = light-duty vehicle. Slow refers to charging points with a power rating of 22 kW and under, while fast refers to higher power ratings. Regional charging point projections can be explored via the interactive [Global EV Data Explorer](#).

In **Europe**, the stock of public charging points doubles by 2030 in the STEPS to reach more than 2 million. The share of fast chargers continues to increase and reaches 30% in 2030 in the STEPS, up from less than 20% in 2024. As such, public charging capacity across Europe reaches 115 GW in 2030, including slow and fast chargers. The increase in the share of fast chargers, as well as the growth in their average power rating, means that while the ratio of electric LDVs per charging point increases from less than 15 in 2024 to close to 25 in 2030, the public charging capacity per vehicle increases to over 2 kW per electric LDV. This level of public charging capacity exceeds the power output targets laid out in the [EU AFIR](#) (1.3 kW per battery electric LDV and 0.8 kW per plug-in hybrid). To reach the level of public charging projected in the STEPS in 2030, Europe must add 210 000 public charging points per year on average through 2030, which is less than the 275 000 public charging points added across Europe in 2024.

Beyond EU regulation, there are national targets for public charging infrastructure in Europe. For example, the French government aims to have [400 000](#) publicly accessible charging stations by 2030, about two-and-a-half times the number available at the end of 2024. The UK government has stated an aim for at least [300 000](#) public charging stations in 2030, about three-and-a-half times the stock in 2024. The German government has also previously set a target of [1 million](#) public charging points by 2030, though energy industry groups have [criticised](#) this target for being more than will be needed.

Annual public charging point additions by region needed to reach the stock in the Stated Policies Scenario, 2030



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Notes: RoW = Rest of World. In all regions shown, except China, the maximum historical public EV charging point additions were observed in 2024; in China the most additions took place in 2023.

In the **United States**, the stock of public LDV charging points grows from almost 200 000 at the end of 2024 to over 500 000 at the end of 2030 in the STEPS. This assumes the historic trend in the increasing ratio of electric LDV stock per public charging point continues, and that in 2030 there are almost 40 electric LDVs per public charging point, up from around 32 in 2024. Although this ratio is significantly higher than the global average, recent [survey findings](#) suggest that over 85% of US EV owners have access to home charging. However, with rising EV sales, this share is expected to decrease. In addition, the majority of EV owners with home chargers still use public chargers weekly.

The share of fast chargers in the United States grows from less than 30% in 2024 to 40% in 2030 in the STEPS, meaning that the available public charging capacity per electric LDV grows to over 1.5 kW per EV. In 2024, the United States added about 35 000 public charging points across the country. To reach the more than 0.5 million projected in the STEPS in 2030, the United States would need to build out an average of 58 000 public charging points per year. At the [end of 2024](#), fewer than 200 stations funded through the NEVI programme were in operation (representing less than 1% of the 2024 public charging additions), but over 3 500 had conditional awards or agreements in place. However, as the policies underlying the implementation of the NEVI Formula Program are now under review, the future of federal funding for EV charging infrastructure is uncertain. Nevertheless, NEVI and other federally funded charging points have previously been [estimated](#) to represent less than 15% of announced non-home charging deployments.

In **India**, the number of public charging points increases from 75 000 at the end of 2024 to around 375 000 by the end of 2030 in the STEPS to support a stock of less than 3 million electric LDVs. As a result, in 2030 in the STEPS there are around 7 electric LDVs per public charging point, up from fewer than 4 in 2024. To reach this projected stock of public charging points, around 50 000 charging points would need to be added on average each year through 2030, about 30% more than the number of additions observed in 2024. India's [PM E-DRIVE](#) Scheme includes INR 20 billion (Indian rupees) (USD 240 million) for public EV charging stations, with plans to support a targeted [22 100](#) EV chargers for electric four-wheeled vehicles through March 2026.

Across other countries, about 630 000 public charging points are added between the end of 2024 and 2030 in the STEPS, or an average of 105 000 new public charging points per year. Governments around the world have set targets for public charging points to support expansion to 2030 and beyond. Japan targets a stock of [300 000](#) public charging points by 2030, about 9 times the stock at the end of 2024. The government of New Zealand aims to have [10 000](#) charge points by 2030, a seven-fold increase from the end of 2024. Across Southeast Asia, Indonesia aims to reach [30 000](#) charging stations by 2030 and Thailand [12 000](#).

Charging electric heavy-duty vehicles

Megawatt-scale chargers are now being deployed

In general, electric heavy-duty vehicles (HDVs) can use the same charging equipment as LDVs, although different charging station configurations may be needed to accommodate the HDVs, given their larger size. In addition, as the batteries of HDVs are larger and therefore take longer to replenish, higher-powered chargers are needed to minimise disruptions to regular operations. The effective deployment of electric HDVs is therefore likely to require the buildout of devoted charging equipment to ensure charging times compatible with the operational efficiency of commercial fleets. Most electric HDV operators today rely on depot charging when the vehicles are not in use, typically overnight, but en route or opportunity chargers are generally also needed to enable longer-range applications.

The growth in deployment of electric buses has been enabled by the buildout of charging depots by national and local governments as well as by transit agencies. For example, in the United Kingdom, the government's Zero Emission Bus Regional Areas scheme supported the establishment of an electric bus charging hub to power [South Yorkshire's](#) first electric buses. Germany's [Deutsche Bahn](#) and various partners have supported charging infrastructure for electric buses that charge exclusively at the depot overnight. In China, [policy](#) support for bus charging

infrastructure has helped to enable huge growth in the electric bus stock, with megawatt-scale charging being demonstrated for buses in [Sichuan](#) at the end of 2024.

As with buses, the roll-out of depot chargers is [expected](#) to lead the first phase of electric truck charging deployment, as fleet operators have the greatest control over private charging infrastructure. However, scaling up public chargers of 350 kW or more will be critical to support wider adoption. The EU [Alternative Fuels Infrastructure Regulation](#) sets specific targets for HDV charging, including charging points with an individual power output of at least 350 kW every 60 km along primary roads and every 100 km along secondary roads. [Megawatt chargers](#) are also expected to play a role in HDV charging, given that reducing charging time is highly valued in the sector. An HDV with a battery pack of 300 kWh (similar to the global sales-weighted average in 2024) would require about 30 minutes to recharge² using a 350 kW charger, but only about 15 minutes using a megawatt charger.

In 2024, the world's first megawatt chargers for trucks were deployed in the [United States](#) and [Europe](#), marking a key technological milestone. Enabling such higher-powered charging requires timely planning, permitting and investment to upgrade power grids. Both depot and public charging frequently require grid reinforcements to enable ultra-fast charging, sometimes in remote locations. Even if overnight charging in depots or service stations is relatively slow, the grid connection must be able to handle the parallel charging of multiple vehicles. Coupling megawatt chargers with battery storage can alleviate grid stress, reducing the need for power grid upgrades and accelerating megawatt charger deployments. This approach could be important for speeding up the roll-out of electric trucks, and has also been announced for ultra-fast charging of cars (see the Box [above](#)).

National statistics on HDV-specific chargers are not readily available for most countries. However, there is evidence that in China, one company alone had built about 1 350 charging stations with over [5 500 charging points](#) for electric trucks by the end of October 2024, each with a charging capacity of more than 320 kW. Based on data compiled by [Atlas EV Hub](#), the United States reported around 500 operational HDV charging points in October 2024 – about double the number at the beginning of 2024 – and over 1 000 more are planned. Less than one-third of the existing chargers are accessible to the public, but around 85% of all planned chargers, including at high-power charging stations, are expected to be publicly accessible.

² Between 20% and 80% of the battery state of charge.

The expansion of HDV charging infrastructure extends beyond these major EV markets. In India, the [PM E-DRIVE](#) scheme proposes installing 1 800 fast chargers for e-buses in larger cities and on selected highways. Elsewhere, Qatar's [Public Bus Infrastructure Program](#) has built over 650 charging points for electric buses to support the country's goal of reaching [100%](#) public bus electrification by 2030. In Latin America, countries are collaborating to build EV recharging [corridors](#), including for buses and trucks, and the first truck charging station in Peru was [opened](#) at the Port of Callao in 2024. In Singapore, Volt has been [awarded](#) a contract to develop and operate an 80-point direct-current charging hub for electric taxis, buses and other EVs. Meanwhile, Malaysian government-owned Prasarana has [issued](#) tenders for electric bus procurement and charging infrastructure deployment.

Industry players are teaming up to deploy charging for heavy trucks

HDV charging infrastructure is still in its early stages and requires significant investments, but it is gaining momentum. Private companies are [joining forces](#) to expand charging networks. In the United States, Greenlane – a joint venture between Daimler Truck North America, NextEra Energy and BlackRock – [announced](#) plans for a commercial EV charging corridor from Los Angeles to Las Vegas, with over 100 chargers. Meanwhile, DTNA, Navistar and Volvo teamed up to establish the [Powering America's Commercial Transportation](#) coalition to accelerate deployment of chargers for medium- and heavy-duty trucks.

In Europe in 2024, Milence, a joint venture between Daimler Truck, TRATON and Volvo, [presented](#) its plans to establish a European charging network of 70 hubs, accounting for more than 570 high-power (some > 1 MW) charging points by the end of 2025. The company has previously announced the goal to reach [1 700 charging points](#) across Europe by 2027. In addition, E.ON and MAN Truck & Bus are collaborating to [set up](#) around 400 electric truck charging stations in 170 different locations in Europe, as part of a project that has received [EUR 45 million](#) in EU funding. The BP subsidiary Pulse, which today owns the [majority](#) of truck charging stations in Germany, also [announced](#) its co-operation with the Polish charging infrastructure manufacturer Ekoenergetyka, although the terms of the collaboration have not yet been disclosed. Various project partners are collaborating under the [CLOSER](#) platform to support electrified logistics, including to develop a [Scandinavian charging network](#) for electric trucks.

International programmes and initiatives can also support the advancement of HDV charging. Zero-Emission Vehicle Infrastructure Support and Expansion (ZEVWISE) leads the [Global Green Road Corridors Initiative](#), aiming to develop at least ten green road corridors worldwide by 2026, with the latest two new

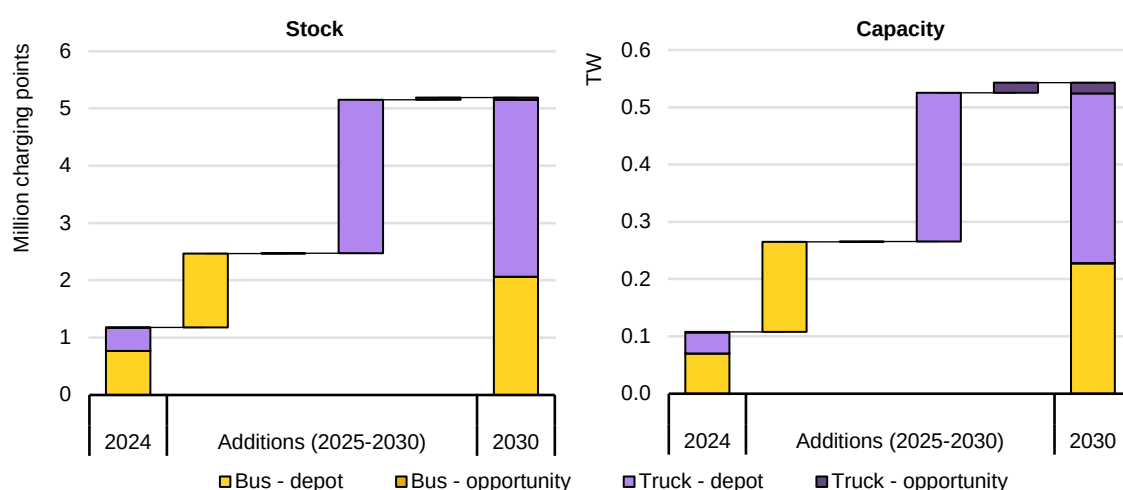
corridors [announced](#) at COP29. These corridors aim to deploy sufficient charging infrastructures along key routes connecting industrial hubs, ports and cities, and focus on creating replicable models for infrastructure deployment and financing, aiming to accelerate global deployment. The Kuehne Climate Center and Smart Freight Centre have also initiated the [Green Freight Support Program in Eastern Africa](#).

Heavy-duty vehicle charging outlook

Charging capacity for trucks and buses increases more than fivefold by 2030

Just as for charging LDVs, overnight charging tends to be the most attractive option for buses and trucks, as it requires lower power and is typically cheaper. This is especially the case among [early adopters](#). While public or opportunity charging infrastructure for electric HDVs is limited, electric fleet owners and/or operators typically choose to install depot chargers at close to a one-to-one ratio to allow the fleet to charge concurrently during the night. Of course, to enable longer daily driving ranges, en route or other opportunity chargers (such as at terminal bus stops or highway service stations) are needed to expand the applications that can be met by electric HDVs.

Heavy-duty vehicle charger stock and capacity in the Stated Policies Scenario, 2024-2030



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Note: Charger stock in 2024 is estimated based on the number of electric buses and trucks.

In the STEPS, the stock of charging points for electric HDVs increases from around 1 million in 2024 to over 5 million in 2030. The vast majority of charging

points remain located at depots through this decade in this scenario. The stock of chargers for trucks grows more quickly than for buses, increasing from a third of all HDV chargers to almost 60% in 2030 in the STEPS.

The charging capacity for electric HDVs grows similarly to the stock – increasing about five times to 2030 in the STEPS to reach more than 500 GW. Given that the role for higher-power opportunity chargers is expected to remain limited this decade, the overall charging capacity for HDVs remains around 100 kW per electric HDV.

Despite the relatively low power rating for depot chargers – typically 50-150 kW compared to 350 kW to 1 MW+ for some opportunity charging – grid upgrades at depots may be needed, especially for larger fleets. Grid upgrades can take from [one to several years](#), depending (in particular) on the voltage. Anticipatory planning is needed to ensure adequate availability of HDV chargers in the medium- to long-term.

Daytime charging of HDVs may also [be suited to renewables](#), such as solar PV, which would support integration and ease grid demand. Co-locating HDV charging stations with battery storage can also be a way to ease grid infrastructure requirements and accelerate the deployment of HDV charging, especially in the context of [record-low](#) battery prices. Battery-swapping and electric road systems are other options being explored that could reduce impacts on the grid.

Government policies and support will be needed to ensure a smooth roll-out of charging for HDVs. The EU [AFIR](#) includes increasing coverage requirements for HDV charging points with a power output of at least 350 kW along the TEN-T Network starting in 2025. According to the [Action Plan](#) for the EU automotive sector, the European Commission will make another EUR 570 million available under the Alternative Fuels Infrastructure Facility towards the roll-out of alternative fuels infrastructure in 2025 and 2026, with a particular focus on HDVs.

Smart charging and vehicle-grid integration

Smart charging gains popularity, bolstered by smart charging roll-out mandates

Electric vehicles represent less than 1% of global electricity demand today, but their contribution to power demand is affected by charging behaviour. Depending on local grid conditions, EV charging can put stress on electricity grids. Extra demand from unmanaged EV charging during peak times can mean grids need to enlist more carbon-intensive power plants and may increase electricity prices for households using electricity at these times. As a result, governments, utilities and private companies have started to develop and deploy technologies to enable

smart charging. Smart chargers can be connected to the internet and accessed remotely, allowing for controlled scheduling. When used in conjunction with differentiated tariffs, smart chargers enable EV owners to charge flexibly and take advantage of the cheapest tariffs under different pricing regimes (e.g. time-of-use, dynamic real-time, critical peak pricing, etc.), while providing demand-side flexibility for grid operators. Smart charging can also support [EV battery health](#), such as by adjusting the maximum charging rate to avoid overcharging and excessive heat, which can degrade batteries over time.

Smart charging is advancing towards wider commercial deployment. The United Kingdom was among the first countries to mandate that all new home charge points for EVs must have smart functionality from [2022](#). Prior to this, only [52%](#) of UK EV owners with home charging capabilities had a smart charger. The EU [AFIR](#) specifies that all chargers that are installed or renovated from April 2024 must support smart charging. China has longstanding policies on smart charging roll-out from previous Five-Year Plans on Electric Vehicle Deployment, with newer chargers now having smart charging capabilities. Elsewhere, Brazil is taking strides in expanding EV infrastructure through its “[electrocenters](#)” – charging hubs designed to optimise power distribution to ensure grid resilience while accommodating multiple vehicles simultaneously, launched in March 2024.

Multiple actors are involved in efforts to implement vehicle-to-grid solutions

While smart charging enables EV owners to choose when to charge their EVs, bi-directional charging provides them with the opportunity to discharge power from their EVs to their homes (vehicle-to-home, or V2H), buildings (V2B), or other appliance loads (V2L) and the grid (V2G). Bi-directional charging can be used to recharge car batteries when electricity is cheapest, and then sell electricity back to the grid (V2G) when prices are higher. It can also be used to discharge car batteries to provide emergency or off-grid power supply to buildings or loads (V2B, V2H, V2L).

For widespread application of V2G, multiple legal and technological hurdles need to be overcome so that demand-side flexibility from EVs can work effectively for the maximum benefit of EV owners and grid operators. Progress across markets is currently mixed due to the complexity of the requirements needed along the V2G pipeline.

As a first step, smart chargers that can schedule charging and discharging from the grid must be deployed across the EV charging network. Secondly, EVs must be capable of bi-directional charging. Today there are over 30 bi-directional-capable models available, an increase of nearly 20% from 2023. Bi-directional models now make up more than one in eight new electric cars sold, with models

such as the Hyundai Ioniq 5 and 6; BYD Dolphin and Yuan Plus; MG 4/Mulan and Kia EV6 among the most popular. In addition, OEMs have begun to work together to address common challenges associated with V2G integration, such as through [ChargeScape](#), which brings together Nissan, BMW, Ford and Honda.

Different market structures will also be needed to support the application of V2G technologies. For example, differentiated tariffs provide financial incentives for EV owners to optimise their charging. Aggregators and ancillary service markets act as middle management between grid distribution operators, to provide bids and pool flexible EVs and other storage devices so that grid operators can then purchase this flexibility. To facilitate the transmission of electricity between these market aggregators, sufficient management of EV batteries connecting to the grid must also be supported by adequate grid infrastructure so as to avoid grid congestion and enable bi-directional charging.

Demonstration trials of V2G projects are currently underway in markets including [Australia](#), China, [Germany](#), Korea and the [United Kingdom](#), where the government is funding [20 V2G projects](#) involving around 600 cars. A demonstration project launched in November 2024 in the Netherlands represents one of the largest V2G car-sharing services in Europe to date, using 500 [Renault 5 E-Tech BEVs](#). In 2023, the [Korea Electric Power Corporation](#) was involved in a 100-vehicle V2G pilot programme. It found that EVs effectively contributed to peak shaving, and that battery degradation was minimal, but further refinement of financial incentives would be needed to make the V2G system financially attractive to a wide consumer base. In August 2024, China's National Development and Reform Commission issued [a notice](#) promoting the piloting of large-scale applications of V2G interactions, and selected 5 cities to kick off at least 50 V2G pilot projects. The notice also established grid communication standards for EV charging equipment that enables V2G bi-directional charging. A national road map for bi-directional charging has been developed by [Australia](#), which suggests that adopting V2G in just 10% of Australia's projected EVs could help meet more than one-third of the national electricity market's storage needs in 2030. As of [February 2025](#), a small number of Australian households have adopted V2G technology and are selling power back to the grid. In the United States, in [March 2025](#), ComEd, an energy provider in northern Illinois, partnered with Nuvve to launch a V2G pilot programme focusing on electric school buses.

Policy measures targeting bi-directional charging are increasingly being introduced in different markets worldwide. In the European Union, updated AFIR requirements will include standards that enable bi-directional charging, starting in [2027](#). In the United States, the [Federal Highway Administration](#) previously mandated via the Infrastructure Investment and Jobs Act (2021) that chargers must conform to and possess hardware capable of implementing both smart

charging and bi-directional charging for compatible vehicles (ISO 15118-20). At the state level, California [enacted legislation](#) to promote V2G adoption in September 2024.

Ensuring compatibility and interoperability of the chargers and EVs involved are the final challenges. The CHAdeMO EV charging system first introduced V2G communication in 2010 and has been the first mover in this domain. Since then, the charging protocols adopted by the CHAdeMo Association have continued to evolve as technology has developed. Several organisations have also been working to define appropriate standards and use cases. Efforts to standardise protocols and grid codes are ongoing through the Electric Vehicle Technology Collaboration Programme [Task 53: Interoperability of Bidirectional Charging](#). In addition, the International Electrotechnical Commission has published [use cases](#) on how EVs might provide distributed energy resource functionality.

Progress in power system measures to enable smart charging and vehicle-to-grid capabilities, 2025

Country	Market access and legal frameworks				Technology availability		
	Differentiated tariffs (e.g. time-of-use, dynamic real-time, critical peak pricing)	Aggregators (grouping multiple users that combine loads or generation)	Ancillary services (electricity market services related to frequency control, voltage control, and emergency and restoration plans)	Local flexibility (DSOs procure local flexibility to reduce congestion, minimise outages and allow for deferral of grid expansion investments)	Standards and legal definitions	Smart charging deployment	V2G model availability
Brazil							
Chile							
China							
Denmark							
Finland							
France							
Indonesia							
Italy							
Japan							
Korea							
Netherlands							
South Africa							
United Kingdom							
United States							
Thailand							

Notes: DSO = distribution system operator. Evaluation overview: green = measures in place; orange = field test/pilot phase, or measures announced; red = no framework. United States assessment is based on an aggregate of state rules and aggregators in the country ([New York Independent System Operator](#), [Massachusetts](#), [Maryland](#))

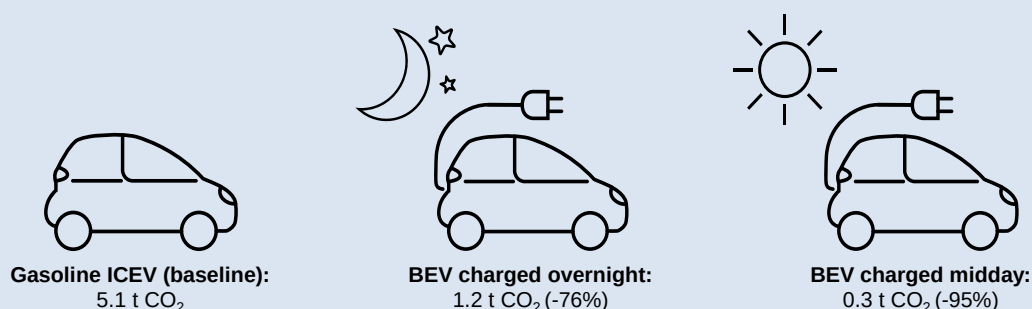
Sources: IEA (2023), [Facilitating Decarbonisation in Emerging Economies through Smart Charging](#); IEA (2024), [Enhancing Indonesia's Power System](#); IEA (2024), [Meeting Power System Flexibility Needs in China by 2030](#); Mobility House (2023), [The V2G status quo - how much progress has been made in which country?](#); United Kingdom, Department for Transport (2018), [Government funded electric car charge points to be smart by July 2019](#); Yeboah, D. et.al. (2023), [Tariff Development for Smart EV Charging for Households](#); Korea, Ministry of Trade, Industry and Energy (2023), [Act No.19437](#); IRENA (2019), [Innovation outlook: Smart charging for electric vehicles](#); Chile, Ministry of Energy (2022) [Approval of regulation on establishing interoperability of EV charging systems](#); Wood Mackenzie (2024) [Ancillary services in Asia-Pacific](#); Otsuki, T. & Ogura, T. (2019), [EV Charging Standards and V2X](#).

Shaping human behaviour around charging will be key to unlocking the full benefits of electric vehicles

Patterns of human behaviour will have a big impact on how EVs affect the grid. Different charging habits will affect the costs of charging, grid congestion and reliability, but with the right incentives to align charging behaviour with the needs of the grid, EVs could become a major source of flexibility and demand response.

Charging behaviour also affects emissions. Many electric grids – such as those in California, Germany, and Spain – have deployed large amounts of solar power, which peaks around midday. If EV charging uses this solar power, while avoiding peak load periods such as early evening when people return home after work, EVs could help stabilise the grid while also maximising emissions reductions. In California, electric cars charged overnight emit 76% less CO₂ than conventional ICE vehicles – but EVs charged around midday go much further, slashing emissions 95% relative to ICEs.

Annual well-to-wheel emissions from gasoline and electric cars in California, 2024



IEA. CC BY 4.0.

Source: Emissions estimated by [UC San Diego](#) based on data from the California Air Resources Board.

Social science research is now looking at how to influence behaviour in ways that help EVs become a reliable resource for the grid and cut emissions. Researchers from the University of California San Diego (UC San Diego), working with the Electric Power Research Institute and others, are using randomised controlled trials at UC San Diego's [network](#) of over 500 charging points. Experiments that derived from 1 200 drivers are assessing whether interventions change habits in the real world.

In one study, they told drivers how midday charging reduces emissions and found that drivers responded by reducing their campus charging at times other than midday by 5%. While modest, this effect is similar in scale to other kinds of informational “nudges” studied with other behaviours that affect the grid, such as household energy choices. A key issue the research team explored is that many EV drivers have little prior knowledge about charging costs and emissions impacts. Information helps fill that void.

A [second project](#) offered discounts for campus charging to test drivers' willingness to relocate their charging. In a twist, incentives to charge on campus actually led drivers to

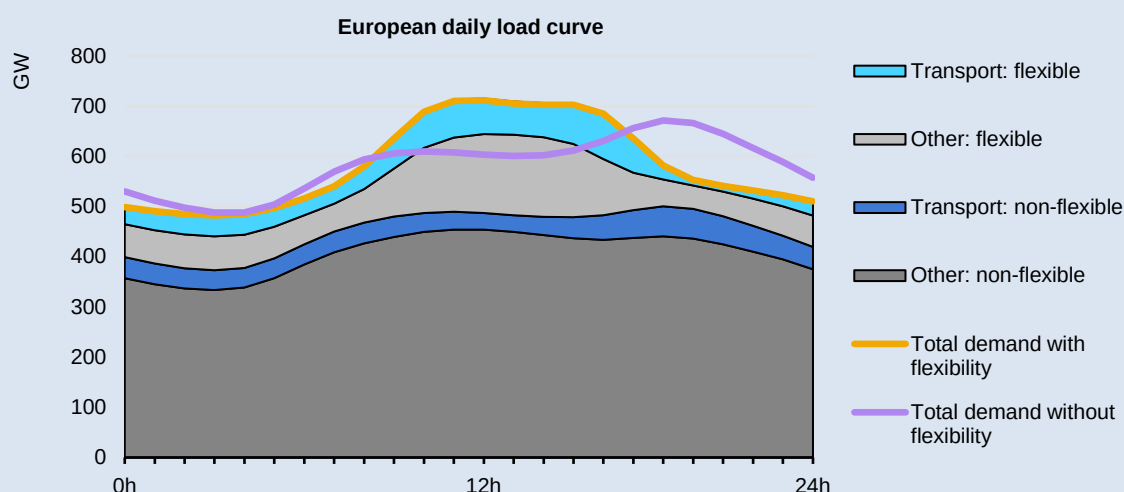
charge more (7%) in the early morning and overnight, rather than during the midday solar peak. The findings suggest that scarcity of chargers was the reason for this unexpected behaviour – drivers expected that the discounts would increase competition for scarce chargers and tended to hoard access as a result.

Some recent preliminary findings suggest that network quality also affects charging behaviour. When drivers have poor charging experiences, they are reluctant to return. This points to the increasing need to focus on the quality of charging networks, not just the quantity of charge points. Some policy makers have begun this shift, such as in [Germany](#).

As the number of EVs on the road increases, choices about charging will have bigger impacts on the grid. That raises the stakes for learning how to get people to charge in more optimal ways, which will often mean at offices and other locations away from home at differing times of the day. Using real-world charging data to test business models will be vital for sustainably building the networks to support such charging.

Transport flexibility through methods such as smart and managed charging has relevance around the world. For example, in a case where EVs represent 80% of the vehicle stock in Europe, and over 40% of final energy demand is met by electricity, around a quarter of this electricity demand has some flexibility potential. Over a third of this flexibility potential comes from EVs, where optimised smart charging and changes in charging behaviour can shift peak demand away from the congestion and higher emissions that occur during evening hours to the middle of the day when the availability of renewables, especially solar, to supply the grid would be higher than the electricity demand without the additional charging load.

Potential for transport demand response flexibility across Europe based on an 80% electric vehicle stock share.



IEA. CC BY 4.0

Notes: In this example, over 40% of total final energy demand in Europe is electrified.

Source: Adapted from the [World Energy Outlook 2024](#).

Innovative charging solutions

While cabled charging is expected to remain the predominant technology for charging EVs into the foreseeable future, alternative solutions are also making headway. Battery swapping systems, for example, have been around in some form for [over a century](#), though use has been somewhat limited, but deployment is now rapidly growing in certain regions and segments. Battery swapping is proving especially successful in commercial applications such as delivery or ride-hailing services, where downtime for charging can be costly.

Battery swapping can offer benefits by reducing the upfront cost of EVs; improving battery longevity, especially with professional handling of swaps; alleviating stress on power grids; and facilitating reuse and recycling efforts when batteries remain under the ownership of the swap company. However, these systems may increase overall demand for batteries and would benefit from design standardisation that could be difficult to achieve at large scales in some markets. Standardising batteries could also inhibit innovation, such as the development of cell-to-chassis architectures that can improve EV efficiency by reducing the weight of battery systems. The benefits of standardisation for battery swapping must be weighed against the risk of constraining market competition and innovation.

Dynamic charging – which takes place while vehicles are moving – is also being explored. This can be accomplished through conductive charging, such as using overhead catenary lines, which are already commonly used to power transport systems like trams and light rail systems, or through inductive, wireless charging, which is at an earlier stage of development and deployment. Both systems can be deployed at strategic locations for stationary charging, such as at bus stops or logistics centres where vehicles already spend time idle.

These systems and other innovations, such as solar-coupled charging systems, can play a role in making charging more convenient and/or a source of flexible demand for renewables, as well as reducing charging-related stress on grids.

Battery swapping for 2/3Ws is increasingly popular in emerging markets

Battery swapping systems for 2/3Ws offer a number of benefits, including improving affordability, which can be particularly helpful for consumers in developing economies, where upfront costs can be a barrier. The “battery-as-a-service” subscription model can lower the upfront investment required for an electric 2W, as the battery typically accounts for around [40%](#) of the total price. In terms of operational costs, for the amount of range provided, battery-swap-enabled 2/3Ws are around [20-50% cheaper](#) than petrol 2/3Ws, and the economic case improves as [daily driving distance](#) increases. Battery swapping can also offer

time savings. While at least 20 minutes (and typically [several hours](#)) is required for recharging an electric 2W, battery swapping can be performed in just [2-5 minutes](#) – approximately the same amount of time needed to refuel a gasoline motorcycle. It can eliminate the need for home charging, making electric 2/3Ws more accessible to drivers with limited electricity access. In addition, in countries with underdeveloped power grids, the more centralised load/demand management offered by some battery swap stations can be beneficial.

Thailand, for example, is targeting [1 450](#) battery swapping stations by 2030. In Indonesia, the start-up SWAP Energi currently operates around [1 500](#) electric 2W battery swap stations in the country. The Indonesian government has set the target of about [67 000](#) battery swap stations, for either motorcycles or cars, by 2030.

Battery swapping has also taken off in India in the past 5 years, thanks to technological improvements for batteries and falling costs coinciding with a rise in gasoline prices. Electric 2/3Ws – sold without the battery – have now [become accessible](#) even to low-income buyers. [Battery Smart](#) is India's largest battery swap operator for 2/3Ws and reached 1 000 stations in April 2024. Indian company [Sun Mobility](#) is also growing fast, with more than 630 swapping stations in 19 Indian cities. There are also plans to deploy [10 000](#) Piaggio electric 3Ws with swappable batteries in the country, alongside 300 new swapping stations.

In Chinese Taipei, the market for electric 2/3Ws has grown significantly due to strong demand and government support, accompanied by an innovative, widespread battery swapping mechanism that has become a [global leader](#). Domestic battery swapping pioneer Gogoro now has around [13 000](#) battery swap stations worldwide, each roughly the size of 2 vending machines and able to hold around [30](#) scooter batteries. In the city of Taipei, there are now [more](#) Gogoro battery swapping stations for 2Ws than gas stations. A total [2 500](#) Gogoro stations use artificial intelligence (AI) and can act as a virtual power plant – drawing power from the grid when usage is low, and returning it when usage is high, and even supplying back-up power in emergencies. After the country was hit by an earthquake in April 2024, battery swap stations made [6 MW](#) of power available, enough to power thousands of homes. However, Gogoro has struggled to find a sustainable [business model](#) and [benefits](#) from government purchase subsidies.

In Africa, Spiro, an electric motorbike manufacturer and battery swapping provider, has put over [22 000](#) e-bikes on the road across a number of different countries. Kenyan company [Arc Ride](#) runs a battery-as-a-service model for 2W battery swapping, with over 140 stations, mostly around Nairobi. Kenya is also a target for Rwandan [Ampersand](#)'s expansion plans, and [Roam](#) is setting up solar-powered fast battery charging and swapping for electric motor cycles in the country.

Battery swapping systems for 2/3Ws are still in their infancy in Europe, a far smaller market for 2/3Ws, although the supermarket chain Kaufland is operating [swapping stations](#) for batteries for small electric cars or electric 2Ws in Romania in co-operation with the e-Mobility Rentals start-up. Honda is also launching battery swap stations in [Sweden](#) for their electric scooters.

Greater standardisation and interoperability would be needed to fully reap the benefits of battery swapping and reduce the need for costly charging infrastructure. This would also enable the aggregation of demand for electric 2/3W batteries and help to guide industry development. In 2022, various Japanese OEMs established a new company, [Gachaco](#), to offer a battery sharing and swapping services for standardised, exchangeable 2W batteries. More recently, in 2024, Thailand launched the [Thailand Standard Swappable Battery Consortium for Small e-Mobility](#) to work towards elevating the national standard to the level of [international standards](#).

Battery swapping for cars is growing in China and entering new markets

Chinese EV manufacturer NIO built its first battery swap station for electric cars in 2018 and has remained the market leader ever since. By the end of 2024, [NIO](#) had built over 3 000 battery swap stations in China and [50 in Europe](#). In just 2 years, the company [more than doubled](#) its battery swap stations in China. In an effort to co-ordinate battery standards and battery swapping technologies, and maximise the utilisation of NIO's network, the company has [agreements](#) with Geely Group, JAC Group and Chery Automobile, which together represented 15% of electric car sales in China in 2024.

Battery maker CATL introduced its battery swap solution, [EVOGO](#), in 2022. The company has since [announced the ambition](#) to reach 3 000 stations by 2027, and eventually 10 000 stations. In 2024, CATL and ride-hailing company DiDi formed a [joint venture](#) to build out battery swap stations and swappable vehicles, and at the end of the year, CATL launched a [Battery Swap Ecosystem](#) with nearly 100 partners to move towards the standardisation of EV battery swapping. The programme also aims to build 30 000 battery swap stations that will also work as battery-to-grid energy storage facilities.

In 2024, Ample announced it was partnering with ENEOS to bring battery swap stations to [Kyoto](#), in a first for Japan. Ample is also partnering with [Stellantis](#), beginning with a programme to provide battery swap stations in Madrid for Fiat 500e cars in the Free2Move car-sharing service.

For trucks, battery swapping can offer savings in terms of reducing charging time

As of June 2023, there were around [400 battery swap stations](#) for trucks in China. While battery swapping for heavy-duty trucks is still at an early stage of deployment, it has the potential to support faster uptake of electric trucks by extending battery lifespan and reducing the wait time for charging, thus enhancing efficiency for commercial operations. For example, even electric truck batteries large enough to enable daily mileage suitable for long-distance transportation can be exchanged in around [10 minutes](#) – almost as fast as refuelling a diesel truck. Battery swapping for trucks can offer greater benefit in terms of preserving battery health compared to other EV segments; the constant use and long distances travelled by trucks result in increased battery degradation, which is compounded by reliance on fast-charging solutions that further accelerate [degradation](#).

Battery swapping is particularly well-suited to fleets of identical trucks with heavy operational demands, operating on well-defined routes. These fleets could justify the significant investment required in automated swapping facilities and additional batteries. As such, battery swapping has been deployed for trucks used in short-haul applications at ports, mining sites, urban and even [regional](#) logistics, particularly in China where sales of swap-capable electric trucks reached [almost 30 000](#) last year. Elsewhere, Rio Tinto announced in 2024 they would trial [eight](#) electric dump trucks with battery swap technology for their mining operations in Mongolia. In Japan, field tests using courier services also began in 2024 for a [Mitsubishi Fuso and Ample](#) truck battery swap demonstration.

Technological advances have enhanced the safety, reliability and convenience of battery swapping systems for trucks in recent years. [Intelligent systems](#) can now automatically assess battery status and perform the swapping service. In China, [new policies](#) were announced in 2024, enacting safety standards for swap-capable HDVs and establishing technical specification systems. However, in other parts of the world, the required level of standardisation may make it difficult for battery swapping to compete with conventional plug-in charging, especially for certain heavy-duty truck segments.

In Europe, the region's [first fully automated](#) heavy-duty electric truck battery swapping station opened in Germany in 2023. Swappable batteries are also being used as hybrid solutions for trucks, for example in German company [Trailer Dynamics](#)' electric trailer with a swappable battery. Similarly, in the United States, [Revoy](#) has launched a battery swapping solution that can integrate with semi-trucks, offering up to 235 miles of range, which can essentially turn a diesel truck into a hybrid vehicle, or serve as a range extender for an electric truck. While

battery swapping demonstrations and technology developments are [ongoing](#), outside of China, manufacturers have been reluctant to separate battery ownership from vehicles, which would disrupt traditional revenue streams, and to standardise, which has been crucial to [China's success](#).

Electric road systems are being tested across major EV markets

Electric road systems (ERS) enable vehicles to receive electricity while moving using one of three main technologies: conductive overhead (catenary) lines, conductive contact rails beneath the vehicles, and inductive wireless systems embedded in the road. Conductive contact rails and inductive systems can charge both light and heavy vehicles, while overhead lines are used for heavy vehicles. In all cases, vehicles must be equipped with appropriate pantographs or receivers.

ERS allow for smaller batteries and could therefore be a [cost-effective solution](#) for electrifying the road sector, especially for heavy-duty trucks that follow well-defined routes, while ERS-enabled smaller batteries can increase a commercial vehicle's payload and profitability. Research has highlighted the [benefits of wireless charging of buses](#) to resolve space constraints at depots and to enable en route charging that can make battery electric buses more comparable to gasoline fuelled buses in terms of operations. Similar benefits exist for [catenary charging](#) solutions strategically located at bus stops. However, ERS infrastructure is expensive to install – depending on the type of system, the [cost per kilometre](#) could range from EUR 1.5 million for overhead catenary to over EUR 3 million for inductive charging.

Test projects for electric road technology are ongoing worldwide, exploring both inductive and conductive methods. Sweden has been a global pioneer, while projects are also being undertaken in the United States, China and Japan. The United States primarily focuses on inductive technology, while Germany and France, historically focused on conductive technology, are now also testing inductive systems. Some of the earliest test projects in Europe, particularly in Sweden, have now been [retired](#).

Selected operational and planned electric road system projects

Location	Description
Datong, China	Trial of pantograph system with trucks launched in 2023 as part of Shanxi project . Project developed by CRRC Datong (part of China National Railway Locomotive & Rolling Stock Industry Corporation) and research partners.
Xinjiang province, China	Plans to electrify more than 1 800 km of highway launched in mid-2023.
Jilin province, China	120 m long high-power dynamic wireless charging road system unveiled at FAW Sci-Tech innovation base in Changchun in 2023.
Chamonix Mont Blanc Valley, France	eRoad Mont Blanc is a 1 km conductive contact rails-based project launched in 2023. It uses Alstom's ground-level power supply system and is funded by the French Government and European Union. Works on the 420 m demonstrator carriageway completed in December 2024; System and vehicle validation checks to be undertaken in 2025.
Greater Paris, France	A 2 km section of the A10 motorway has been equipped with Elonroad's conductive rail charging system , in partnership with VINCI Autoroutes. Testing expected to begin in 2025.
Schleswig-Holstein, Germany	A 5 km e-Highway field trial using catenary lines launched in 2019 has enabled pantograph-equipped trucks to cover more than 55 000 km .
Hessen, Germany	17 km overhead catenary system , installed by Siemens, in operation since May 2019, with 11 trucks in operation (one BEV).
Baden-Württemberg, Germany	3.4 km-long eWayBW overhead catenary system , supplied by Siemens, in operation since 2021 with five trucks in regular operation.
Bayern, Germany	Planned electrified road system.
Rhein-Main/Rhein-Neckar, Germany	Lkw-Innovationscluster planned electrified road system.
Cologne, Germany	100-m E-Charge inductive charging track installed by ElectReon undergoing testing.
Balingen, Germany	ELINA project by ElectReon with 1 km of induction charging to power an electric bus announced in 2022.
Karlsruhe, Germany	100-m ElectReon induction charging system to power an electric public bus in the Port of Karlsruhe .
Bavaria, Germany	Planned 1km ERS announced in 2022 as part of EIMPOWER pilot project .
Brescia, Italy	Arena del Futuro test project uses 1km of induction charging.
Kashiwa, Japan	Tests began in October 2023 on a system using embedded wire coils for inductive power transfer at traffic lights.
Trondheim, Norway	Induction charging installed by ElectReon to power an electric bus, with funding from the Norwegian government.
United States	In late 2023, the country's first wireless charging road system entered operation. Technology developer ElectReon is now partnering with parcel delivery service UPS and electric truck manufacturer Xos to test both stationary and dynamic wireless charging technologies for commercial vehicles.
Indiana, United States	Construction of a test bed for wireless charging began in April 2024, with plans to electrify a section of an Indiana interstate in the next 4-5 years.

Sources: IEA analysis and the International Council on Clean Transportation (2024) [Market Spotlight](#).

Wide application of ERS faces many hurdles – besides the large investments required for infrastructure development, vehicles must be adapted to the specific charging technology. Governance can also be difficult, as ERS requires a market design appropriate for both the [transport and energy market](#), which have distinct regulatory regimes. The costs of ERS must also be evaluated in the context of alternative charging systems: A 2024 report commissioned by the Swedish government (which had previously announced ambitions to build [3 000 km](#) of electric roads by 2035) [recommended against](#) further expansion of ERS in Sweden, in part as the development of batteries for EVs has progressed rapidly. Plans to build the world's first [permanent electrified road](#), which would have connected Stockholm, Gothenburg and Malmö, were paused in 2023.

7. Electric vehicle batteries

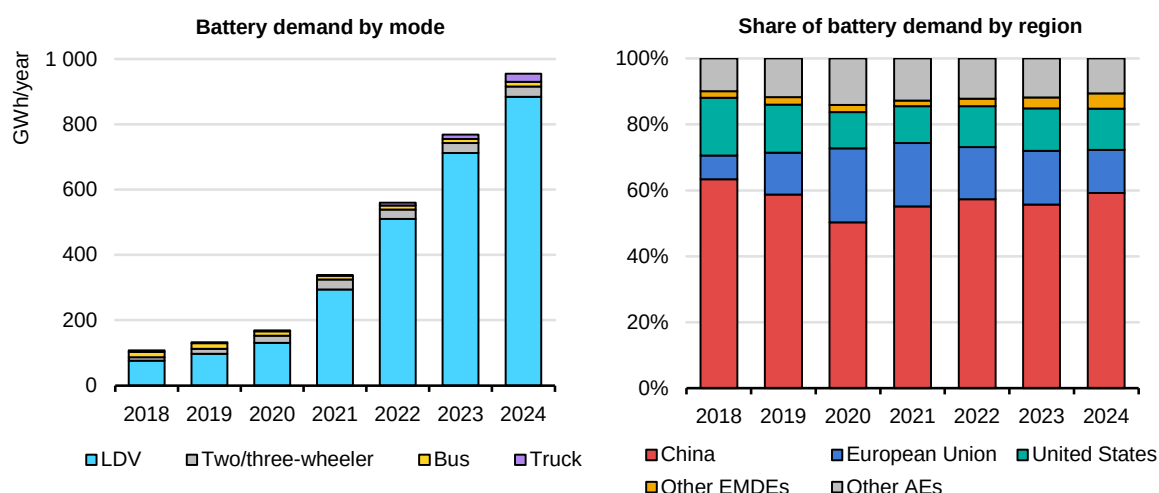
Trends in battery demand

Global battery demand for the energy sector hit the 1 TWh milestone in 2024

Electric cars remain the main driver of battery demand, but demand for trucks nearly doubled

Battery demand in the energy sector, for both EV batteries and storage applications, reached the historical milestone of 1 TWh in 2024. Demand for one average week alone in 2024 exceeded the total demand for an entire year just a decade earlier. Demand was largely driven by growth in EV sales, as demand for EV batteries grew to over 950 GWh – 25% more than in 2023. Electric cars remain the principal factor behind EV battery demand, accounting for over 85%. Compared to 2023, the sector whose demand grew the most was electric trucks, growing over 75% in 2024 to reach nearly 3% of global EV battery demand. Electric truck battery demand was driven by growth in China, but demand also ramped up in Europe (about 25%), which accounted for about 10% of the global total.

Electric vehicle battery demand by mode and region, 2018-2024



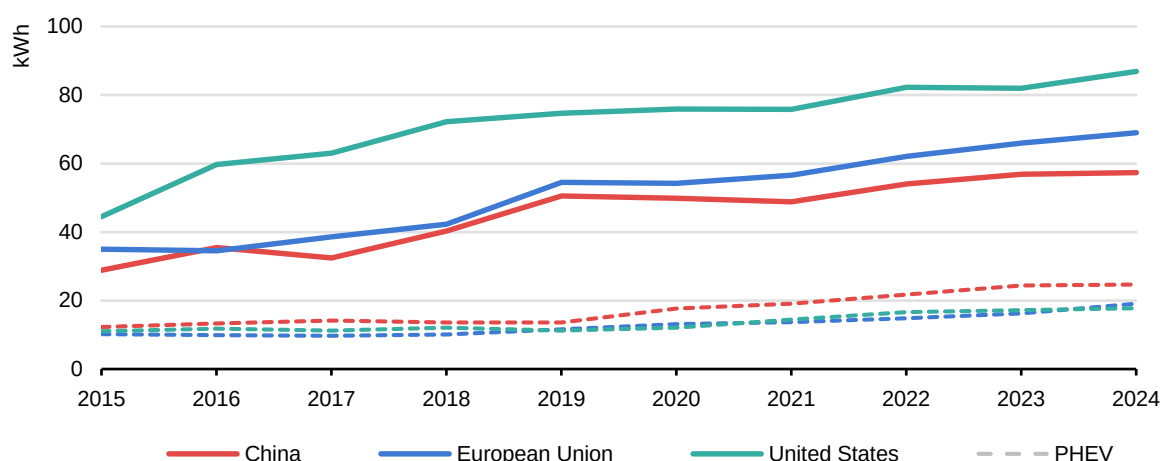
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Notes: LDV = light-duty vehicle, including cars and vans; EMDEs = Emerging markets and developing economies; AEs = Advanced economies. Battery demand is defined here as the volume-weighted average battery size multiplied by vehicle sales by mode and region. It reflects the batteries installed in vehicles sold in each region, and not the battery demand for vehicles manufactured in each region. Electric vehicle and battery stockpiling are excluded from the analysis.

Source: IEA analysis based on [EV Volumes](#).

In 2024, EV battery demand grew by over 30% in China, and by 20% in the United States, in stark contrast with the European Union, where demand stalled. Battery demand in the United States nearly matched that of the European Union in 2024, in part as a result of its approximately 25% larger battery size per EV. Emerging markets and developing economies other than China continued to represent only a small share of global battery demand, reaching nearly 5% in 2024. Nevertheless, their share has doubled since 2022, underpinned by sustained growth in Southeast Asia, India and Brazil.

Average electric car battery pack size by region and powertrain, 2015-2024



IEA. CC BY 4.0.

Notes: PHEV = plug-in hybrid electric vehicle. Solid lines represent the sales-weighted average battery pack size for battery electric cars, while dashed lines indicate the same for plug-in hybrid electric cars.

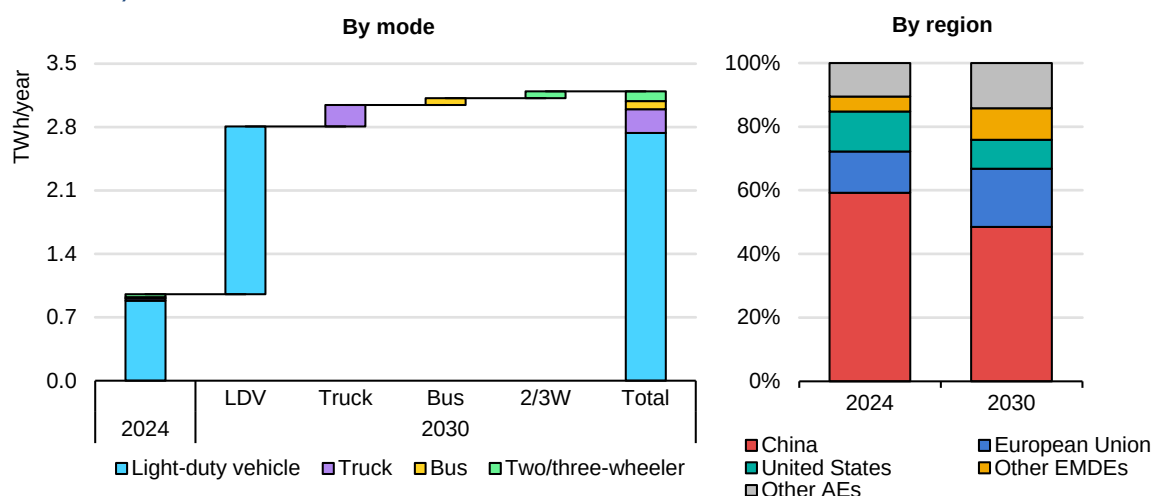
Source: IEA analysis based on [EV Volumes](#).

Outlook for battery demand

Electric vehicle battery demand jumps more than threefold by 2030

EV battery demand continues to grow, and is expected to reach more than 3 TWh in 2030 in the STEPS, up from about 1 TWh in 2024. While electric cars will remain the primary driver of battery demand, other modes are set to gain market share. Notably, the contribution of electric trucks to EV battery demand triples by 2030 to reach more than 8%, up from nearly 3% in 2024.

Battery demand for electric vehicles by mode and region in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: LDV = light-duty vehicle, including cars and vans; 2/3W = two/three-wheeler; EMDEs = emerging markets and developing economies; AEs = advanced economies. Battery demand is defined here as the volume-weighted average battery size multiplied by vehicle sales by mode and region. It reflects the batteries installed in vehicles sold in each region, and not the battery demand for vehicles manufactured in each region. Electric vehicle and battery stockpiling are excluded from the analysis.

Battery demand is also set to become more geographically diverse. In the STEPS, emerging markets and developing economies other than China are expected to double their share of EV battery demand, from nearly 5% in 2024 to 10% in 2030. The share of global demand in the European Union and other advanced economies, such as the United Kingdom, Canada, Japan and Korea, is also projected to grow, while the share of the United States is projected to decline from about 13% in 2024 to less than 10% by 2030. Meanwhile, China's share of global battery demand declines from 60% in 2024 to just under 50% by 2030, although it remains by far the single largest source of demand.

Battery industry trends

Chinese manufacturers are increasing their competitive advantage

Low critical mineral prices and intense competition drove down battery prices in 2024, but China's price advantage is widening

Prices for lithium-ion battery packs fell 20% in 2024 – the largest drop since 2017 – as a result of low critical mineral prices and battery margins being [squeezed](#) through competition, predominantly in China. Lithium prices, in particular, dropped

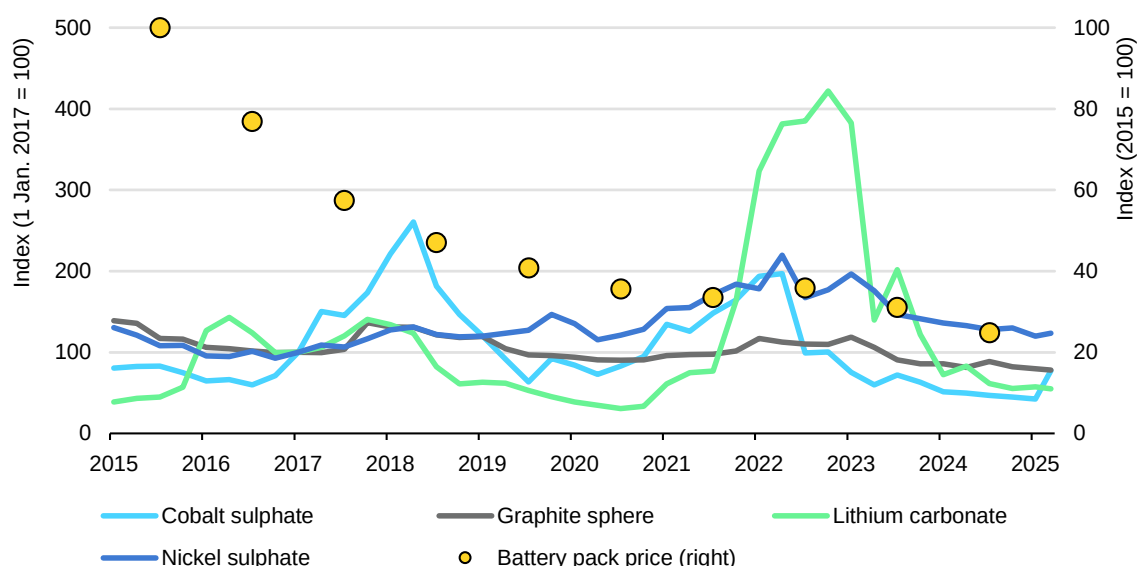
nearly 20% in 2024, reaching similar prices to those at the end of 2015, despite lithium demand in 2024 being about six times bigger than in 2015.

Low critical mineral prices are primarily driven by supply surplus, which is making it [difficult](#) for some mining companies to compete, thus increasing the level of supply chain concentration among established players. This surplus is [expected](#) to persist over the next few years, but low prices could discourage future investments and might cause supply [shortages](#) for [lithium](#) and [nickel](#) by 2030. In addition, the high [geographical](#) and [ownership](#) concentration of their supply chains may cause market distortions, increasing market risk.

An undersupply of lithium would push up prices, to the benefit of the mining sector but to the detriment of battery and EV makers, as well as final consumers. The recycling sector, which could help curb cost increases, would also benefit from higher mineral prices. However, due to feedstock limitations, it will take about a decade before recycling has a significant impact on reducing primary mineral demand (see the Box on [battery recycling](#) below).

[Technology innovation](#), particularly related to [sodium-ion batteries](#) or [direct lithium extraction](#), could be instrumental in reducing the risk of lithium undersupply and its potential impact, and avoiding price spikes similar to those seen in 2022. Additionally, vertical integration through [upstream investments](#) can help battery suppliers to lower production costs while safeguarding against the risk of volatile critical mineral prices.

Price of selected battery metals (left) and lithium-ion battery packs (right), 2015-2025



IEA. CC BY 4.0.

Notes: "Battery pack price" refers to the volume-weighted average pack price of lithium-ion batteries across the electric vehicles and battery storage sectors. 2025 refers to data up to the end of March 2025.

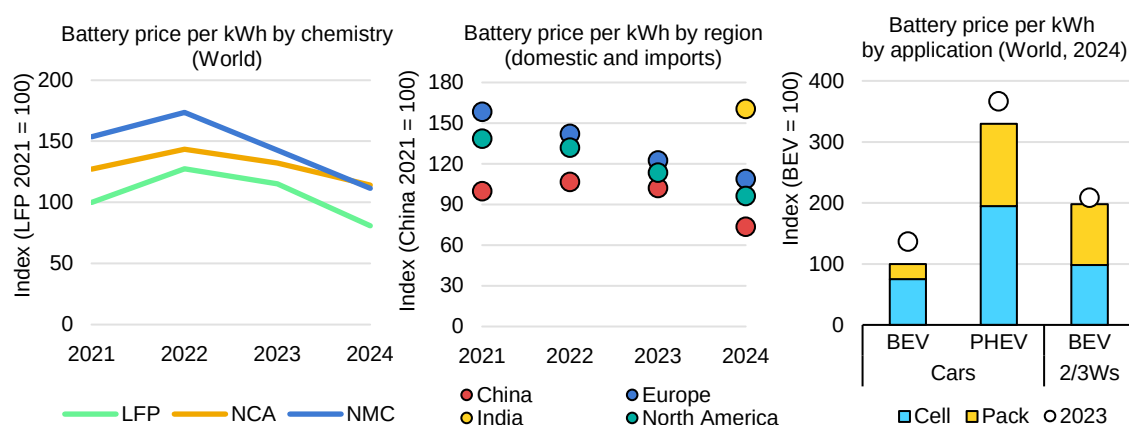
Sources: IEA analysis based on data from [Bloomberg](#) and [Bloomberg New Energy Finance](#) Lithium-Ion Price Survey (2024).

Battery pack prices fell in all markets, but the extent of the drop varied significantly, with the fastest declines seen in China, where prices fell nearly 30% in 2024, compared to 10-15% in Europe and the United States. This widened the gap between battery prices in China and the rest of the world, increasing the competitive advantage of Chinese EV and battery producers. The faster pace of battery [cost reduction](#) and [innovation](#) in China has been enabled by fierce competition that has driven [down](#) profit margins for most producers (though [not all](#)), at the same time as driving up manufacturing [efficiency and yields](#), as well as access to a large skilled workforce, and battery supply chain integration.

Battery chemistry also plays an important role, with lithium iron phosphate (LFP) batteries – the [main](#) battery chemistry used in China – being almost 30% [cheaper](#) per kilowatt-hour (kWh) than lithium nickel cobalt manganese oxide (NMC) batteries, which remain the most widely used batteries in the United States and Europe. NMC batteries still provide an energy density advantage, though the gap has [narrowed](#) in recent years. The energy density of LFP battery packs is about one-fifth lower by mass (Wh/kg) and about one-third lower by volume (Wh/L) than that of NMC packs. This is, however, partially offset by LFP's ability to reach [100%](#) state of charge when required without significant degradation, whereas NMC batteries are typically limited to [80%](#) to preserve long-term performance.

The higher energy density of NMC batteries remains an advantage for applications requiring longer ranges or operation in cold climates, where LFP technology is typically [less effective](#). However, LFP batteries have now reached a performance level sufficient for most EV applications, making their lower cost a key advantage for automakers aiming to mass markets.

Average battery pack price per watt-hour index by selected battery chemistry, region and mode, 2021-2024



IEA. CC BY 4.0.

Notes: LFP = lithium iron phosphate; NCA = lithium nickel cobalt aluminium oxide; NMC = lithium nickel manganese cobalt oxide; BEV = battery electric vehicles; PHEV = plug-in hybrid electric vehicle; 2/3Ws = two- and three-wheelers. Battery price refers to price per kWh for battery packs. Battery prices by region refer to the average battery price in a given region, including locally produced batteries and imports across EVs and battery storage applications. Data for India is not available between 2021 and 2023. Battery price by application refers to an average-sized vehicle.

Source: IEA analysis based on data from [Bloomberg New Energy Finance](#).

The battery price per kWh is also heavily dependent on the targeted application, with BEVs enabling the lowest costs. In 2024, battery pack prices per kWh for plug-in hybrid electric cars were more than three times those for battery electric cars, because of their smaller size and greater power requirements. In 2024, the average price of a 20 kWh PHEV battery pack – roughly the global sales-weighted average for standard plug-in hybrids – was about the same as a 65 kWh BEV battery pack, the global sales-weighted average for battery electric cars.

Pack components such as the battery management system are common to BEV and PHEV battery packs, but given that PHEV packs are smaller, the price of such components is spread across fewer battery cells, increasing the price per kWh. PHEV battery packs may also require more complex designs to accommodate the internal combustion engine, which increases their production cost. Additionally, because of the smaller pack size, each battery cell in the PHEV pack has higher power requirements to guarantee minimum acceleration standards while driving in full electric mode. This demands different battery designs, such as thinner electrodes, to improve battery power at the expense of its energy density,¹ further increasing the cost per kWh compared to BEVs. Smaller battery sizes also increase prices per kWh for 2/3W batteries.

Battery specifics, however, only determine prices for high volume. For instance, in China, electric truck battery prices per kWh are slightly lower than for battery electric cars, thanks to their larger size and therefore the reduced contribution of the battery pack cost. Electric truck markets in other countries are far less mature, and their battery price per kWh remains significantly higher – in 2024, prices were more than double those in China.

Lithium iron phosphate batteries continue to gain market share, and with them so do Chinese manufacturers

In 2024, LFP batteries made up nearly half of the global EV battery market, underpinning the efforts of manufacturers to [lower](#) EV prices and production costs in order to maintain or gain market share in an increasingly competitive market. China leads on the uptake of LFP batteries, which met nearly three-quarters of its domestic battery demand in 2024, and their share shows no sign of slowing down, reaching 80% of batteries sold in [November](#) and [December](#) 2024.

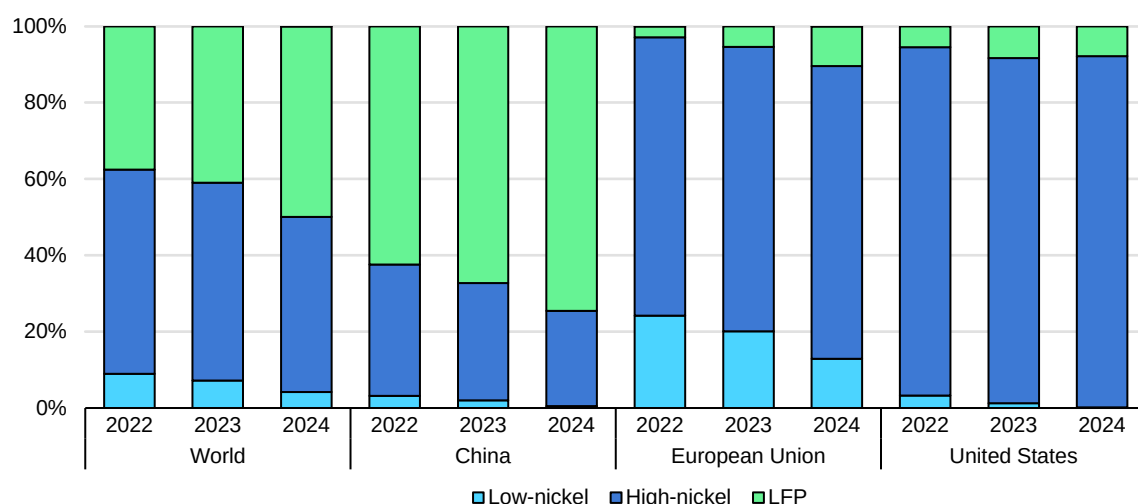
In the United States, the share of LFP batteries used in EVs slightly contracted in 2024, remaining below 10%, which may be a result of [tariffs](#) on Chinese batteries. In contrast, in the European Union, LFP battery adoption grew by about 90% for

¹ “Energy density” is used here as a general term referring to the amount of energy stored per unit of mass or volume. It can be divided into two specific metrics: specific energy (Wh/kg) and energy density (Wh/L). Specific energy influences the additional weight the battery adds to the vehicle, thereby affecting its efficiency. Energy density determines the amount of energy that can be stored in a battery pack of a given size, typically defined by the vehicle's chassis dimensions and shape.

the second consecutive year to reach more than 10% of the EU EV market. Notably, nearly all the LFP batteries for electric cars sold in Europe or the United States were produced in China, which today has a de facto [monopoly](#) on this type of battery. Market penetration of LFP batteries is moving even faster in other markets. In Southeast Asia, Brazil and India, the share of electric car batteries using LFP reached more than 50% in 2024. In Southeast Asia and Brazil, LFP uptake is led by imports from China, mostly by BYD, whereas in India it is driven by cars produced domestically, led by Tata Motors.

In the United States, the vast majority (three-quarters) of EVs equipped with LFP batteries are produced domestically, whereas in the European Union nearly two-thirds are imported from China. In both regions, LFP batteries are primarily sourced from China, with Tesla playing a central role – accounting for 85% of LFP battery-powered EVs produced in the United States and almost half of those sold in the European Union. Of Tesla's LFP EVs sold in the European Union, over half are produced in Germany, with the remainder imported from China.

Share of electric vehicle battery sales by chemistry and region, 2022-2024



IEA. CC BY 4.0.

Notes: LFP = lithium iron phosphate. Low-nickel includes lithium nickel manganese cobalt oxide (NMC) 333, NMC442, and NMC532. High-nickel includes NMC622, NMC721, NMC811, lithium nickel cobalt aluminium oxide (NCA), and lithium nickel manganese cobalt aluminium oxide (NMCA). LFP also includes lithium iron manganese phosphate (LFMP). Battery chemistry sales share is based on the battery capacity of EVs registered in the different regions. This calculation assumes that 95% of electric trucks, buses and light commercial vehicles sold in China use LFP, and that 70% of electric trucks and electric buses sold outside of China use high-nickel chemistries. Two/three-wheelers are excluded from the analysis. Battery sales reflect the batteries installed in vehicles sold in each region, and not the battery demand for vehicles manufactured in each region. Electric vehicle and battery stockpiling are excluded from the analysis.

Sources: IEA analysis based on data from [EV Volumes](#) and [China Automotive Battery Industry Innovation Alliance](#).

European OEMs are looking increasingly favourably on LFP batteries as a way of reducing production costs and are therefore interested in securing more supplies. Initiatives such as the recently announced [joint venture](#) between Stellantis and CATL for an LFP battery manufacturing plant of up to 50 GWh in Spain could

therefore help the European automotive industry to reduce costs and increase its competitiveness in the coming years. However, investments in LFP battery manufacturing in Europe might suffer as a result of the recent [proposition](#) from the Chinese government to limit exports of key battery technologies, including LFP cathode production and lithium processing. Overall, renewed interest in the LFP chemistry [exacerbates](#) the difficulties facing the European battery industry, which has historically focused on NMC batteries.

The year 2024 was a challenging one for the European battery industry, with both small and large producers suffering for different reasons. New players such as Northvolt, which filed for [bankruptcy](#) in the [United States](#) and [Sweden](#), faced serious difficulties in scaling up production, leading to insufficient manufacturing [yield](#) and high production costs. The case of Northvolt was further [aggravated](#) by limited experience, ambitious expansion plans, and excessively widened scope, leading to insufficient focus on scaling up high-quality battery cell production. Falling battery prices worldwide also weighed heavily on small producers, which have fewer resources and insufficient production volumes to withstand [lower profit margins](#), and are now turning to a more [cautious](#) growth path.

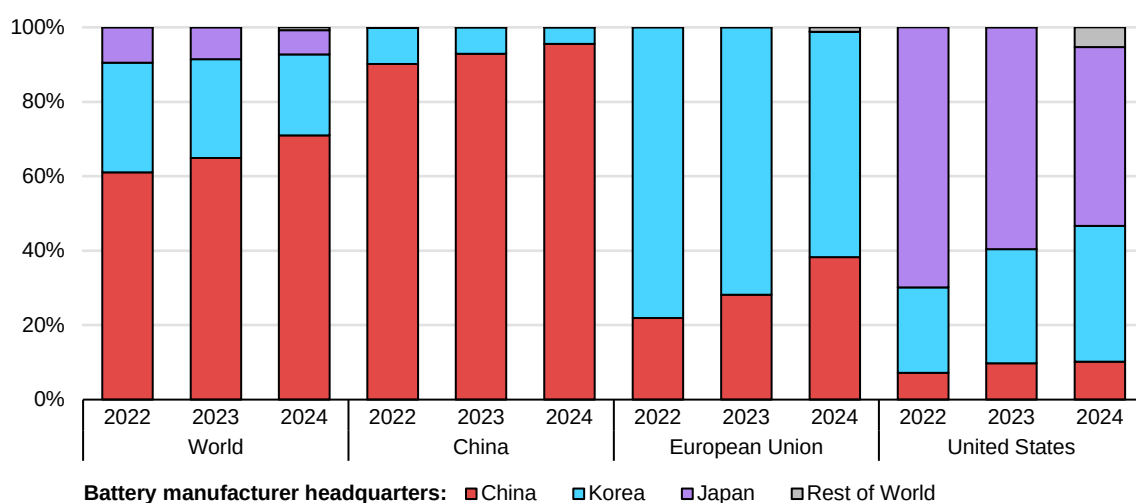
Korean companies, such as LG Energy Solution in Poland, are the largest battery producers in Europe, but their market share is also under pressure. Over the past 2 years, the market share of Korean manufacturers in the European Union has fallen from nearly 80% in 2022 to 60% in 2024, to the benefit of Chinese manufacturers. A key reason for this is the increased success of the LFP chemistry. In contrast, the share of Korean companies in the United States grew from about 20% in 2022 to over 35% in 2024, at the expense of Japanese manufacturers.

Korean manufacturers are rising to the challenge and are now [investing](#) in LFP, including through [innovation](#) efforts, and are scaling up LFP battery production, including in [Europe](#) and the [United States](#). LFP battery development is also advancing in Japan: In early 2025, Nissan [announced](#) plans to build an LFP battery plant after receiving [government certification](#) in late 2024. Yet Chinese manufacturers are continuing to innovate LFP [chemistry](#) and [performance](#) simultaneously, further raising the bar for other producers. At the same time, the Chinese government's [proposed](#) export restrictions on [advanced](#) LFP technologies could limit technology transfer.

In the United States, Panasonic – historically Tesla's main battery partner – remained the country's largest battery producer in 2024, accounting for nearly half of the electric car market. However, its share is declining as Korean producers like LG Energy Solution, Samsung and SKI invest heavily in the US market. Tesla also ramped up its own battery production in 2024, primarily for use in the Cybertruck.

Battery production in the United States is expanding rapidly, spurred by the implementation of [tax credits](#). Manufacturing capacity has doubled since 2022, reaching more than 200 GWh in 2024, with nearly 700 GWh of [additional capacity](#) under construction. Around 40% of existing and committed capacity is being operated or developed by established battery makers in close collaboration with automakers. Nevertheless, the cost of production remains [higher](#) than in Asia, if not accounting for incentives, and sudden policy shifts could affect the emerging US battery industry, [increase](#) production costs, or slow expansion in the near to medium term.

Share of electric car battery sales by battery manufacturer's headquarters, 2022-2024



IEA. CC BY 4.0.

Notes: Battery refers to battery cells. It reflects the batteries installed in vehicles sold in each region, and not the battery demand for vehicles manufactured in each region. Electric car and battery stockpiling are excluded from the analysis.

Sources: IEA analysis based on data from [EV Volumes](#).

Battery innovation is accelerating, and it is not limited to new chemistries

Advanced battery technologies under development include solid-state, sodium-ion, lithium-sulphur, iron-air, and redox-flow batteries, among others. Some of them, like iron-air and redox-flow batteries, target different applications to established lithium-ion technologies, such as longer-duration storage for grid applications. Others, like sodium-ion batteries, aim to reduce dependence on lithium. Lastly, technologies like solid-state and lithium-sulphur batteries could also accelerate electrification in sectors that require or would benefit from higher energy densities, such as long-haul electric trucks or short-haul boats and planes. However, their deployment in these sectors will depend on meeting stringent [safety requirements](#) and on their [total cost of ownership](#).

Sodium-ion batteries gained significant attention in 2022 as lithium prices surged, leading to the [first](#) EVs using the technology. Despite enthusiasm waxing and waning as a result of material supply chain challenges and falling lithium prices in 2023 and 2024, CATL – the world’s largest battery producer – announced its [second generation](#) of sodium-ion batteries in 2025, alongside the launch of a dedicated sodium-ion battery [brand](#). Meanwhile, BYD is also investing in sodium-ion battery production for [EVs](#) and [battery storage](#). In March 2025, HiNa launched its [new](#) sodium-ion battery, which offers improved energy density and faster charging compared to the previous generation, heralding a promising year for this technology. However, recent [analyses](#) indicate that sodium-ion batteries will require either increased energy density or more favourable operating conditions – particularly higher lithium prices – to compete with LFP batteries on a price per kWh basis. Nevertheless, sodium-ion technologies could play a significant role during times of elevated lithium prices and may offer a cheaper option for batteries in cold climates, where LFP batteries typically perform [less well](#).

In 2024, **solid-state batteries** moved closer to commercial reality with new large prototypes and manufacturing investments from [Samsung SDI](#), [Toyota](#), [NIO](#), [Honda](#), [Quantum Scape](#), [BASQUEVOLT](#), and [Factorial](#), among others, and the creation of a government-led Chinese battery [alliance](#), including large producers such as CATL, BYD, SAIC and Geely, to accelerate solid-state battery development. Despite this, their potential advantages, including enabling higher ranges and safety, still need to be [demonstrated](#) for battery packs manufactured at scale and tested under controlled, realistic and standardised conditions. The technology readiness level (TRL) of solid-state batteries therefore remains at large pilot stage ([TRL 6](#)), although this could change rapidly with companies like [Toyota](#) and [BYD](#) planning first mass production by 2027-2028. However, volumes will be [limited](#) initially, and it will take several years following roll-out for solid-state batteries to eventually become competitive with lithium-ion batteries. Additionally, “solid-state batteries” is often used as a generic term covering a [range](#) of options between fully solid-state and incumbent lithium-ion batteries, which creates some confusion. The first “solid-state batteries” to be commercialised might be semi- or quasi-solid-state batteries – for example using gel-like electrolyte² or incorporating small volumes of liquid electrolytes – as they could help address some scale-up [challenges](#) and reduce production costs.

Lithium-sulphur (Li-S) batteries, promising higher specific energy (Wh/kg) and lower reliance on critical minerals, have also gained momentum. The US start-up Lyten [announced](#) the world’s first Li-S gigafactory, while Stellantis [partnered](#) with Zeta to commercialise this technology by 2030. However, several challenges remain, including improving volumetric energy density (Wh/L), enhancing

² French company Blue Solutions already [markets](#) a semi-solid-state battery using lithium metal anode and a gel electrolyte that requires the battery to be heated during use, and [plans](#) to invest more than EUR 2 billion in a factory in France by 2030.

durability, and addressing safety concerns related to the use of lithium metal anodes. Overcoming these hurdles will be key to enabling real-world applications.

Advances in battery **recycling** are also being made, for example [combining](#) pyrometallurgy and hydrometallurgy processes, [increasing](#) the recovery efficiency of reactive metals such as lithium, recycling the [graphite](#) in the anodes, or through the development of new recycling approaches, such as [electrochemical extraction](#). However, recycling feedstock availability remains limited, restricting the impact of recycling in the short term (see Box [below](#)).

Options for **battery reuse** at the end of their first life for less demanding applications are also under development, with the [majority](#) of companies in the sector based in Europe. However, the economic viability of reuse is complicated by upstream competition from recyclers looking for access to end-of-life batteries, downstream competition from the falling prices of new batteries, and [challenges](#) associated with battery dismantling and repurposing while ensuring strict safety standards. [Second-hand](#) EV markets may play a larger role in supporting reuse and also increasing [affordability](#).

Innovation extends far beyond battery chemistries, and the already broad landscape of battery innovation is getting even broader.³ In 2023 and 2024, there was a remarkable surge in **improvements for incumbent lithium-ion batteries**, from [superfast charging](#) and [“no-degradation”](#) batteries to [ultra-energy-dense](#) batteries and new [charging platforms](#), [manufacturing processes](#), [cell formats](#) and [pack designs](#), among others. Advances in manufacturing are also notable: for example, [artificial intelligence](#) for image analysis can enable the [early detection](#) of battery defects and their root causes, thereby improving production yields and reducing scrap rates. This capability is critical for scaling up production given the pace of modern gigafactories – a 50 GWh facility can produce up to 10 million (cylindrical) or hundreds of thousands (prismatic) EV battery cells per day.⁴ The nature and pace of innovations in legacy technologies are already making a big impact on the market, posing a formidable challenge for emerging technologies to compete.

³ See IEA (2025) [State of Energy Innovation](#) for deeper insights into how this landscape is evolving.

⁴ Assuming an average plant utilisation factor of 85% over the year, a cell voltage of 4 volts, and a cell capacity of 60 ampere hours (prismatic) and 3 ampere hours (cylindrical).

Battery recycling is important, but its benefits will take time to materialise

Battery recycling is crucial for the battery industry's long-term sustainability, and is being promoted by industry organisations and governments through dedicated [investments](#) and regulations. For instance, the EU [Batteries Regulation](#) sets requirements for minimum recycling efficiency and recycled contents that will increase progressively. Recycled battery metals such as nickel, cobalt and lithium can incur [80% less](#) GHG emissions than primary materials produced from mining and refining, while also [reducing](#) local environmental impacts, including water use and biodiversity loss near mines.

In addition to sustainability, governments are prioritising supply chain security. Recycling can enhance resilience for consumer countries without direct access to battery minerals, but only if there is a simultaneous development of the midstream battery supply chain, particularly the cathode active material (CAM) industry. To realise the security benefits, end-of-life batteries must be recycled, and the recovered minerals processed and utilised domestically, or in a partner country, to produce CAMs for batteries. However, the CAM industry is progressing more [slowly](#) than the battery industry in Europe and the United States. In the absence of a domestic industry, the recycled minerals would need to be exported for processing and then reimported as CAMs, or within batteries or EVs, thereby forfeiting the supply chain security advantage.

Recycling industries in Europe and North America have focused on NMC batteries – the [main](#) chemistry used for electric cars in these regions, but [advances](#) in LFP batteries are now making them more attractive outside of China, where LFP already leads the EV battery market. The rise of [cheaper](#) batteries such as LFP poses a [challenge](#) to the economic viability of battery recycling, which requires sufficiently high concentrations of valuable minerals in batteries to be profitable. Nevertheless, this does not preclude LFP battery recyclability, and NMC recycling facilities can be modified to process LFP batteries, though this might require different business models. [Toll-based models](#) – through the implementation of [gate fees](#) – can ensure the economic viability of LFP recycling, especially when lithium prices are low. Regulations would need to define how these toll fees are distributed to guarantee the proper management of all end-of-life batteries.

It will take time for the battery recycling industry to significantly affect primary mineral demand, as feedstock remains limited and EV batteries may last [longer](#) than previously expected. End-of-life EV and storage batteries are expected to account for only [one-third](#) of recyclable feedstock by 2030 and even less in the interim, with manufacturing scraps making up the rest. It will require about a decade for end-of-life batteries to become the main feedstock. In 2035, if countries fulfil their announced climate pledges, recycling would [reduce](#) global primary demand for cobalt by over 15% (40% in 2050), and for lithium and nickel by only about 5% (25% in 2050).

Battery production and trade

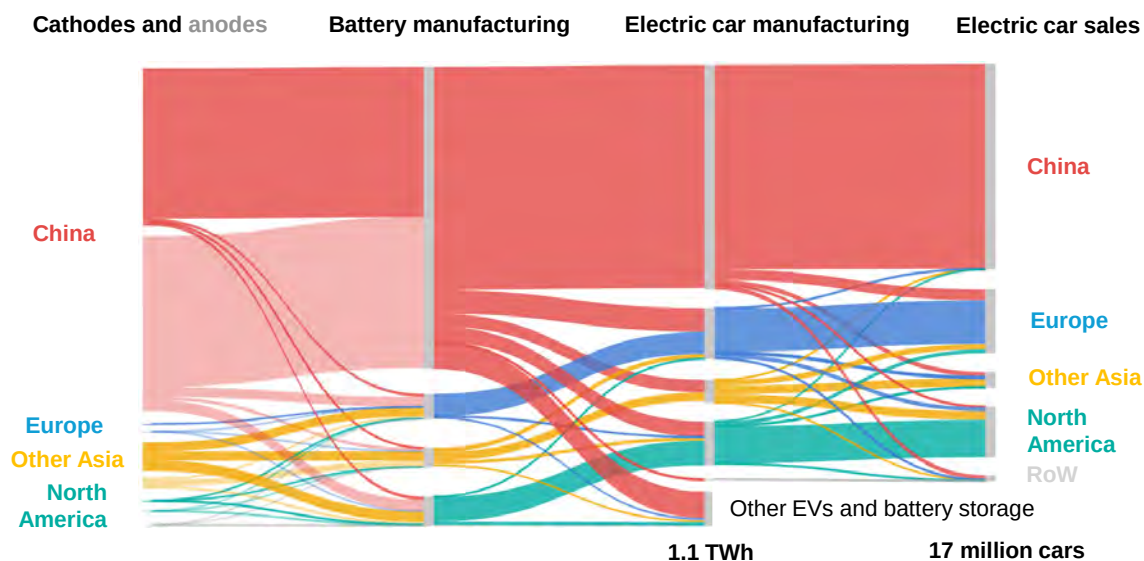
The battery market is being reshaped by two distinct trends: increasing consolidation, and government-led efforts to geographically diversify battery supply chains. Whereas markets used to be regionalised and small, they are now global and very large, and uncertainty over technological development is giving way to standardisation. In this [new phase](#), economies of scale, partnerships along the supply chain, manufacturing efficiency, and the capacity to bring innovations swiftly to market will be even more crucial for manufacturers to remain competitive.

The battery supply chain remains geographically concentrated

The EV and battery supply chain becomes increasingly geographically concentrated when moving upstream from car manufacturing to battery cell and component production. China was responsible for 80% of global battery cell production in 2024, while the remainder was produced in the United States, the European Union, Korea and Japan. Importantly, the production of lithium-ion battery manufacturing [equipment](#) is also highly concentrated, with China, Korea, and Japan [leading](#) the market. China has also established a near monopoly on battery components production, supplying almost 85% of cathode active materials – including NMC and LFP chemistries – and over 90% of anode active material production, predominantly graphite. Outside of China, only Korea and Japan offer sizeable production capacity for cathode components. Korea also produces anodes, and Indonesia is [expected](#) to bring some diversification to the market. Nonetheless, China is set to remain the largest producer of batteries and their components by some distance in the medium term, based on announced projects and [competitive advantages](#).

The [geographical concentration](#) of [battery mineral](#) mining and refining needed for battery cathodes and anodes is also a concern. In 2023, Australia, Chile and China mined about 85% of global lithium, with almost 65% refined in China and another 25% in Chile. Indonesia accounted for over half of nickel mining in 2023, while China and Indonesia together refined more than 60%. In the same year, the Democratic Republic of Congo was home to almost two-thirds of the world's cobalt mining, though three-quarters of all cobalt refining was handled in China. Graphite supply, the only critical mineral used for anodes today, is even more concentrated, with China responsible for 80% of mining and over 90% of refining.

Global manufacturing and trade flows of electric cars, lithium-ion batteries, and key components, 2024



IEA. CC BY 4.0.

Notes: RoW = Rest of World; EV = electric vehicle; Cathodes and anodes refer to cathode and anode active materials. Flows are normalised to the battery (cell) manufacturing step, with cathode and anode active materials normalised such that their sum is scaled to the battery cell volume. Numbers below the charts refer to the total demand, not only the traded volume. The lighter-colour version of the flows going to battery manufacturing represents the anodes (anode active materials). Battery applications different from EVs and battery storage are excluded from the analysis. Electric vehicle and battery stockpiling are excluded from the analysis.

Sources: IEA analysis based on [EV Volumes](#), [Benchmark Mineral Intelligence](#), and [Bloomberg New Energy Finance](#).

Battery manufacturing capacity continues to grow

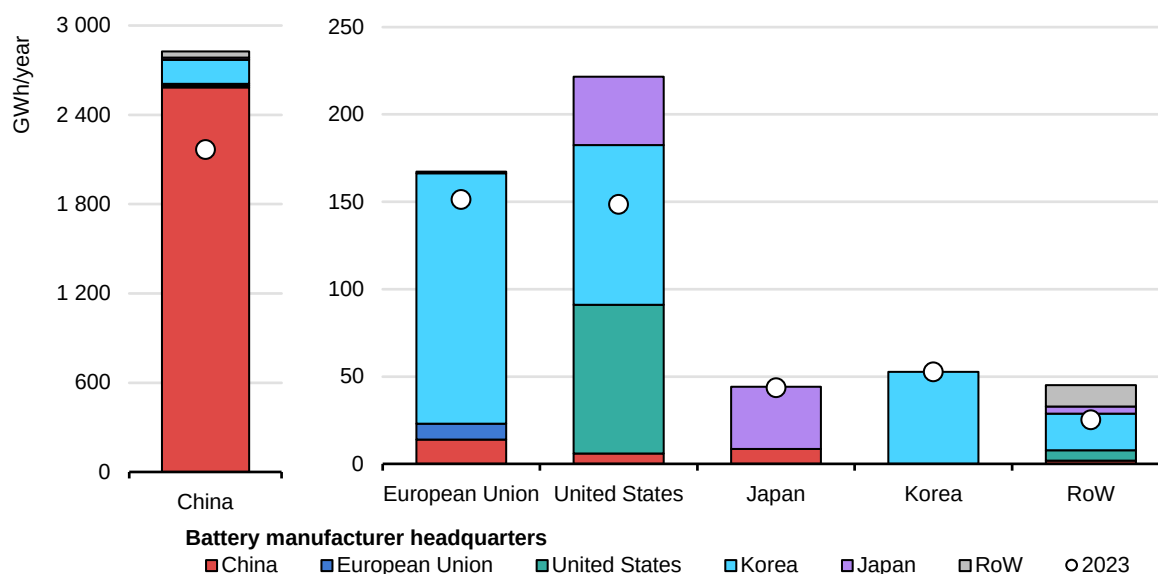
Global battery (cell) manufacturing capacity grew almost 30% in 2024 to reach more than 3 TWh – three times EV and battery storage demand in the same year. About 85% of global manufacturing capacity is in China, showing little change from 2023, and over 75% is owned by Chinese producers. Manufacturing capacity in the United States grew by almost 50%, led by Korean companies [attracted](#) by [tax credits](#), which accounted for nearly 70% of the growth in 2024. This led installed capacity in the United States to surpass that in the European Union, which nonetheless increased by 10% in 2024 despite the Northvolt plant in Sweden being halted following its [bankruptcy](#). The first [Indian](#) and [Indonesian](#) battery plants also opened in 2024, totalling more than 5 GWh/year and 10 GWh/year of manufacturing capacity, respectively.

Korean manufacturers remained the largest investors in overseas battery manufacturing capacity,⁵ accounting for over 400 GWh globally, compared to 60 GWh for Japanese and 30 GWh for Chinese producers. Korean manufacturers, such as LG Energy Solution (with capacity in Poland), and

⁵ This refers solely to existing manufacturing capacity as of 2024, and it accounts only for factories located outside the home country of the battery producer's headquarters.

Samsung and SKI (in Hungary), continue to be the main source of capacity in the European Union, and their importance is growing in the United States. If all announced projects are completed in full, the manufacturing capacity of Korean manufacturers outside of Korea would reach more than 1.1 TWh by 2030, 85% more than the announced overseas manufacturing capacity of Chinese battery producers.

Installed lithium-ion battery cell nameplate manufacturing capacity by region and location of manufacturer's headquarters, 2024



IEA. CC BY 4.0.

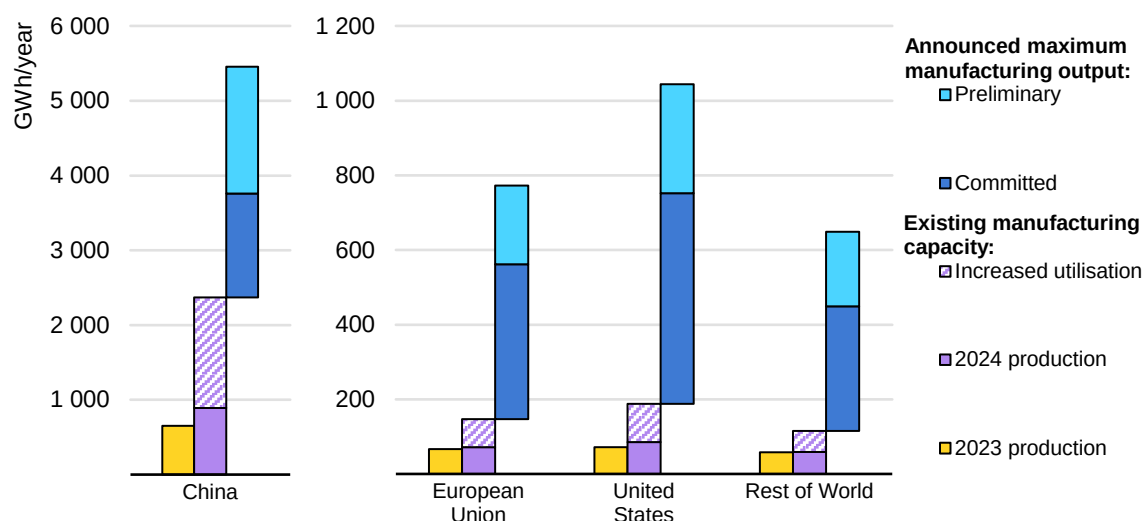
Notes: RoW = Rest of World. Lithium-ion battery manufacturing capacity installed in China, European Union, United States, Japan, Korea, and other countries sorted as a function of the company headquarters location (colours). For companies headquartered in a country but owned by companies headquartered in a second country, the headquarters of the owning company is considered for this analysis. The manufacturing capacity of joint ventures between automakers and battery producers is classified according to the battery producer headquarters.

Source: IEA analysis based on data from [Benchmark Mineral Intelligence](#).

Asian manufacturers are leading battery market expansion

Expansion plans for manufacturing capacity can drive geographical diversification in the battery industry. Committed projects – i.e. those that are either under construction or have reached a final investment decision – would increase manufacturing capacity in China by nearly 60%, and almost quadruple capacity in the European Union and the United States. This expansion would lead global manufacturing capacity to grow to about 6.5 TWh (and more than 9 TWh if accounting for all announcements), up from 3.3 TWh in 2024, and reduce China's share of global manufacturing capacity to about two-thirds by 2030, down from 85% in 2024. Ownership distribution is expected to diversify less, given that capacity expansion is predominantly driven by established manufacturers headquartered in China, Korea or Japan, whose expertise in the battery sector provides a significant competitive edge.

Historical production and announced expansion of battery manufacturing maximum output by region, 2023, 2024 and 2030



IEA. CC BY 4.0.

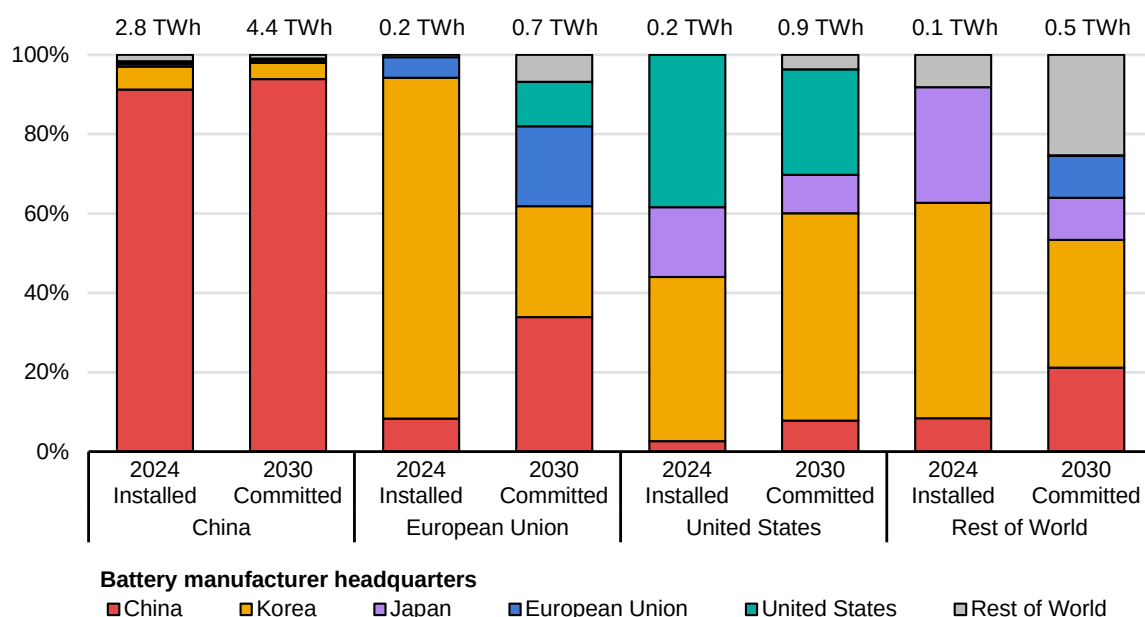
Notes: Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%, which is assumed to be the maximum average utilisation rate. A utilisation rate of 85% is also used for both committed and preliminary manufacturing capacity in 2030. Manufacturing capacity refers to companies already certified to serve both the EV and stationary storage markets and companies not yet certified to serve the EV market. Committed refers to plants that have reached a final investment decision and are starting or have already started construction works, and preliminary to plants that have been announced but are not yet being built. Production refers to EV battery and battery storage, and EV and battery stockpiling are excluded from the analysis. Data to end of Q1 2025.

Sources: IEA analysis based on data from [Benchmark Mineral Intelligence](#), [Bloomberg New Energy Finance](#), and [EV Volumes](#).

The European Union is the largest single destination for [overseas investments](#) by Chinese battery producers, whose share of manufacturing capacity in the region could quadruple, rising from less than 10% in 2024 to more than 30% by 2030. These investments are an opportunity for technology transfer, bringing the expertise needed to scale up production in the region and [drive down](#) costs, which would benefit domestic automakers at a critical time for the industry. However, this may also create challenges for the region's established and emerging battery producers.

The share of battery manufacturing capacity in the European Union owned by Korean producers is expected to fall sharply from about 85% in 2024 to nearly 30% in 2030, while the share of EU-based companies could reach 20%, up from 5% at the end of 2024. However, this includes plants facing significant uncertainty, such as the Northvolt plant in [Germany](#), for which Germany assumed over [EUR 600 million](#) in debt, and which is [not](#) directly affected Northvolt's [bankruptcy](#). More generally, [concerns](#) are growing about the ability of smaller European producers to [scale up](#) production and compete with established global players, which may lead to a much smaller share of the future EU battery market being captured by domestic manufacturers.

Share of nameplate manufacturing capacity by region and location of battery producer's headquarters, 2024-2030



IEA. CC BY 4.0.

Notes: Committed refers to the sum of the installed manufacturing capacity (2024) and plants that have reached a final investment decision and are starting or have already started construction works. Manufacturing capacity refers to battery cells. For companies headquartered in a country but owned by companies headquartered in a second country, the headquarters of the owning company is considered for this analysis. The manufacturing capacity of joint ventures between automakers and battery producers is classified according to the battery producer headquarters. Numbers above each bar indicate the total nameplate manufacturing capacity in terawatt-hours (TWh) of batteries per year. Data to end of Q1 2025. Sources: IEA analysis based on data from [Benchmark Mineral Intelligence](#) and [Bloomberg New Energy Finance](#).

Collaboration between Korean or Japanese battery producers and OEMs operating in the United States is proving successful, with Korean companies leading investments in the country. They held or participated in 40% of the battery manufacturing capacity in the United States in 2024, and committed investments are expected to boost their share to over 50% by 2030. Meanwhile, based on committed projects, the share of Japanese companies would fall by almost half by 2030, and that of domestic companies like Tesla would drop from nearly 40% in 2024 to less than 30% in 2030. In addition, some companies primarily or fully owned by Chinese groups, such as Envision and Gotion, have also invested or announced plans to invest in the United States, but recent [policies](#) might lead to the cancellation of these plans.

Outside of today's three main EV markets, 60% of committed capacity is set to be added in other advanced economies thanks to growing demand and government support, including in [Canada](#), other [European](#) countries, [Korea](#), and [Japan](#). The remaining more than 150 GWh of committed manufacturing capacity is being built in Southeast Asia, India and Morocco. Although these regions have attracted fewer investments to date due to limited domestic battery demand, they are increasingly generating interest from battery manufacturers.

Southeast Asia is attracting significant Chinese investments, which could speed up technology and innovation transfer. Indonesia, home to half the world's mined nickel needed for NMC batteries, is also investing heavily in battery component production – such as cathode and anode active materials – and its first [graphite anode](#) plants began production in 2024. India also has the potential to [unlock](#) a substantial battery market and is [investing](#) in domestic battery production, but realising its ambition to become a major battery manufacturer will require [additional investments](#) and clear policy signals supporting EV demand. In Morocco, abundant phosphate reserves – a mineral essential for LFP batteries – along with an established car manufacturing industry and free trade agreements with the European Union and the United States, have spurred over [USD 15 billion](#) in announced investments. These investments comprise lithium processing and battery and component manufacturing, including a large battery manufacturing plant of [100 GWh](#), the first in Africa.

8. Outlook for energy demand

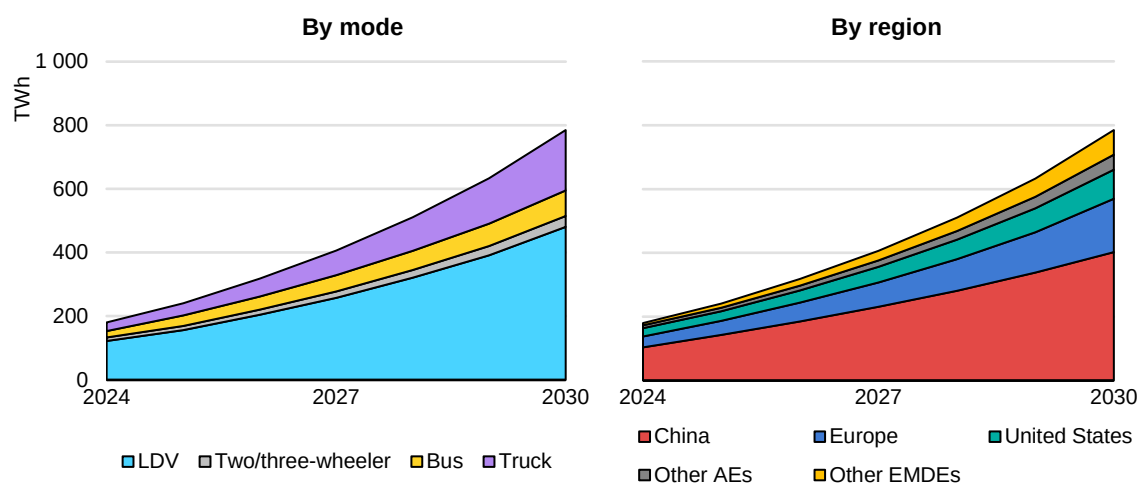
Electricity demand

Electric vehicles could account for more than 4% of European electricity demand by 2030

In 2024, the global fleet of EVs consumed around 180 TWh of electricity,¹ almost 60% more than the previous year. To put this in perspective, 180 TWh is more than the annual electricity consumption of Argentina. At the global level, EVs represented about 0.7% of final electricity consumption in 2024.

The stock of EVs is set to more than triple to 2030, but electricity demand could increase more than fourfold, reaching 780 TWh in the STEPS. This is driven by increasing consumption from electric trucks, as well as greater EV uptake in markets where people drive more per year. Total energy demand for road transport increases by only 5% in 2030 in the STEPS, while total road activity (in terms of vehicle kilometres travelled) increases by almost 20% during the same period, reflecting the greater energy efficiency of EVs.

Electricity demand by mode and by region in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: LDV = light-duty vehicle; AEs = advanced economies; EMDEs = emerging markets and developing economies. The analysis is carried out for each region in the transport model within the IEA's [Global Energy and Climate Model](#) (GEC-Model) separately and then aggregated for global results. Regional data can be interactively explored via the [Global EV Data Explorer](#).

¹ Electricity demand includes vehicle charging losses, which vary based on charging speed; it does not include transmission and distribution losses. For further information, see the [model documentation](#).

Globally, electric LDVs remain the greatest consumer of electricity for road transport, though their share of road electricity demand falls by around 5 percentage points in 2024 to slightly above 60% in 2030 in the STEPS. In China in 2024, LDVs were responsible for only around 55% of road electricity demand, and this remains the same in 2030 in the STEPS, illustrating China's success in EV adoption across a range of applications. In contrast, over 90% of electricity demand for road in the United States came from electric cars in 2024, though this falls to around 75% in 2030 in the STEPS, as demand from electric buses and commercial vehicles picks up. In Europe, the increasing number of electric heavy-duty trucks means their share of road transport electricity demand increases from less than 5% to more than 20% in 2030 in the STEPS.

In both China and Europe, the share of electricity demand from EVs reached the milestone of 1% in 2024. By 2030 in the STEPS, the share of electricity for EVs in Europe exceeds the share in China, as electricity demand for other end uses, such as industry and buildings, grows faster in China than in Europe. Globally, EVs represent 2.5% of electricity demand in 2030 in the STEPS.

Share of electricity consumption from electric vehicles relative to final electricity consumption by region and scenario in the Stated Policies Scenario, 2024 and 2030

Country/region	2024	2030
China	1.2%	3.6%
Europe	1.0%	4.3%
United States	0.6%	2.2%
Japan	0.1%	0.5%
India	0.2%	1.1%
Southeast Asia	0.2%	1.0%
Latin America	0.1%	1.0%
Global	0.7%	2.5%

Notes: Total electricity consumption is taken from the IEA's [Global Energy and Climate Model](#) (GEC-Model). Regional data can be interactively explored via the [Global EV Data Explorer](#).

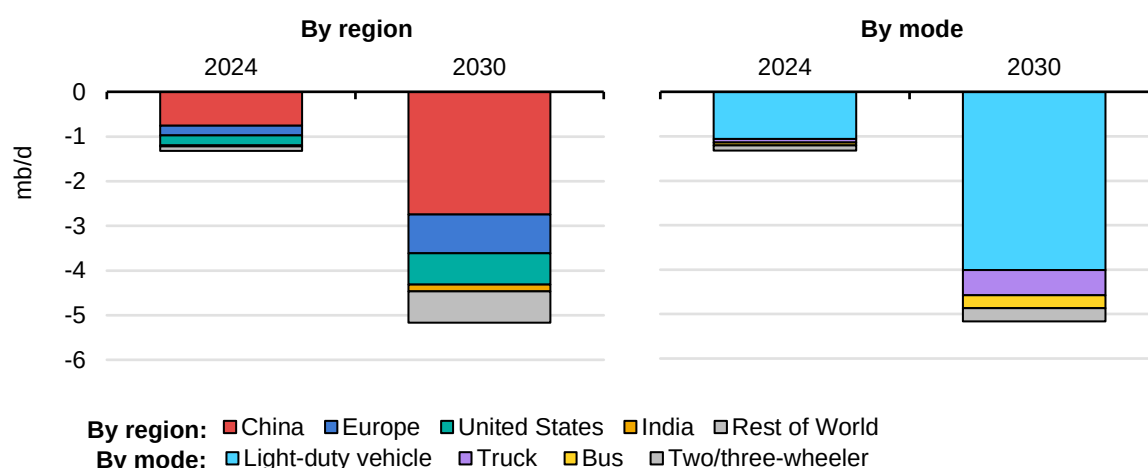
Oil displacement

Electric vehicles displace more than 5 mb/d by 2030

Expanding EV adoption continues to reduce oil demand, with oil displacement growing by 30% to over 1.3 mb/d in 2024 – equivalent to Japan's entire transport sector oil demand today. By the end of the decade, EVs are set to displace over 5 mb/d of diesel and gasoline in the STEPS, and China's EVs to account for half of displaced oil.

Electric LDVs drive most of the oil displacement, accounting for 80% today and around 77% by 2030. The relative impact of LDVs becomes smaller over time as technology developments and the expansion of charging infrastructure drive electrification in the heavy-duty segment, with electric trucks and buses together displacing nearly 1 mb/d in the STEPS by 2030.

Oil displacement by region and mode in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: Oil displacement is based on internal combustion engine (ICE) vehicle fuel consumption to cover the same mileage as the electric vehicle (EV) fleet. Oil displacement is calculated by assuming that the distance (total kilometres) travelled by EVs by segment each year would have been otherwise travelled by ICE vehicles or hybrid electric vehicles (HEVs). In the case of plug-in hybrid electric vehicles (PHEVs), where the powertrain uses both oil-based fuel and electricity, only the distance covered by electricity is included. This method of estimation assumes that EVs replace ICE or hybrid vehicles of the same segment, and that these vehicles follow the same driving behaviour. The accuracy of this assumption is uncertain; there is some evidence to suggest that EVs are driven further than their ICE counterparts, for example.

Governments will need to adapt tax policies to ensure both future revenues and growth of electrification

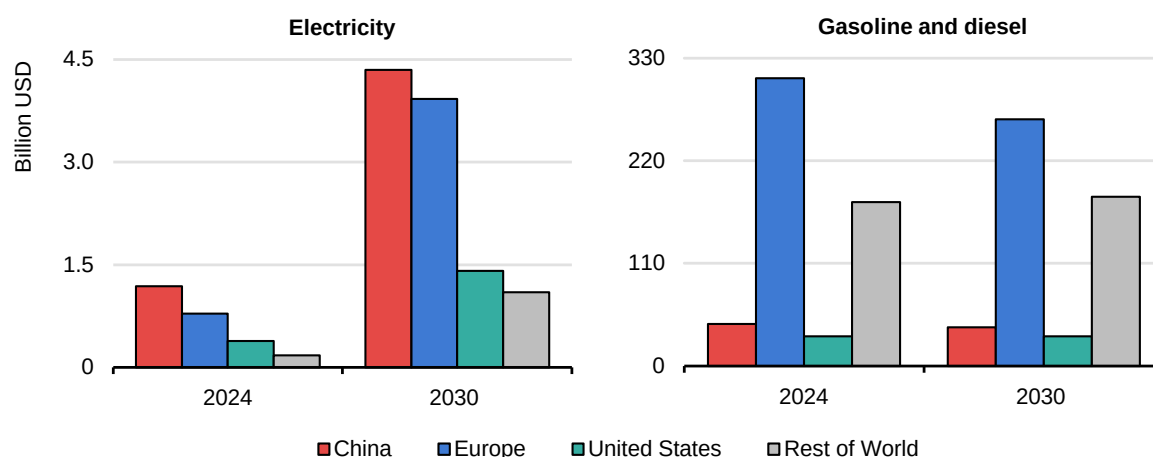
One of the primary financial challenges of vehicle electrification for governments is the resulting reduction in revenue from fossil fuel taxes. While efficiency improvements in ICEs have already had an impact on tax receipts, the fuel shift could lead to a further decline in tax income. Although EV drivers contribute to additional revenue through electricity taxes, this remains insufficient to fully compensate for the loss in gasoline and diesel tax income.

In 2024, electricity tax revenue increased by nearly 50% to reach more than USD 2.5 billion globally, while gasoline and diesel tax revenues accounted for USD 560 billion. As the global EV stock continues to rise, fossil fuel tax revenue is projected to decrease significantly to nearly USD 520 billion by 2030 in the STEPS, while electricity tax revenue grows to over USD 10 billion. If the decline in fossil fuel tax revenue is not compensated with alternative taxation measures, the effect of electrification displacing gasoline and diesel would result in a net tax

shortfall for governments reaching more than USD 65 billion globally by 2030. In this scenario, Europe would account for 55% of net tax shortfall if no changes are made to fuel taxation.

China's fossil fuel tax revenues are projected to decrease from USD 45 billion to USD 41 billion as the share of electric cars in the total fleet rises to around 35% by 2030 in the STEPS. However, the increase in China's electricity tax revenue due to vehicle fleet electrification would nearly fully offset the loss. In Europe, which sees the largest decrease in fossil fuel tax revenue, the net impact of electrification is expected to result in a tax revenue decline of USD 40 billion in the STEPS by 2030. In the United States, fossil fuel tax revenue is projected to increase by USD 0.1 billion due to slow electrification and growth in the overall vehicle fleet. Meanwhile, the rest of the world is set to experience an increase in combined fossil fuel and electricity tax revenue totalling around USD 6.5 billion by the end of the decade, driven by expected growth in both ICEs and EVs.

Electricity, gasoline and diesel tax income by region, 2024, and in the Stated Policies Scenario, 2030



IEA. CC BY 4.0.

Notes: Fuel tax rates are assumed to remain constant. Only federal tax rates are included.

Source: Analysis based on tax rates from [IEA Energy Prices](#).

Tax reforms to address tax income loss due to rising electromobility have tended to target three main areas: energy use (e.g. fuel excise duty), vehicle stock (e.g. registration tax) or road use (e.g. road tolls). For example, [New Zealand](#) ended its exemption for EVs from road use charges in 2024, and its new rate of NZD 76 (New Zealand dollars) (USD 46) per 1 000 km for BEVs is estimated to have generated tax revenue in the order of USD 50 million in 2024. To stabilise tax revenues, Norway, a world leader on electromobility, with nearly 90% share of car sales being battery electric in 2024, introduced a vehicle weight tax of NOK 12.08 Norwegian kroner (USD 1.1) per kilogramme on BEVs, generating

around USD 0.15 billion in 2024. Prior to this, in 2023, Norway introduced a 25% VAT rate on BEVs priced at more than NOK 500 000 (around USD 46 000), and estimates having earned around (USD 0.14 billion) in 2024 from this new VAT tax measure. However, maintaining the VAT exemption for battery electric cars priced below NOK 500 000 resulted in revenue loss of around NOK 13 billion (USD 1.2 billion).

Prior to 2025, the [United Kingdom](#) waived vehicle excise duty (VED) for electric, zero, or low-emission cars, vans and motorcycles. From 1 April 2025, however, new electric cars are taxed GBP 10 (USD 13) in the first year and the standard rate, GBP 195 (around USD 255), in subsequent years. This measure boosts government coffers by nearly USD 3 billion by 2030 in the STEPS. Considering the gain from EV VED alongside the reduction in VED from ICE vehicles, the net tax increase from total car VED is projected to reach more than USD 1 billion by 2030.

Another option open to policy makers could be taxing vehicles based on efficiency, rather than imposing a flat rate, which would mean owners of less efficient, older vehicles bear a higher tax burden. While this could further incentivise EV growth, it might disproportionately affect people in lower-income demographics who are [more likely](#) to own an older vehicle, potentially reducing the public acceptance of electromobility in the long-term.

Similarly, there is a risk of public pushback in response to the introduction of taxes on EVs to cover fuel excise duty losses. To minimise this risk, any tax reform will need to be designed in a way that protects low-income households, while avoiding penalising early EV adopters. As the shift towards EVs continues, it will be essential for governments to introduce tax measures that gradually address the revenue gap while continuing to incentivise a just transition to a low-emissions transport system.

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Annex

Annex A: Total cost of ownership

The truck total cost of ownership (TCO) analysis uses the following inputs and assumptions.

Works consulted

General literature that contributed to developing the methodology and validating assumptions and values used in the total cost of ownership (TCO) analysis

Institution	Components	Includes estimates or references for
European Commission	HRS, EV charging	Capital and installation costs over time, for a variety of scales, operation and maintenance cost, lifetimes
NREL	EV charging	Capital and installation costs, maintenance and land costs, effect of scale
Ricardo	Diesel, battery electric and fuel cell trucks	Component costs for all three powertrains, low, average, high values for each, indirect costs and margins, component sizing
ICCT	Diesel, battery electric and fuel cell trucks	TCO analysis, residual value, truck retail price by class, component costs and sizing over time, financing assumptions, maintenance costs, Europe-focused
ICCT	Diesel, battery electric and fuel cell trucks, EV charging	TCO analysis, residual value, component costs and sizing over time, financing assumptions, maintenance costs, United States-focused
UC Davis	Diesel, battery electric and fuel cell trucks	TCO analysis, residual value, component costs and sizing, financing assumptions, maintenance costs, United States-focused
TNO	Diesel, battery electric and fuel cell trucks, HRS, EV charging	TCO analysis, residual value, component costs and sizing over time, margins, financing assumptions, maintenance costs, Europe-focused
NREL	Diesel, battery electric and fuel cell trucks	TCO analysis, dwell time considerations, residual value, component costs and sizing, financing assumptions, maintenance costs, various duty cycles, United States-focused
UC Davis	Diesel, battery electric and fuel cell trucks	Maintenance and repair costs for the three powertrains over time

Institution	Components	Includes estimates or references for
BNEF *	Battery electric truck	Battery pack prices for commercial BEVs in 2024
ITF	Diesel, battery electric and fuel cell trucks	Methodology, limitations, uncertainty analysis

Notes: HRS = Hydrogen refuelling station; EV = electric vehicle; BEV = battery electric vehicle; ICCT = International Council on Clean Transportation, ITF = International Transport Forum, NREL = National Renewable Energy Laboratory, TCO = Total cost of ownership, *the specific report from which the figures are derived is behind a paywall.

Vehicle production costs, specifications, and payload

Truck powertrain components in the United States, the European Union, and China used in the analysis

Powertrain type	Component	Value
Diesel	Engine power	325 kW
	Electric drive power	350 kW
Battery electric	Battery pack size	800 kWh
	On-board charger	44 kW
Fuel cell electric	Electric drive power	350 kW
	Fuel cell power	362 kW
	Battery pack size	70 kWh
	On-board charger	6.6 kW
	700 bar hydrogen tank size	60 kg

Notes: Powertrain sizing values are for a United States class 8 (or equivalent) tractor truck. The 60 kg hydrogen tank has a usable capacity of 50 kg. Fuel cell power is sized to provide 275 kW of power after 25 000 hours of operation.

Sources: Diesel engine power and battery electric battery pack size are adapted from [National Renewable Energy Laboratory](#), fuel cell stack and fuel cell battery sizing are taken from [US Department of Energy](#), electric drive power, on-board charger, and hydrogen tank sizes are taken from [Riccardo](#).

Direct manufacturing costs of powertrain components in the United States, the European Union, and China used in the analysis, 2024 and 2030

	Units	United States		European Union		China	
Component	2024 USD	2024	2030	2024	2030	2024	2030
Electric drive	USD/kW	80	75	70	70	44	42
Power electronics (e-drive inverter box)	USD/kW	27	26	24	24	15	14
DC/DC converter	USD	540	525	485	470	295	290
Heating, Ventilation, and Air Conditioning; electrical and air brakes	USD	8555	8340	6590	6425	2995	2920

Component	Units	United States		European Union		China	
	2024 USD	2024	2030	2024	2030	2024	2030
Battery and electronics thermal management (BEV)	USD/kW	19	17	17	16	11	10
Battery and electronics thermal management (FCEV)	USD/kW	8	7	7	7	5	4
Fuel cell system	USD/kW	365	230	330	210	200	130
Battery (FCEV)	USD/kWh	510	385	510	385	280	210
Battery (BEV)	USD/kWh	190	100	190	100	85	70
On-board charger	USD/kW	65	60	60	55	36	33
700-bar hydrogen tank	USD/kg	1220	1035	1095	930	670	570

Notes: “BEV” = battery electric vehicle; “FCEV” = fuel-cell electric vehicle. “Battery” includes battery cells, pack and the battery management system. In the case of BEVs the battery chemistry is assumed to be lithium iron phosphate (LFP), for FCEVs it is lithium nickel cobalt manganese oxide (NMC). “Fuel cell system” costs include economies of scale and learning effects equal to production volumes of 1 000 units and 20 000 units per year in 2024 and 2030, respectively. Values below USD 50 have been rounded to the nearest USD 1; values above USD 50 have been rounded to the nearest USD 5.

Sources: Battery costs are adapted from [Bloomberg New Energy Finance](#), fuel cell system costs are adapted from [US Department of Energy](#), electric drive, battery and electronics thermal management, on-board charger, DC/DC converter, hydrogen tank, and power electronics are adapted from [Riccardo](#).

Estimated purchase price of a heavy-duty diesel truck in the United States, the European Union, and China used in the analysis, 2024 and 2030

	United States		European Union		China	
	2024	2030	2024	2030	2024	2030
Driveline, cab, and chassis	40 400	39 300	31 100	30 300	14 100	13 800
Powertrain	66 000	69 300	48 400	53 400	23 100	24 300
Manufacturing and assembly	7 400	7 600	5 700	5 900	2 600	2 700
Indirect costs and margins	41 000	41 800	31 500	32 300	14 300	14 700
Total	154 800	158 000	119 100	121 900	54 100	55 500

Notes: Prices in 2024 USD for a United States class 8 (or equivalent) tractor truck with a 325 kW engine, as specified in the previous tables. “Powertrain” includes the engine and all balance of plant. Manufacturing and assembly costs are assumed to be 7% of production costs of the components, and indirect costs and margins are 36% of the total production cost, equally applied across all regions. All values are rounded to the nearest USD 100. The bottom-up calculated totals were validated against values from the [California Air Resources Board](#) (United States and Europe) and [ICCT](#) (China).

Sources: Values for the share of total costs from the driveline, cab and chassis; from manufacturing and assembly costs; and from indirect costs and margins are taken from [Riccardo](#).

Estimated purchase price of a heavy-duty fuel cell electric truck in the United States, the European Union, and China used in the analysis, 2024 and 2030

	United States		European Union		China	
	2024	2030	2024	2030	2024	2030
Finished chassis and cab	40 400	39 300	31 100	30 300	14 100	13 800
Powertrain	41 200	39 200	37 000	35 300	22 600	21 500
Battery	35 800	26 800	35 800	26 800	19 700	14 800
Fuel cell	132 700	84 100	119 400	75 700	73 000	46 300
Hydrogen tank	73 100	62 100	65 800	55 900	40 200	34 200
Manufacturing and assembly	22 600	17 600	20 200	15 700	11 900	9 100
Indirect costs and margins	124 500	96 900	111 300	86 300	65 300	50 300
Total	470 300	366 000	420 600	326 000	246 800	190 000

Notes: Costs are for a United States class 8 (or equivalent) tractor truck with a 380 kW fuel cell system, hydrogen tank with 50 kg of usable capacity, and a 350 kW electric drive unit. Powertrain includes the electric drive unit, electronics and thermal management units, a 70 kWh battery, and all balance of plant. Manufacturing and assembly costs are assumed to be 3% of production costs of the components, with indirect costs and margins of 36% of the total production cost, equally applied across all regions. All values are rounded to the nearest USD 100. The bottom-up calculated totals were validated against values from the [California Air Resources Board](#) (United States and Europe) and [ICCT](#) (China).

Sources: Values for the share of total costs from the driveline, cab, and chassis; from manufacturing and assembly costs; and from indirect costs and margins are adapted from [Riccardo](#).

Estimated purchase price of a heavy-duty battery electric truck in the United States, the European Union, and China used in the analysis, 2024 and 2030

	United States		European Union		China	
	2024	2030	2024	2030	2024	2030
Finished chassis and cab	40 400	39 300	31 100	30 300	14 100	13 800
Powertrain	47 500	44 900	42 700	40 400	26 100	24 700
Battery	152 000	78 900	152 000	78 900	69 700	55 600
Manufacturing and assembly	16 800	11 400	15 800	10 500	7 700	6 600
Indirect costs and margins	92 400	62 800	87 000	57 600	42 300	36 300
Total	349 100	237 300	328 600	217 700	159 900	137 000

Notes: Costs are for a United States class 8 (or equivalent) tractor truck with a 350 kW electric drive unit, and an 800 kWh battery. Powertrain includes the electric drive unit, electronics and thermal management units, on-board charger, and all balance of plant. Manufacturing and assembly costs are assumed to be 3% of production costs of the components, with indirect costs and margins of 36% of the total production cost, equally applied across all regions. All values are rounded to the nearest USD 100. The bottom-up calculated totals were validated against values from the [California Air Resources Board](#) (United States and Europe) and [ICCT](#) (China).

Sources: Values for the share of total costs from the driveline, cab, and chassis; from manufacturing and assembly costs; and from indirect costs and margins are adapted from [Riccardo](#).

Estimated maintenance, insurance, and labour costs for battery electric, fuel cell electric, and diesel trucks 2024 and 2030

		Maintenance USD/km		Insurance %		Labour USD/hour	
		2024	2030	2024	2030	2024	2030
Diesel internal combustion engine vehicle	United States	0.26	0.26	3.0%	3.0%	42.1	44.3
	European Union	0.26	0.26	3.0%	3.0%	24.6	26.1
	China	0.18	0.18	3.0%	3.0%	11.6	14.0
Battery electric vehicle	United States	0.19	0.17	3.6%	3.2%	42.1	44.3
	European Union	0.19	0.17	3.6%	3.2%	24.6	26.1
	China	0.13	0.12	3.6%	3.2%	11.6	14.0
Fuel cell electric vehicle	United States	0.22	0.21	4.5%	4.1%	42.1	44.3
	European Union	0.22	0.21	4.5%	4.1%	24.6	26.1
	China	0.16	0.15	4.5%	4.1%	11.6	14.0

Notes: Maintenance costs are the same in years 1-5. Insurance costs are expressed as a share of the capital cost of the truck and represent the first year's premium, every year thereafter premiums fall by 2.5% for diesel vehicles, and 3.5% for battery electric vehicles and fuel cell electric; these figures are estimates derived from stakeholder engagement. Figures for labour cost are inclusive of employer's contributions.

Sources: Maintenance costs are adapted from [UC Davis](#), labour costs are adapted from the [International Labour Organization](#) (United States and Europe) and from the [Economic Research Institute](#) (China).

Estimated unladen weight of a heavy-duty tractor-trailer, 2024 and 2030

	2024			2030		
	Diesel	BEV	FCEV	Diesel	BEV	FCEV
Truck chassis and cab	6 700	6 700	6 700	5 200	5 200	5 200
Powertrain or motors	2 200	600	600	2 200	600	600
Battery	-	4 200	300	-	3 500	300
Fuel cell	-	-	1 200	-	-	800
Hydrogen tank	-	-	1 800	-	-	1 800
Trailer	7 000	7 000	7 000	7 000	7 000	7 000
Total (kg)	15 800	18 500	17 600	14 400	16 300	15 700

Notes: Estimates are for a United States class 8 (or equivalent) tractor-trailer. The weight of the diesel battery is included in powertrain. Battery electric trucks are assumed to use lithium iron phosphate (LFP), and fuel cell electric trucks lithium nickel cobalt manganese oxide (NMC); in 2024 and 2030 these are assumed to have energy densities of 190 Wh/kg and 230 Wh/kg, and 250 Wh/kg and 280 Wh/kg. All values are rounded to the nearest 100 kg.

Sources: Values for the specific mass of diesel trucks, hydrogen tanks, fuel cells, powertrain or motors, and trailers come from the [ICCT](#), and were validated against assumptions from [Ricardo](#).

Gross maximum vehicle weight of a tractor-trailer combination, derogations, and resulting payload in the United States, the European Union, and China.

	United States		European Union		China	
	2024	2030	2024	2030	2024	2030
Maximum gross vehicle weight	36 300	36 300	40 000	40 000	49 000	49 000
Derogation (current)	900	900	2 000	2 000	0	0
Diesel payload	21 400	22 800	26 200	27 600	33 200	34 600
BEV payload	18 700	20 900	23 500	25 700	30 500	32 700
(penalty relative to diesel)	(12.6%)	(8.6%)	(10.2%)	(7.1%)	(8.1%)	(5.6%)
FCEV payload	19 600	21 400	24 400	26 300	31 400	33 300
(penalty relative to diesel)	(8.3%)	(5.9%)	(6.8%)	(4.9%)	(5.4%)	(3.9%)

Notes: "BEV" = battery electric vehicle; "FCEV" = fuel cell electric vehicle. Payloads are calculated as the maximum gross vehicle weight, minus the estimated unladen weights from the previous table, plus the derogation, if applicable. The US maximum gross vehicle weight is set to the 80 000 lb (36 288 kg) limit and does not include allowances for [different configurations](#), the derogations refers to the [2 000 lb](#) (907 kg) additional allowance for natural gas and electric vehicles but is assumed to also apply to FCEVs as per [amendments](#) made to several state laws. The [proposed 4 000 kg](#) (additional 2 000 kg on top of existing derogation) in the European Union is not included in the table but would reduce the penalty relative to diesel in 2024 to 2.6% and -0.8%, and in 2030 to -0.2% and -2.4% for BEV and FCEV respectively, with negative values implying they would, in theory, be permitted to run at a greater gross vehicle weight than their diesel counterparts. No derogation currently applies or is proposed for China.

Energy prices and fuel economy

Prices of diesel, electricity, and hydrogen, 2024 and 2030

Fuel	Units	United States		European Union		China	
	2024 USD	2024	2030	2024	2030	2024	2030
Diesel	USD/kWh	0.11	0.12	0.17	0.19	0.11	0.11
Diesel	USD/L	1.14	1.18	1.70	1.88	1.10	1.14
Electricity	USD/kWh	0.16	0.16	0.24	0.23	0.08	0.08
Hydrogen	USD/kWh	0.12	0.15	0.23	0.30	0.15	0.14
Hydrogen	USD/kg H ₂	3.88	4.87	7.84	9.88	4.86	4.83

Notes: Hydrogen prices are composed of the weighted levelised cost of production and distribution, an assumed margin of 20%, and 10% tax. Underlying electricity prices are the same at both the depot and during en route charging, with the difference between them due exclusively to the differences in the infrastructure costs.

Fuel economy of diesel, battery electric and fuel cell heavy-duty trucks, 2024 and 2030

Powertrain	Units	2024	2030
Diesel ICEV	kWh/km	3.5	3.5
Diesel ICEV	L/100 km	35.2	34.5
BEV	kWh/km	1.6	1.5
FCEV	kWh/km	2.6	2.4
FCEV	kg H ₂ /100 km	7.7	7.3

Notes: "ICEV" = internal combustion engine vehicle; "BEV" = battery electric vehicle; "FCEV" = fuel cell electric vehicle. BEV fuel economy based on a charging efficiency of [97.5%](#).

Infrastructure costs and specifications

Capital and operating costs of a 50 kW and 350 kW heavy-duty electric fast charger, 2024 and 2030

		CAPEX (2023 USD)		OPEX	Utilisation factor (350 kW)
		50 kW	350 kW		
United States	2024	23 000	289 500	5%	5%
	2030	19 500	246 500	5%	10%
European Union	2024	22 000	218 500	5%	5%
	2030	19 000	185 500	5%	10%
China	2024	4 500	31 500	5%	5%
	2030	3 500	27 000	5%	10%

Notes: CAPEX = Capital expenditure and includes installation cost. OPEX = Operating expenditure, which is an annual cost expressed as a share of CAPEX. Utilisation factor refers to the share of hours in a day during which the charger is occupied. It is assumed that each battery electric vehicle requires the installation of one 50 kW charger at the depot, with a 15-year lifetime and 8% discount rate, and [no additional land costs](#). For each year of operation one year of levelised cost of the depot charger is added to the infrastructure costs of the battery electric truck. For the 350 kW charger, vehicle footprint including 10% setback is assumed to be 54m² plus 20m² per charging pile for the pile itself, cabling, or other equipment. Industrial land values for the United States and Europe are assumed to be USD 1 642/m² and USD 242/m² in China and include a 23% markup for permitting and preparation. 350 kW charger costs are levelised assuming a 10-year lifetime and 8% discount rate. Diesel refuelling station infrastructure cost of 2% of the sale price of the fuel assumed throughout to account for both capital and operating costs.

Sources: The estimate for additional area required per charging pile is adapted from the [ICCT](#), permitting and preparation costs associated with land purchase are taken from [Argonne National Laboratory](#), industrial land values are adapted from [CommercialEdge](#) (United States and Europe) and [CEIC](#) (China).

Capital and operating costs of a 700 bar, 2 500 kg/day hydrogen refuelling station, 2024 and 2030

		CAPEX	OPEX		Utilisation factor	Average fill rate (kg _{H2} /min)
		2023 USD	Fixed	Variable (kWh _e /kg _{H2})		
United States	2024	8 840 000	4%	1.4	35%	2.5
	2030	8 030 000	4%	1.4	40%	3.6
European Union	2024	8 840 000	4%	1.4	35%	2.5
	2030	8 030 000	4%	1.4	40%	3.6
China	2024	2 660 000	4%	1.4	35%	2.5
	2030	2 480 000	4%	1.4	40%	3.6

Notes: CAPEX = Capital expenditure and includes installation cost; OPEX = Operating expenditure. "Fixed" is an annual cost expressed as a share of CAPEX, "Variable" is per unit of hydrogen dispensed. For a hydrogen refuelling station "utilisation factor" refers to the share of maximum daily hydrogen capacity which is dispensed each day. Hydrogen is delivered to the station and dispensed as a gas at 700 bar. Costs are levelised assuming a 10-year lifetime and 8% discount rate. A total station footprint of 1 759 m² is assumed. Industrial land values for the United States and Europe are assumed to be USD 1 642/m² and USD 242/m² in China, and include a 23% markup for permitting and preparation. Diesel refuelling station infrastructure cost of 2% of the sale price of the fuel assumed throughout to account for both capital and operating costs.

Sources: Station footprints, as well as permitting and preparation costs associated with land purchase, are taken from [Argonne National Laboratory](#); industrial land values are adapted from [CommercialEdge](#) (United States and Europe) and [CEIC](#) (China); station costs are adapted from the [European Commission](#).

Methodology

Total cost of ownership base and sensitivity case parameters by scenario, 2024 and 2030

Parameters for EV chargers and HRS applied to all regions							
		Base case		High cost		Low cost	
		2024	2030	2024	2030	2024	2030
EV charger	UF	5%	10%	2.5%	5%	10%	20%
	Charging power	350 kW	350 kW	150 kW	150 kW	1 MW	1 MW
HRS	UF	35%	40%	17.5%	20%	70%	80%
	Fill rate	2.5 kg/min	3.6 kg/min	1.5 kg/min	1.5 kg/min	3.6 kg/min	5 kg/min
A payload penalty is only applied in the high-cost case							
Payload penalty	United States		European Union		China		
	BEV	12.6%	8.6%	10.2%	7.1%	8.1%	5.6%
	FCEV	8.3%	5.9%	4.9%	5.4%	5.4%	3.9%
Only the diesel fuel price was varied as part of the sensitivity analysis							
Diesel price		High	Low	High	Low	High	Low
	USD/litre	1.39	0.77	2.08	1.44	1.20	0.85

Notes: BEV = Battery electric vehicle; EV = Electric Vehicle; FCEV = Fuel cell electric vehicle; HRS = Hydrogen Refuelling Station; UF = Utilisation Factor. The "high cost" case corresponds to the scenario where the total cost of ownership is expected to be the highest. The "payload penalty" is calculated in a previous table of this Annex. HRS fill rate and charging power impact the total cost of ownership via the "dwell costs", which is the financial penalty incurred when refuelling takes longer than the minimum rest period. In the case of charging power the capital costs also vary.

Driving and refuelling profile

The daily driving range is assumed to be 500 km, where half of the daily distance is travelled before the driver's rest period and the other half afterwards. It is assumed that all truck types refuel during the rest periods. Regulations require rest periods durations of 20, 30, and 45 minutes in China, the United States, and the European Union, respectively. It is assumed that the diesel trucks can sufficiently refuel within the rest periods, and thus incur no dwell costs (see below for how dwell costs are calculated for battery electric and fuel cell electric trucks). En route charging is assumed to occur with 350 kW chargers. Battery electric trucks are also assumed to charge overnight, up to 10 hours, using a 50 kW (peak) charger. It is assumed that the trucks can operate seven days per week, forty-eight weeks per year for a total of 168 000 km travelled per year.

Dwell costs for battery electric trucks

Maximum and minimum charge levels of 20% and 80% are maintained to preserve battery health and for enhanced safety. Battery electric trucks are assumed to charge for the full length of their rest period and during their stay in depot. If required, the battery electric truck remains charging after the rest period until the state of charge is sufficient to complete the remaining 250 km to return to depot, charge overnight at the depot, and then complete the 250 km required to reach the rest period the following day. This additional daily charging, if required, is multiplied by labour cost to give the dwell cost.

Financing period and additional considerations

The truck is purchased with a 100% loan at 5% interest. A discount rate of 8% is applied throughout. The analysis takes into account the first 5 years after the purchase of the truck, equivalent to a total distance travelled of 840 000 km. Diesel trucks have a [residual value](#) of 26% throughout, BEV and FCEV trucks are assumed to also have a 26% residual value when purchased in 2024 and 33% if purchased in 2030, after having driven comparable distances over that period to those modelled in this analysis.

Annex B: United States regional groupings

Mid West

Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Wisconsin

Northeast

Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

Pacific

California, Oregon, Washington

Rocky Mountain

Colorado, Idaho, Montana, Nevada, Utah, Wyoming

Southeast

Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia

Southwest

Arizona, New Mexico, Oklahoma, Texas

Annex C: Regional and country groupings

Unless otherwise specified, regional groupings used in the Global EV Outlook and EV data explorers are as follows:

Africa

Algeria, Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Kingdom of Eswatini, Libya, Madagascar, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Senegal, South

Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Tunisia, Uganda, Zambia, Zimbabwe and other African countries and territories.¹

Asia Pacific

Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, The People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.²

Central and South America

Argentina, Plurinational State of Bolivia (Bolivia), Bolivarian Republic of Venezuela (Venezuela), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay and other Central and South American countries and territories.³

Eurasia

Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, the Russian Federation (Russia), Tajikistan, Turkmenistan and Uzbekistan.

Europe

European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Iceland, Israel,⁴ Kosovo, Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

¹ Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Mauritania, Sao Tome and Principe, Seychelles, Sierra Leone and Somalia.

² Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga and Vanuatu.

³ Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Saint Maarten (Dutch part), Turks and Caicos Islands.

⁴ The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

European Union

Austria, Belgium, Bulgaria, Croatia, Cyprus,⁵ ⁶ Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

Latin America and the Caribbean (LAC)

Central and South America regional grouping and Mexico.

Middle East

Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

North America

Canada, Mexico and United States.

Southeast Asia

Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Annex D: Glossary

Abbreviations and acronyms

ACC	Advanced Clean Cars
ACEA	European Automobile Manufacturers Association
ACF	Advanced Clean Fleets
ACT	Advanced Clean Trucks
AFDC	Alternative Fuels Data Center
AFIR	Alternative Fuels Infrastructure Regulation
BEV	battery electric vehicle

⁵ Note by Republic of Türkiye: The information in this document with reference to “Cyprus” relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the “Cyprus issue”.

⁶ Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

CAAM	China Association of Automobile Manufacturers
CAD	Canadian dollars
CAFE	Corporate average fuel efficiency
CAM	Cathode active material
CAPEX	capital expenditure
CATL	Contemporary Amperex Technology Co. Limited
CNY	Yuan renminbi
COP	Conference of the Parties
CO ₂	carbon dioxide
DC	direct current
DSO	Distribution system operator
EAFO	European Alternative Fuels Observatory
EMDE	emerging market and developing economy
EPA	Environmental Protection Agency
EREV	extended range electric vehicle
ERS	electric road systems
EU	European Union
EV	electric vehicle
EVI	Electric Vehicle Initiative
EVSE	electric vehicle supply equipment
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FCEV	fuel cell electric vehicle
GACC	General Administration of Customs of the People's Republic of China
GEC	Global Energy and Climate Model
GEVO	Global EV Outlook
GHG	greenhouse gases
HD	heavy duty
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HRS	hydrogen refuelling station
H ₂	hydrogen
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IFC	International Finance Corporation
INR	Indian rupee
IRENA	International Renewable Energy Agency
ITF	International Transport Forum
KRW	Korean won
LCV	light commercial vehicle
LDV	light-duty vehicle
LEZ	Low emissions zone
LFMP	lithium iron manganese phosphate
LFP	lithium iron phosphate
Li-S	lithium sulphur

MD	medium-duty
MPV	multi-purpose vehicle
NCA	lithium nickel cobalt aluminium oxide
NEV	new energy vehicle
NEVI	National Electric Vehicle Infrastructure
NMC	nickel manganese cobalt oxide
NMCA	lithium nickel manganese cobalt aluminium oxide
NREL	National Renewable Energy Laboratory
NOK	Norwegian kroner
NZD	New Zealand dollars
OEM	original equipment manufacturer
OPEX	Operating expenditure
PHEV	plug-in hybrid electric vehicle
PLDV	passenger light-duty vehicle
PM-E-DRIVE	PM Electric Drive Revolution in Innovative Vehicle Enhancement
SEK	Swedish kronor
STEPS	Stated Policies Scenario
SUV	sports utility vehicle
TCO	total cost of ownership
TEN-T	Trans-European Transport Network
THB	Thai baht
TRL	technology readiness level
UNECE	United Nations Economic Commission for Europe
VAT	value added tax
VED	vehicle excise duty
VND	Vietnamese dong
V2G	vehicle-to-grid
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
ZETI	Zero-Emission Technology Inventory
ZEVWISE	Zero-Emission Vehicle Infrastructure Support and Expansion
2/3W	two/three-wheeler

Units of measure

bar	bar
GWh	gigawatt-hour
kg	kilogramme
km	kilometre
km/hr	kilometres per hour
kW	kilowatt
kWh	kilowatt-hours
L	litre
lb	pounds
m	metre
mb/d	million barrels per day
MW	megawatt
m ²	metre squared
t	tonne

t CO ₂	tonne of carbon dioxide
TWh	terawatt-hour
V	volt
W	watt
Wh/kg	watt-hour per kilogramme
Wh/L	watt-hour per litre

See the [IEA glossary](#) for a further explanation of many of the terms used in this report.

Currency conversion

Market exchange rates (2024)	1 US dollar (USD) equals:
British pound sterling	0.78
Canadian dollar	1.37
Chinese yuan renminbi	7.20
Euro	0.92
Korean won	1 363.37
New Zealand dollar	1.65
Indian rupee	84.60
Thai baht	35.29

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Form 1.1 - Total State Planning Area
California Energy Demand Forecast, 2024 - 2040 Baseline Forecast
Electricity Consumption by Sector (GWh)

Year	Residential	Residential_LDEV	Commercial	Commercial_LDEV	Industrial	Mining	AGWP	TCU	Streetlighting	Total_Consumption
2000	79,518	0	93,965	0	47,819	6,104	17,723	14,257	1,396	260,780
2001	75,237	0	91,375	0	44,542	5,827	18,954	12,977	1,446	250,359
2002	76,765	0	93,161	0	44,924	5,742	20,836	13,093	1,407	255,928
2003	81,711	0	97,072	0	42,564	6,274	19,425	13,017	1,419	261,481
2004	83,833	0	99,187	0	43,743	7,115	21,941	13,413	1,443	270,674
2005	85,644	0	99,767	0	44,179	7,321	19,526	14,191	1,544	272,173
2006	89,717	0	103,109	0	44,181	7,618	20,673	14,464	1,556	281,318
2007	89,091	0	104,438	0	44,455	7,945	22,767	14,833	1,562	285,091
2008	90,918	0	105,592	0	43,808	8,040	19,529	15,448	1,598	284,933
2009	90,022	0	102,251	0	39,435	8,019	19,335	16,687	1,585	277,334
2010	87,340	0	100,023	0	39,394	7,814	20,107	16,572	1,539	272,790
2011	88,554	0	100,409	0	39,843	8,001	20,135	16,036	1,489	274,467
2012	90,839	0	102,730	0	40,147	7,637	21,023	15,940	1,437	279,754
2013	89,696	0	102,831	0	40,127	7,537	20,656	15,707	1,359	277,912
2014	89,322	0	105,371	0	40,843	7,912	18,716	16,170	1,340	279,673
2015	89,074	0	104,485	0	41,346	8,038	19,012	16,368	1,429	279,751
2016	88,539	0	103,792	0	41,409	7,805	21,329	16,559	1,383	280,816
2017	91,468	0	103,718	0	41,098	9,083	22,173	15,205	1,342	284,087
2018	89,618	0	102,908	0	40,444	9,001	19,881	15,128	1,278	278,258
2019	89,472	0	101,015	0	39,420	9,316	19,497	15,341	1,104	275,164
2020	99,208	0	92,732	0	37,268	8,171	18,638	14,579	1,038	271,634
2021	96,330	0	94,997	0	38,194	8,116	19,135	15,388	1,234	273,393
2022	97,685	0	100,066	0	38,144	8,189	19,471	15,662	1,208	280,426
2023	94,116	0	98,173	0	36,867	7,602	22,663	15,776	1,071	276,268
2024	96,466	967	103,477	599	36,295	7,725	22,503	15,885	1,074	283,426
2025	97,664	2,032	107,800	1,307	36,379	7,735	23,847	15,965	1,074	290,465
2026	98,992	3,267	111,491	2,174	36,552	7,791	24,600	16,064	1,073	296,563
2027	100,903	5,008	115,775	3,463	36,730	7,775	25,047	16,194	1,068	303,493
2028	103,293	6,829	124,879	4,748	36,918	7,768	25,317	16,474	1,060	315,708
2029	105,807	8,690	132,520	6,317	37,050	7,751	25,497	16,608	1,046	326,280
2030	108,424	10,583	139,455	7,759	37,175	7,743	25,664	16,905	1,034	336,399
2031	110,244	11,729	146,561	9,310	37,259	7,735	25,836	17,118	1,022	345,775
2032	112,237	13,015	151,092	10,711	37,384	7,744	25,997	17,319	1,013	352,786
2033	113,837	13,937	155,942	11,918	37,460	7,737	26,165	17,502	1,003	359,646
2034	115,378	14,860	160,479	13,175	37,564	7,741	26,326	17,698	995	366,181
2035	116,842	15,759	164,891	14,501	37,614	7,726	26,482	18,034	988	372,577
2036	118,576	16,934	168,265	15,408	37,674	7,715	26,631	18,196	982	378,039
2037	120,324	18,164	171,081	16,335	37,697	7,700	26,778	18,353	977	382,910
2038	122,014	19,439	173,506	17,281	37,692	7,677	26,922	18,513	974	387,299
2039	123,718	20,726	175,798	18,222	37,691	7,655	27,065	18,815	972	391,714
2040	125,425	22,035	177,816	19,168	37,677	7,628	27,209	19,144	970	395,870

* Residential and commercial electric vehicle consumption is included in the residential and commercial totals.

* Residential and commercial electric vehicle consumption is incremental to 2023.

* Consumption includes self-generation.

* Last Historical year is 2023.

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MULTI-TECHNOLOGY PATHWAYS TO ACHIEVE CALIFORNIA'S GREENHOUSE GAS GOALS:

LIGHT-DUTY AUTO CASE STUDY

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APPENDICES

Appendix A: Scenario Analysis Assumptions and Detailed Methodology
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ACRONYMS AND ABBREVIATIONS

AB:	Assembly Bill
ACC:	Advanced Clean Cars
ANL:	Argonne National Laboratory
BEV:	battery electric vehicle
CA-GREET:	California's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
CAP:	criteria air pollutant
CARB:	California Air Resources Board
CARBOB:	California reformulated gasoline blendstock for oxygenate blending
CaRFG:	California reformulated gasoline
CEC:	California Energy Commission
CEQA:	California Environmental Quality Act
CH ₄	methane
CI:	carbon intensity
CO ₂ :	carbon dioxide
CO ₂ e:	carbon dioxide equivalent
cVMT:	combustion vehicle mile traveled
CY:	calendar year
DSL:	diesel
E3:	Energy + Environmental Economics
EA:	environmental assessment
EER:	energy economy ratio
eGRID:	Emissions & Generation Resource Integrated Database
EMFAC:	EMission FACtors Model
EPA:	Environmental Protection Agency
EV:	electric vehicle
eVMT:	electric vehicle mile traveled
FCEV:	fuel cell electric vehicle
g:	gram
GHG:	greenhouse gas
GREET:	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GWP:	global warming potential

H ₂ :	hydrogen
HEV:	hybrid electric vehicle
ICE:	internal combustion engine
ICEV:	internal combustion engine vehicle
IPCC:	International Panel on Climate Change
ISOR:	Initial Statement of Reasons
kWh:	kilowatt-hour
LCFS:	Low Carbon Fuel Standard
LDA:	light-duty auto
LDT1:	light-duty truck 1
LDT2:	light-duty truck 2
LDV:	light-duty vehicle
Li-ion:	lithium ion
mi:	mile
MJ:	megajoule
MMT:	million metric tons
MPG:	miles per gallon
MPGe:	miles per gallon equivalent
MT:	metric ton
MSS	Mobile Source Strategy
MY:	model year
N ₂ O	nitrous oxide
NG:	natural gas
NMC:	nickel manganese cobalt
PHEV:	plug-in hybrid electric vehicle
SMR:	steam methane reforming
SOC:	state of charge
SRIA:	Standardized Regulatory Impact Assessment
US:	United States
VMT:	vehicle mile traveled
ZEV:	zero emission vehicle

EXECUTIVE SUMMARY

The California Air Resources Board (CARB or Board) Advanced Clean Cars program aims to reduce criteria air pollutants (CAP) and greenhouse gas (GHG) emissions throughout the state by setting regulations and standards aimed at light-duty vehicles (LDVs). The newest generation of rulemaking that has been drafted is the Advanced Clean Cars II (ACC II) proposal and is expected to be presented to the Board in summer 2022. This proposal introduced by CARB includes setting zero emission vehicle (ZEV) sales mandates for model year 2026 and later passenger cars and light-duty trucks (i.e., light-duty vehicles, LDVs). This proposed sales mandate would begin at 35% in 2026 and ramp up to 100% for the 2035 model year and beyond.¹ The stated aim of the ACC II proposal is to reduce CAP and GHG emissions through a ZEV sales mandate. This technology mandate is different from traditional CARB motor vehicle regulations that set engine emission standards or emission-based performance standards that allowed multiple lower-emitting technologies to compete. Although a stated goal is to reduce GHG emissions, the current ACC II proposal does not consider or analyze the full life cycle emissions for “zero emission” vehicles, account for greenhouse gas emissions leakage that would be caused outside of the state of California by the ACC II proposal, or include a technology-neutral analysis of alternatives that could help meet the greenhouse gas reduction goals. Simply put, CARB’s ACC II proposal focuses on a complete transition to ZEVs without a full accounting of GHG emissions impacts, and without consideration of other vehicle technologies or a future role for renewable and other low carbon fuels.

Ramboll has conducted an analysis of California’s light-duty auto (LDA) fleet to evaluate whether alternative vehicle technology and fuel pathways could achieve life cycle GHG emission reductions similar or greater than the ACC II proposal. Unlike CARB’s analysis, Ramboll has evaluated the full life cycle impacts of ZEV technologies under the ACC II proposal to more completely characterize the potential near-term and long-term GHG emissions performance and considers other pathways that would not require a replacement of the entire transportation infrastructure system. These alternative pathways would also not require the wholesale transformation of electric energy production and distribution infrastructure on an unprecedented short time scale, but they would allow battery, hydrogen, and low-carbon intensity gaseous and liquid fueled vehicles to compete to achieve the State’s GHG targets for light-duty transportation in the quickest and most cost-effective manner.

Ramboll’s **multi-technology pathways analysis** demonstrates that there are multiple light duty vehicle technology and fuel pathways that can meet California’s GHG emission reduction targets.

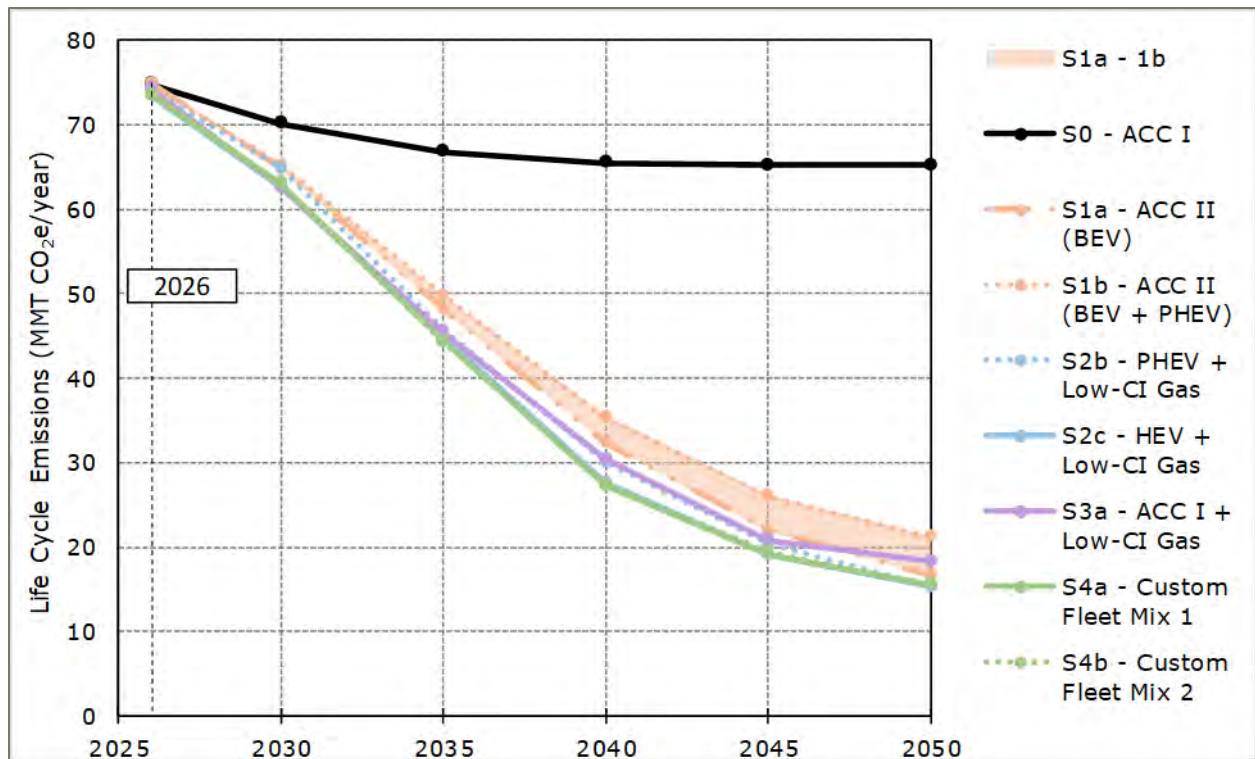
The main conclusions of our analysis are:

- Zero emission vehicle technology is only one of many different technology/fuel scenarios that could be utilized to meet California’s GHG emission reduction targets;
- A full life cycle emission assessment is necessary if GHG reductions are a goal of the regulation, in order to understand the cradle-to-grave effects of a given vehicle/fuel technology pathway;

¹ California Air Resources Board (CARB). 2022. Appendix A-5: Proposed Regulation Order for Section 1962.4 Zero-Emission Vehicle Standards for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appa5.pdf>. Accessed: May 2022.

- BEV technology of the scope and schedule proposed under ACC II would require technology and electrical generation/infrastructure developments that CARB has not analyzed and cannot mandate, control, or incentivize;
- There is a growing potential for renewable and low carbon fuels, including some with negative carbon intensity (CI), to meet long-term GHG reduction targets for light-duty transportation;
- Low-CI gasoline (included in scenarios represented by the blue, purple, and green lines in **Figure ES-1**) could decarbonize the transportation sector at a rate comparable to a ZEV-only regulation (represented by the pink shaded region in **Figure ES-1**); and
- Allowing the market flexibility to meet emission reduction targets could lead to a more diverse deployment of fuel and vehicle technologies to meet State targets.

Figure ES-1: Life Cycle Emissions for Key Scenarios



These conclusions show that GHG reductions attributed by CARB to the proposed ACC II regulation are incomplete and emphasize the need for CARB to conduct a full life cycle GHG emission assessment to quantify the cradle-to-grave effects of the draft ACC II proposal. As demonstrated in this study, a full life cycle analysis demonstrates that there are multiple GHG-reducing vehicle/fuel technologies that, individually or in combination, have equivalent GHG reductions as ZEV-mandated ACC II proposal. CARB should revise the environmental analysis to consider all feasible vehicle/fuel pathways that could achieve the State's emission reduction goals. This must be done in the alternative analyses presented

in the Standardized Regulatory Impact Assessment (SRIA)² and the Environmental Assessment (EA)³ for the proposed ACC II, including evaluations of the environmental, cost, and socioeconomic impacts of the different technology pathways. Consistent with rule development precedent, the results of this broader alternative analyses should inform the appropriate revisions to the draft ACC II rule language.

² CARB. 2022. Appendix C-1: Standardized Regulatory Impact Assessment (SRIA). April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appc1.pdf>. Accessed: May 2022.

³ CARB. 2022. Appendix E-1: Draft Environmental Analysis for the Proposed Advanced Clean Cars II Program. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appe1.pdf>. Accessed: May 2022.

1. INTRODUCTION

1.1 Proposed ACC II Regulation Summary

The California Air Resources Board (CARB) Advanced Clean Cars program aims to reduce criteria air pollutants (CAP) and greenhouse gas (GHG) emissions throughout the state by setting regulations and standards aimed at LDVs. The newest generation of rulemaking that has been drafted is the Advanced Clean Cars II (ACC II) proposal and is expected to be presented to the Board in summer 2022. This proposal introduced by CARB includes setting zero emission vehicle (ZEV) sales mandates for model year 2026 and later passenger cars and light-duty trucks (i.e., light-duty vehicles, LDVs). This proposed sales mandate begins at 35% in 2026 and would ramp up to 100% for the 2035 model year and beyond.⁴ The stated aim of the ACC II regulation is to reduce CAP and GHG emissions through a ZEV sales mandate. This technology mandate is different from traditional CARB motor vehicle regulations that set engine emission standards or emission-based performance standards that allowed multiple lower-emitting technologies to compete. Although a stated goal is to reduce GHG emissions, the current ACC II proposal does not consider or analyze the full life cycle emissions for “zero emission” vehicles, account for greenhouse gas emissions leakage that would be caused outside of the state of California by the ACC II proposal, or include a technology-neutral analysis of alternatives that could help meet the greenhouse gas reduction goals. Simply put, CARB’s ACC II proposal focuses on a complete transition to ZEVs without a full accounting of GHG emissions impacts, and without consideration of other vehicle technologies or a future role for renewable and other low carbon fuels.

The current ACC II proposal takes a narrow approach to achieving the State’s GHG emission goals by setting a ZEV mandate, rather than setting performance-based emission targets. The alternatives analyzed in the Standardized Regulatory Impact Assessment (SRIA)⁵ and the Environmental Assessment (EA)⁶ for the proposed ACC II represent varying penetration rates for ZEV sales mandates for the 2026 through 2035 model years, and do not include a performance-based analysis of technology/fuel alternatives.

Additionally, CARB has not conducted a full life cycle GHG analysis for the vehicle/fuel system to assess GHG emission impacts of their proposal and alternatives. CARB did not consider the upstream fuel cycle GHG emissions from out-of-state fuel production and transportation activities for California reformulated gasoline (CaRFG) and hydrogen (H₂), and vehicle cycle GHG emissions associated with the vehicle production. These life cycle emissions are significant, particularly for battery electric vehicles (BEVs) as compared to internal combustion engine vehicles (ICEVs), due to the energy-intensive nature of producing a BEV battery. Failure to consider these GHG emissions has the effect of overstating the emissions benefits of the proposed ACC II regulation.

⁴ California Air Resources Board (CARB). 2022. Appendix A-5: Proposed Regulation Order for Section 1962.4 Zero-Emission Vehicle Standards for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appa5.pdf>. Accessed: May 2022.

⁵ CARB. 2022. Appendix C-1: Standardized Regulatory Impact Assessment (SRIA). April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appc1.pdf>. Accessed: May 2022.

⁶ CARB. 2022. Appendix E-1: Draft Environmental Analysis for the Proposed Advanced Clean Cars II Program. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appe1.pdf>. Accessed: May 2022.

1.2 Purpose of this Study

The proposed ACC II regulation would prescribe a ZEV-centric pathway to achieve the State's long-term climate goals through sales mandates. Ramboll conducted an analysis of California's light-duty auto (LDA) fleet to evaluate alternative vehicle technology and fuel pathways that could achieve life cycle GHG emission reductions similar or greater than the ACC II proposal. Ramboll's analysis approaches the State's climate goals from an emission reduction or environmental performance perspective, rather than a technology mandate and a potential means to allow increased market flexibility. This analysis evaluates the life cycle impacts of ACC II to more fully characterize the potential near-term and long-term GHG emissions reductions of that proposal and considers alternative technology/fuel pathways that would not require an overhaul of the entire transportation infrastructure system. These alternative pathways would not require the wholesale transformation of energy production and distribution infrastructure on an unprecedented short time scale, but they would allow battery, hydrogen, and low carbon intensity gaseous and liquid fueled vehicles to potentially co-exist in a market to achieve the State's GHG targets in the quickest and most cost-effective manner.

This white paper provides a summary of the methodology, results, and conclusions of Ramboll's analysis.

2. MULTI-TECHNOLOGY SCENARIOS: LIGHT-DUTY VEHICLE FLEET EXAMPLE

The CARB ACC II proposal would prescribe a sales mandate for ZEVs in the LDV fleet in order to meet California's long-term climate goals. **Table 2-1** below presents the proposed ZEV sales requirements for the statewide LDV fleet as contained in the draft ACC II regulation released on April 12, 2022. As shown in the table, the draft ACC II regulation requires manufacturers that produce and deliver LDVs for sale in California to meet increasing ZEV sales fractions from 35% in the 2026 model year, 68% in 2030, and 100% by the 2035 model year and beyond. In the proposed ACC II regulation, CARB does not consider or assess other scenarios that could use a mix of alternative vehicle and fuel technologies to achieve the California's long-term climate goals.

Table 2-1. ZEV Sales Requirements in the Proposed ACC II Regulation⁷	
Model Year	Percentage Requirement
2026	35%
2027	43%
2028	51%
2029	59%
2030	68%
2031	76%
2032	82%
2033	88%
2034	94%
2035 and subsequent	100%

Ramboll's analysis presented in this report evaluates the potential GHG emission benefits for a series of technology and fuel scenarios for a subset of the statewide LDV fleet consisting of light-duty autos (LDAs)⁸ from calendar year 2026 through 2050. Specifically, Ramboll's scenario analysis considers gasoline-fueled ICEVs, BEVs, plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs).⁹ Additional information on each of the vehicle technologies considered in this analysis is presented in **Section 3.1**. The purpose of this analysis is to evaluate if there are alternative vehicle/fuel

⁷ CARB. 2022. Appendix A-5: Proposed Regulation Order for Section 1962.4 Zero-Emission Vehicle Standards for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appa5.pdf>. Accessed: May 2022.

⁸ LDVs subject to ACC II ZEV sales requirements include the LDA, LDT1, and LDT2 vehicle classes in EMFAC2021. Only the LDA vehicle class is considered in Ramboll's analysis.

⁹ Natural gas vehicles are excluded as they are not included in the default EMFAC2021 LDA fleet. Diesel vehicles are not included in this analysis because they comprise less than 0.3% of the total LDA population in EMFAC2021.

technology pathways besides CARB's ACC II proposal that could achieve life cycle GHG emission reductions similar or greater than the ACC II proposal and meet the State's long-term climate goals. Because CARB does not provide a breakdown between the classes of LDVs included in the ACC II proposal, Ramboll's analysis of the proposed ACC II scenarios assumes the sales mandates and other requirements (e.g., range requirements, battery warranty, etc.) for LDVs in the ACC II proposal apply to LDAs. Additionally, because the ZEV sales mandates in the ACC II proposal can be met with a combination of PHEVs, BEVs and FCEVs, Ramboll's analysis considers several scenarios to outline the range of potential fleet mixes allowable under the proposed ACC II regulation.

A brief description of the analyzed scenarios is presented below. **Figure 2-1** and **Figure 2-2** present new vehicle sales fractions by model year while **Figure 2-3** and **Figure 2-4** show the resulting fleet mix. **Figure 2-5** through **Figure 2-7** presents the resulting fuel usage for these scenarios. A detailed matrix of all scenarios can be found in **Appendix A**.

- **S0 – ACC I:** This scenario serves as the baseline and is based on EMFAC2021 fleet mix defaults, which represents ACC I PHEV and BEV sales requirements. As shown in **Figure 2-2**, the fleet is comprised primarily of ICEVs, with a small but increasing percentage of PHEVs and BEVs. PHEVs and BEVs represent approximately 4% and 12% of new vehicle sales, respectively, for model years 2026-2050 (**Figure 2-1**). Note, in all scenarios, the existing sales fraction and population of PHEVs and BEVs in EMFAC2021 defaults served as the minimum penetration of these vehicle technologies. Thus, while additional BEVs and/or PHEVs were added in some scenarios, only ICEVs in the EMFAC2021 default fleet were replaced with other vehicle types as applicable in each scenario.
- **S1 – Baseline ACC II Scenarios:** In this set of scenarios, Ramboll evaluated multiple possible outcomes allowable under the proposed ACC II regulation to understand the range of potential emission reductions.
 - **S1a – ACC II (BEV):** This scenario assumes that any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0-ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with BEVs.
 - **S1b – ACC II (BEV + PHEV):** This scenario assumes that the ZEV sales needed to meet the ZEV sales requirements in the draft ACC II proposal are met with the maximum allowable fraction of PHEVs (20% of ZEV sales requirement) and BEVs (80% of ZEV sales requirement).
 - **S1c – ACC II (CARB SRIA):** This scenario assumes that the ZEV sales needed to meet the draft ACC II proposal are met with combination of PHEVs, BEVs, and FCEVs as noted in the CARB's SRIA for the ACC II proposal.
 - **S1d – ACC II (FCEV):** This scenario assumes that any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0-ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with FCEVs. The carbon intensity (CI) of hydrogen fuel used to power FCEVs in this scenario was developed based on the feedstock projections in CARB's SRIA for the ACC II proposal. Refer to **Section 3.2.4** for further discussion of hydrogen pathways.
 - **S1d-1 – ACC II (FCEV) + AB32 H₂:** This sensitivity scenario is identical to scenario S1d – ACC II (FCEV) with the following exception: the CI for hydrogen

fuel used to power FCEVs was developed based on the assumptions in the Assembly Bill (AB) 32 Source Emissions Initial Modeling Results¹⁰ ("AB 32 Initial Modeling") for the draft 2022 Scoping Plan Update.

- **S2 – Alternative Scenarios Part 1:** In this set of scenarios, Ramboll evaluated alternatives to the draft ACC II proposal where the ZEV sales requirements are met with PHEVs or HEVs instead of BEVs and FCEVs. Some of these scenarios also include the phase-in of a lower CI renewable drop-in fuel ("low-CI gasoline") used as a replacement for CaRFG that is used to fuel internal combustion engines (ICEs) in ICEVs, PHEVs, and HEVs. The carbon intensity of low-CI gasoline analyzed in these scenarios is 19g CO₂e/MJ (see **Section 3.2.2** for further discussion of low-CI gasoline).
 - **S2a – PHEV:** This scenario assumes that any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0-ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with PHEVs.
 - **S2b – PHEV + Low-CI Gas:** This vehicle fleet mix for this scenario is identical to scenario S2a – PHEV. However, it also includes the gradual phase-in of low-CI gasoline (see orange area in **Figure 2-6**) beginning as a replacement of 1% of CaRFG in 2026 and increasing to a replacement of 30% and 100% of CaRFG by 2035 and 2050 respectively.
 - **S2c – HEV + Low-CI Gas:** This scenario assumes that any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0-ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with all HEVs. It also includes a phase-in of low-CI gasoline (see orange area in **Figure 2-6**) beginning as a replacement of 2% of CaRFG in 2026 and increasing to a replacement of 35% and 100% of CaRFG by 2035 and 2050 respectively.
- **S3 – Alternative Scenarios Part 2:** In this set of scenarios, Ramboll utilized the same vehicle fleet mix as scenario S0 – ACC I along with a phase-in of low-CI gasoline as a replacement for CaRFG that is used to power internal combustion engines in the analyzed LDAs. The scenarios considered under S3 evaluate a range carbon intensities and phase in timetables for low-CI gasoline.
 - **S3a – Low-CI Gas:** This scenario analyzes the same vehicle fleet mix as S0 – ACC I with a gradual phase-in of low-CI gasoline (see orange area in **Figure 2-6**) beginning as a replacement of 1% of CaRFG in 2026 and increasing to a replacement of 45% and 100% of CaRFG by 2035 and 2050 respectively. The CI of the low-CI gasoline used in this scenario is 19 g CO₂e/MJ (see **Section 3.2.2** for further discussion of low-CI gasoline).
 - **S3a-1 – Low-CI Gas (Upper Range):** This sensitivity scenario is identical to scenario S3a – Low CI Gas with the following exception: the carbon intensity of the low-CI gasoline is increased by 10 g CO₂e/MJ to 29 g CO₂e/MJ.

¹⁰ Energy + Environmental Economics (E3). 2022. AB 32 Initial Model Results. March 15. Available at: <https://ww2.arb.ca.gov/sites/default/files/2022-03/SP22-Model-Results-E3-ppt.pdf>. Accessed: May 2022.

- **S3a-2 – Low-CI Gas (Lower Range):** This sensitivity scenario is identical to scenario S3a – Low-CI Gas with the following exception: the carbon intensity of the low-CI gasoline is reduced by 10 g CO₂e/MJ to 9 g CO₂e/MJ.
- **S3b – Low-CI Gas (Delayed):** This scenario is identical to scenario 3a with the following exception: the phase in of low-CI gasoline is delayed and occurs more slowly from 2026-2035 (replacement of 1% to 20% of CaRFG from 2026-2035) but increases rapidly from 2035-2040 (replacement of 97% and 100% of CaRFG by 2045 and 2050 respectively), as compared with scenario 3a (see orange area in **Figure 2-6**).
- **S4 – Alternative Scenarios Part 3:** In this set of scenarios, Ramboll evaluated various vehicle fleet mixes that utilize a combination of HEVs, PHEVs, BEVs, and/or FCEVs along with a gradual phase-in of low-CI gasoline as a replacement for CaRFG that is used to power ICEs in the analyzed LDA fleet.
 - **S4a – Custom Fleet Mix 1:** This scenario evaluates a custom fleet mix (see **Figure 2-4**) that assumes early implementation of HEVs from 2026-2035, with HEV sales declining after 2035 (see green area in **Figure 2-2**). PHEV sales increase by 1% per year from 2026-2040 and 2% per year thereafter (see gold area in **Figure 2-2**). BEV sales increase by 1% per year from 2030-2044 and 2% per year thereafter (see blue area in **Figure 2-2**). This scenario also includes a phase-in of low-CI gasoline (CI of 19 g CO₂e/MJ) beginning as a replacement of 2% of CaRFG in 2026 and increasing to a replacement of 100% of CaRFG by 2050 (see orange area in **Figure 2-6**).
 - **S4b – Custom Fleet Mix 2:** This scenario evaluates a custom fleet mix (see **Figure 2-4**) similar to S4a – Custom Fleet Mix 1, but with aggressive early implementation of HEVs from 2026-2035 and HEV sales declining after 2035 (see green area in **Figure 2-2**). PHEV sales increase by 1% per year from 2028-2031, stay constant from 2031-2035, increase by 2% per year from 2036-2039, increase by 4% per year in 2040 and 2041, and then stay constant at 39% from 2042 and thereafter (see gold area in **Figure 2-2**). Phase-in of additional BEVs is delayed until 2036, beginning at 7% in 2036 and increasing by 1% per year from 2036-2041. Additional BEV sales then increase by 3.5% per year until 2046 and remain constant thereafter at 42% (see blue area in **Figure 2-2**). This scenario also includes a phase-in of low-CI gasoline (CI of 19 g CO₂e/MJ) beginning as a replacement of 2% of CaRFG in 2026 and increasing to a replacement of 100% of CaRFG by 2050 (see orange area in **Figure 2-7**).
 - **S4c – Custom Fleet Mix 3:** This scenario evaluates a custom fleet mix (see **Figure 2-4**) similar to scenario S4a - Custom Fleet Mix 1, but with more FCEVs and less BEVs. Specifically, HEV and PHEV implementation is the same as scenario 4a (see green and gold areas in **Figure 2-2**), while BEV sales increase by only 0.5% per year from 2031-2044 and 1.5% per year thereafter (see blue area in **Figure 2-2**). FCEV sales start at 1% in 2030 and increase by 0.5% per year thereafter (see purple area in **Figure 2-2**). This scenario also includes a phase-in of low-CI gasoline (CI of 19 g CO₂e/MJ) beginning as a replacement of 2% of CaRFG in 2026 and increasing to a replacement of 100% of CaRFG by 2050 (see orange area in **Figure 2-7**). Similar to scenario S1d – ACC II (FCEV), the carbon intensity (CI) of hydrogen fuel used to

power FCEVs in this scenario was developed based on the feedstock projections in CARB's SRIA for the ACC II proposal. Refer to **Section 3.2.4** for further discussion of hydrogen pathways.

Figure 2-1. LDA New Vehicle Sales Fractions for Scenarios 0, 1a, 1b, 1c, 1d, and 2a

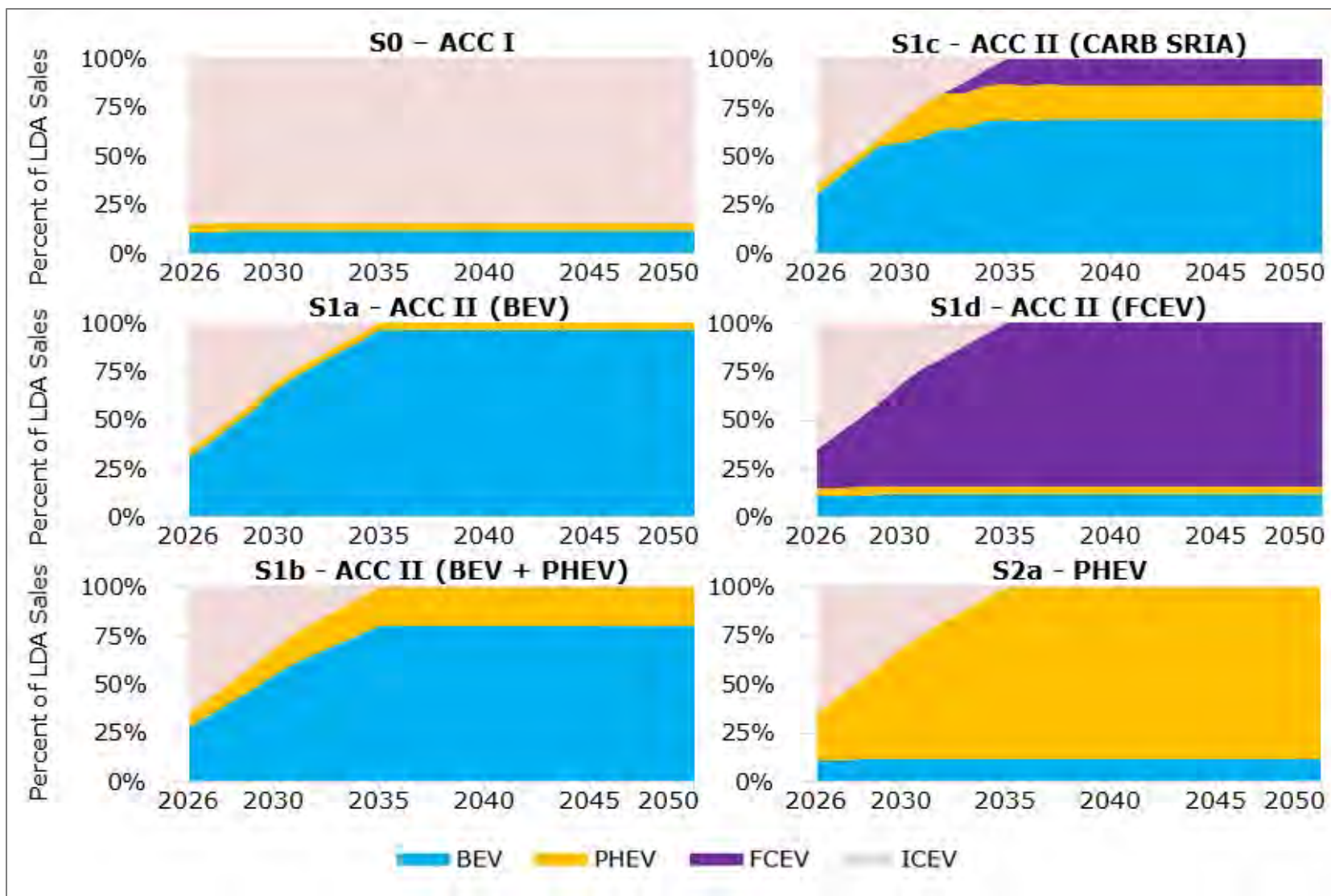


Figure 2-2. LDA New Vehicle Sales Fractions for Scenarios 2b, 2c, 3a, 4a, 4b, and 4c

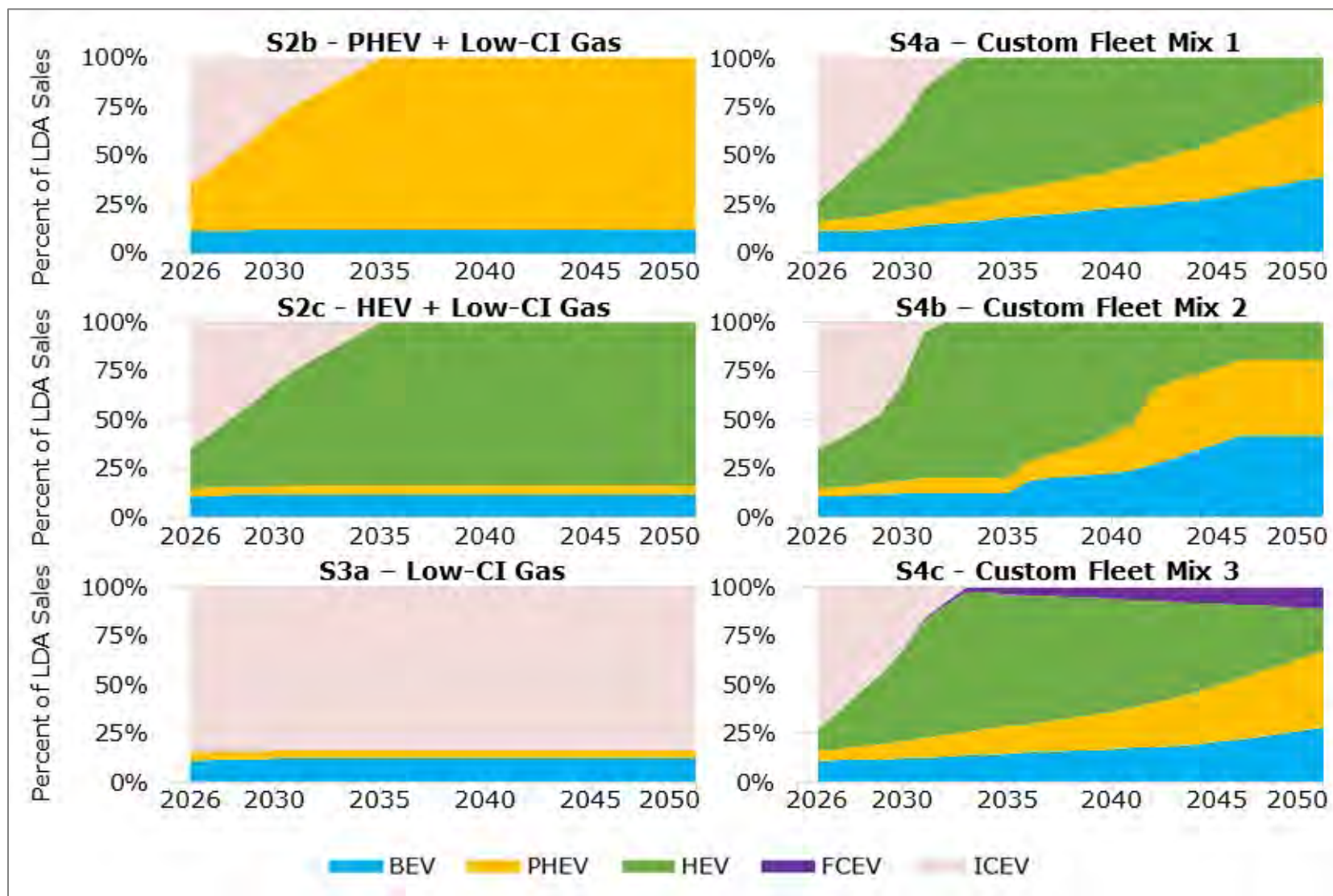


Figure 2-3. LDA Fleet Mixes for Scenarios 0, 1a, 1b, 1c, 1d, and 2a

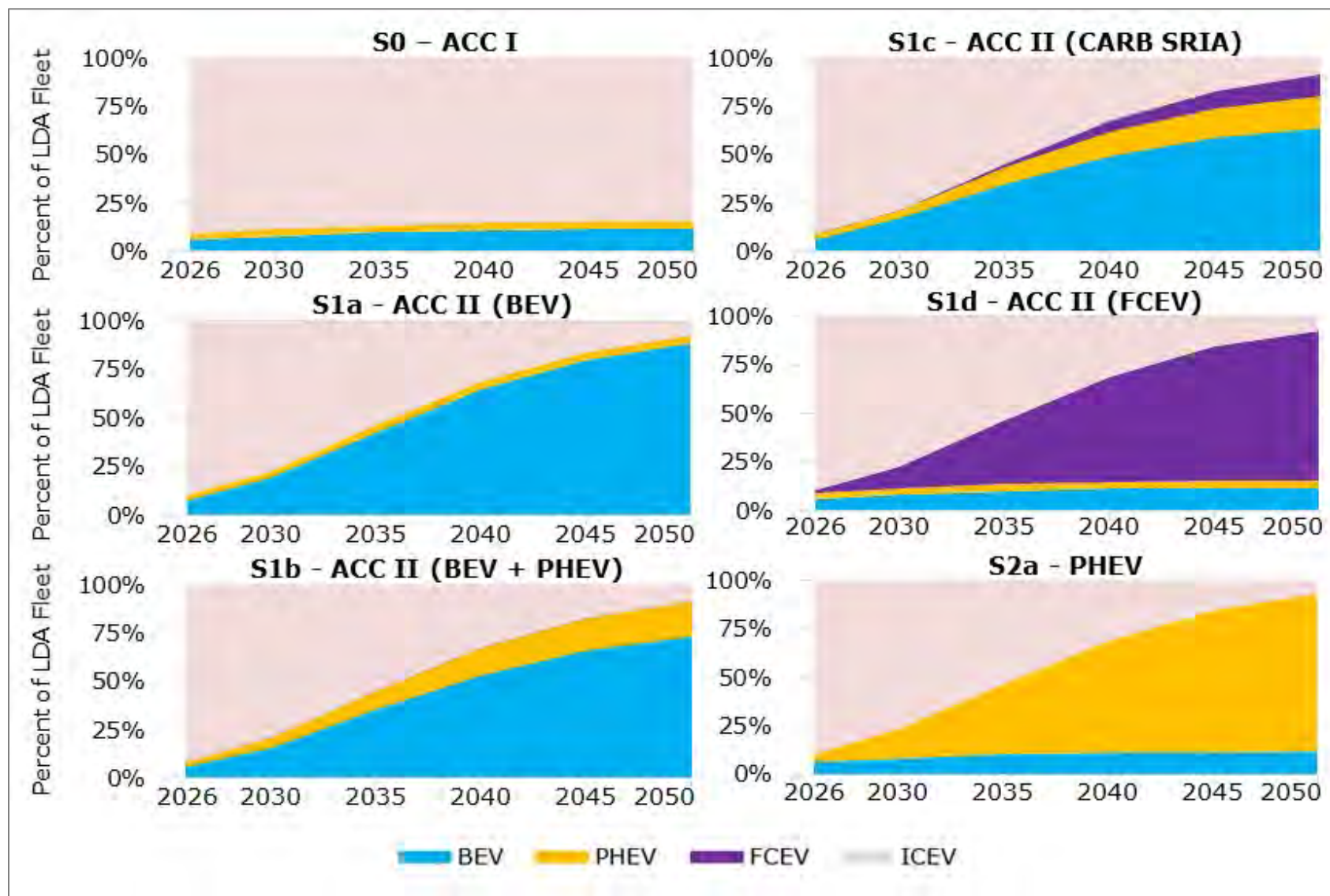


Figure 2-4. LDA Fleet Mixes for Scenarios 2b, 2c, 3a, 3b, 4a, 4b, and 4c

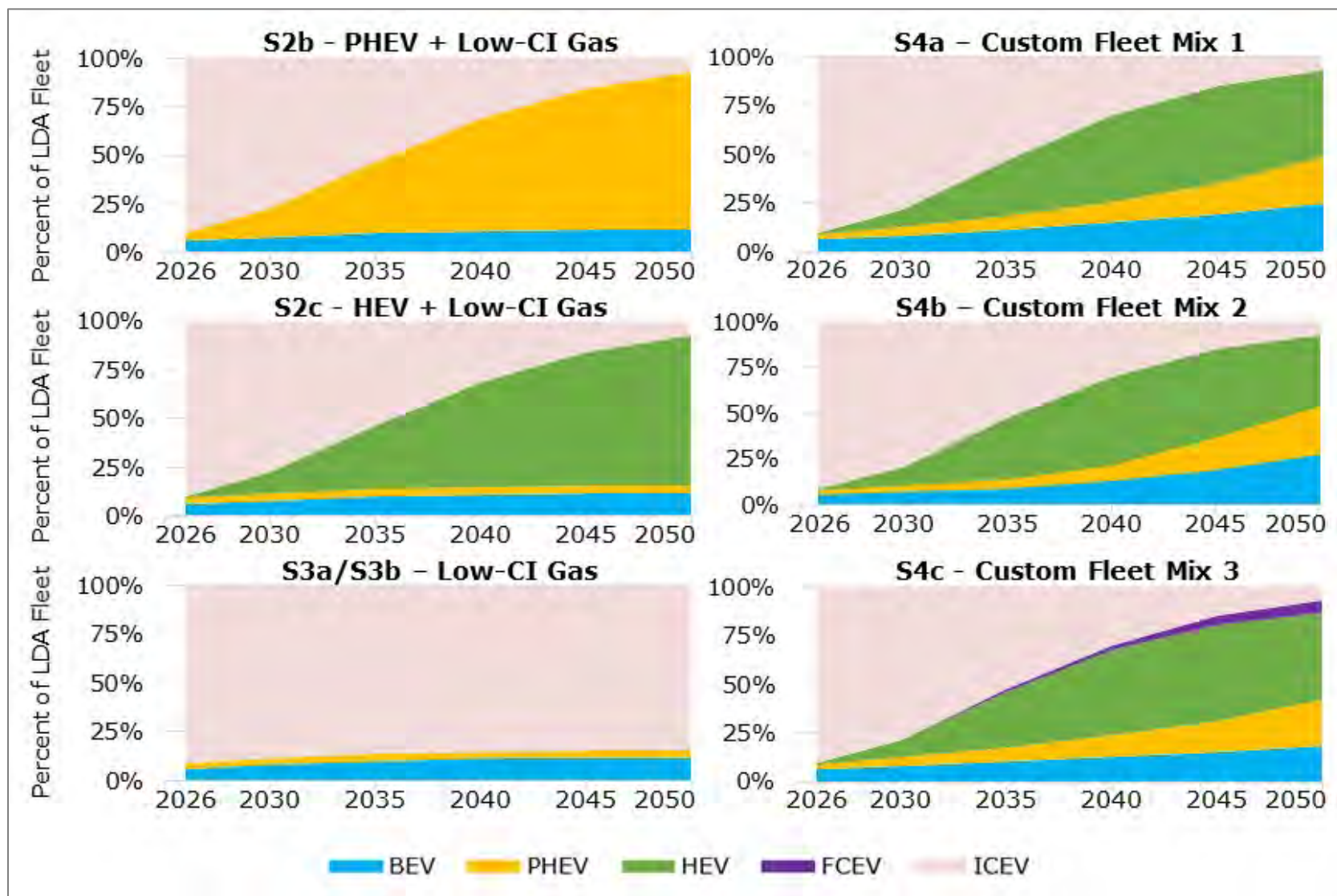


Figure 2-5. Fuel Usage Fractions for Scenarios 0, 1a, 1b, 1c, 1d, and 1d-1

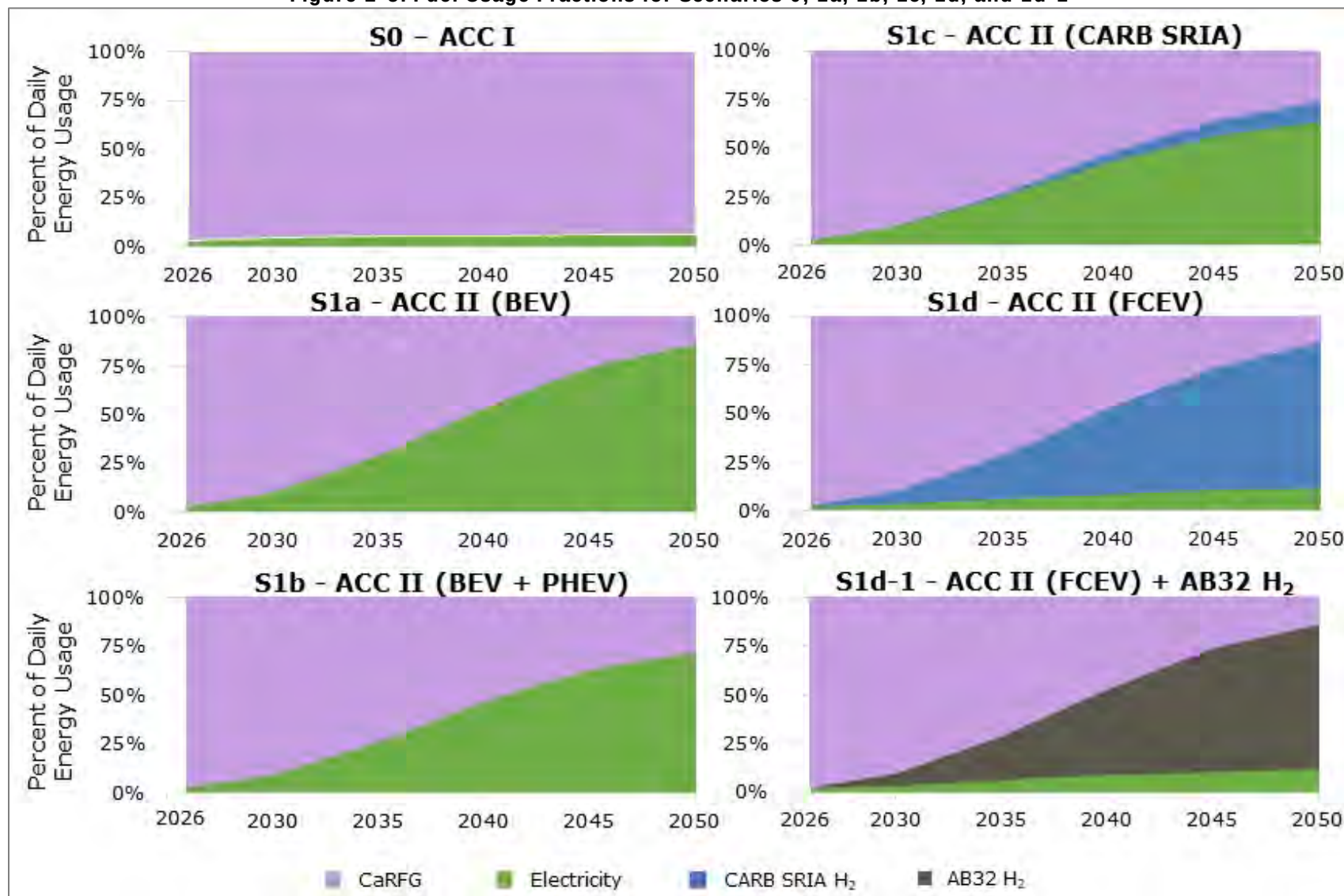


Figure 2-6. Fuel Usage Fractions for Scenarios 2a, 2b, 2c, 3a, 3b, and 4a

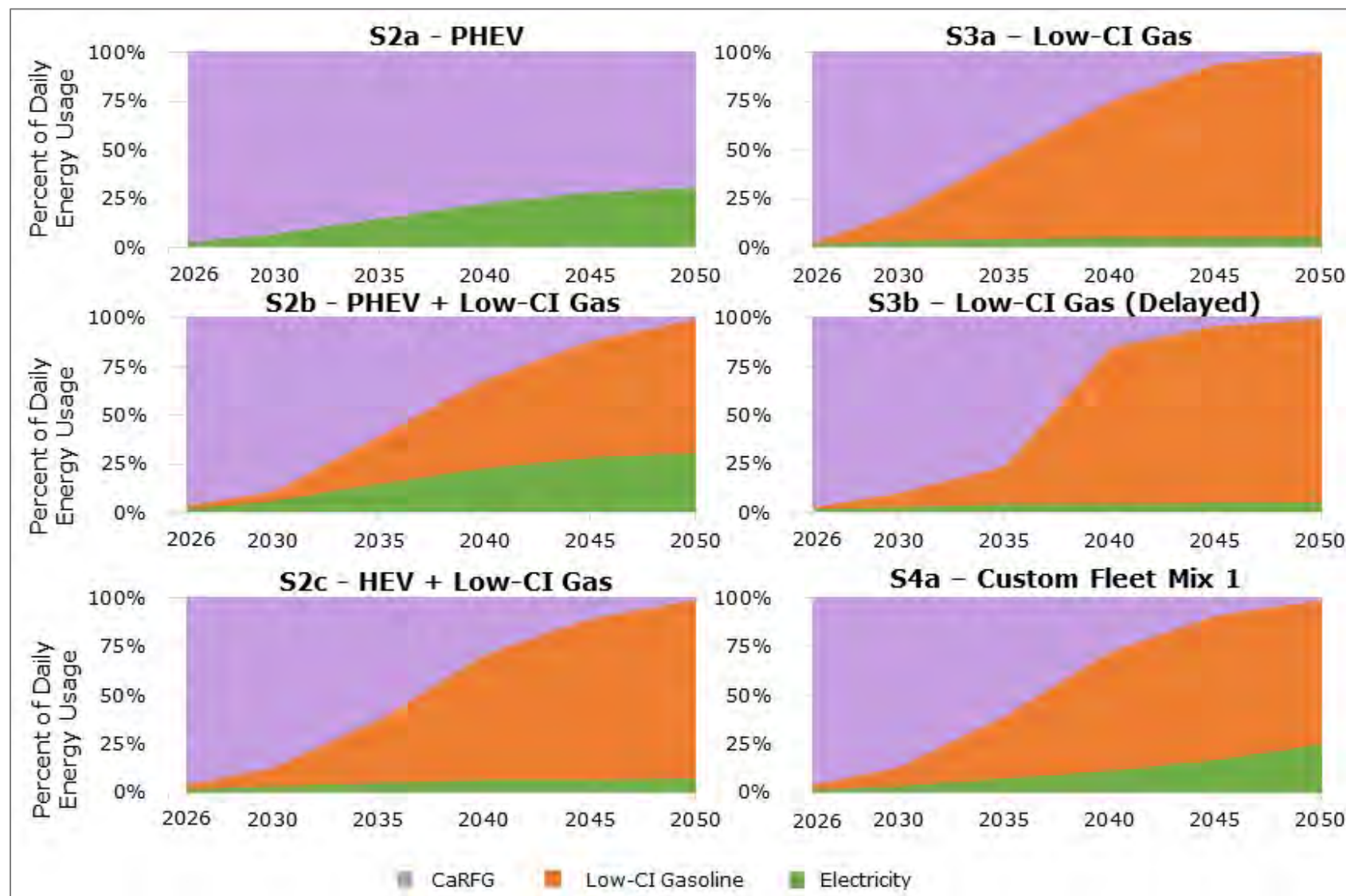
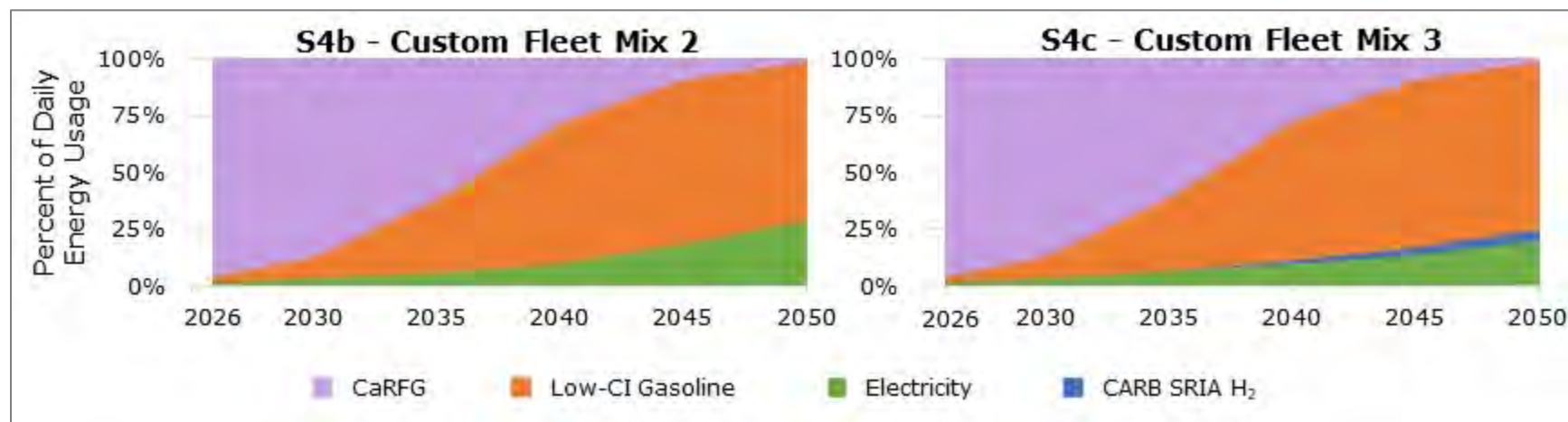


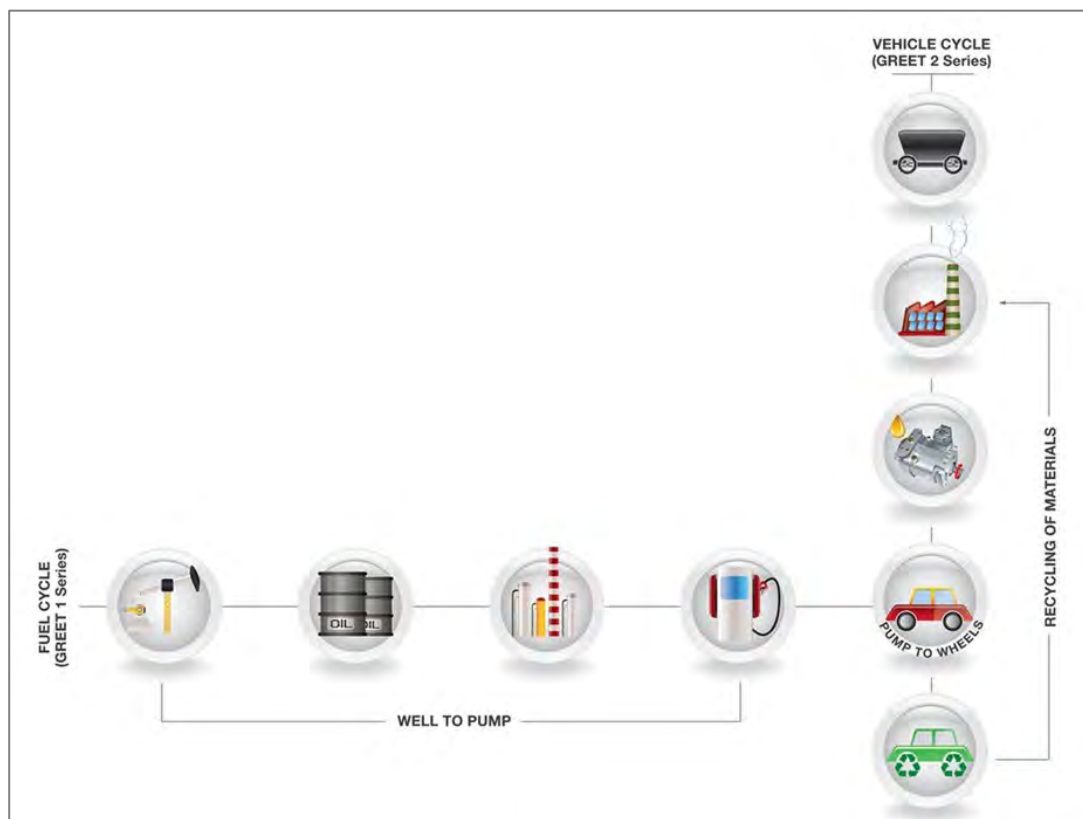
Figure 2-7. Fuel Usage Fractions for Scenarios 4b and 4c



3. SCENARIO ANALYSIS METHODOLOGY

An accurate assessment of future vehicle/fuel technology pathways requires full life cycle emissions analysis, including fuel cycle emissions and vehicle cycle emissions. The vehicle cycle analysis includes emissions associated with vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal and recycling, while the fuel cycle analysis considers energy use and emissions associated with fuel production and distribution activities as well as energy use and emissions associated with vehicle operation.^{11,12} The various processes included in the fuel cycle and vehicle cycle are represented in **Figure 3-1** below.

Figure 3-1. Fuel Cycle and Vehicle Cycle Emissions Representation in the GREET Model¹³



¹¹ P. Moon, A. Burnham, M. Wang. 2006. "Vehicle-Cycle Energy and Emission Effects of Conventional and Advanced Vehicles (abstract)". April 3. Available here: <https://greet.es.anl.gov/publication-hkjun004>. Accessed: May 2022.

¹² USEPA. Lifecycle Analysis of Greenhouse Gas Emissions under the Renewable Fuel Standard. Available at: <https://www.epa.gov/renewable-fuel-standard-program/lifecycle-analysis-greenhouse-gas-emissions-under-renewable-fuel>. Accessed: May 2022.

¹³ ANL. 2021. Greenhouse gases, Regulated Emissions, and Energy use in Technologies model. Available at: <https://greet.es.anl.gov/>. Accessed: May 2022.

The following sections provide a high-level description of the methodology used for Ramboll's scenario analysis. Detailed modeling inputs, outputs, and methodology are provided in **Appendix A**.

3.1 Vehicle Technologies

Several LDA vehicle technologies are considered in Ramboll's analysis, as described in the following sections. Of these vehicle technologies, ICEVs, PHEVs, and BEVs are present in the EMFAC2021 default fleet mix for LDAs while FCEVs and HEVs are not. As described previously, LDAs fueled by diesel and natural gas are not included in this analysis.¹⁴

3.1.1 Internal Combustion Engine Vehicles

ICEVs are vehicles that use only an internal combustion engine to attain propulsion power. As described previously, only gasoline-fueled ICEVs are considered in this analysis. ICEVs comprise the majority of the LDA fleet in the EMFAC2021 default fleet mix and are replaced to varying degrees with other vehicle technologies in the scenarios described in **Section 2**. Key data for ICEVs used to perform the analysis were derived from EMFAC2021.¹⁵ Specifically, Ramboll used EMFAC2021 data to derive fuel economy, daily vehicle miles travelled (VMT) per vehicle, and tailpipe emission factors for ICEVs by model year for each calendar year. Fuel economy for ICEVs was determined using fuel consumption and VMT data from EMFAC2021 and vary by model year and calendar year, ranging from about 18 miles per gallon (MPG) for the oldest vehicles to 35 MPG for the newest vehicles. Similarly, daily VMT per vehicle was calculated using VMT and population data from EMFAC2021 and ranges from 5 miles per vehicle per day for the oldest vehicles to 55 miles per vehicle per day for the newest vehicles. The methodology used to calculate tailpipe emissions is discussed in **Section 3.3**. See **Appendix A (Tables A-8 through A-25)** for ICEV fuel economy, tailpipe emission factors, and daily VMT per vehicle by model year for each calendar year considered in this analysis.

Daily VMT per vehicle for ICEVs serves as the basis for calculating VMT for other vehicle technologies as ICEVs are replaced with PHEVs, BEVs, HEVs, or FCEVs in each scenario. Specifically, this analysis assumes that any vehicle technology replacing an ICEV travels the same number of miles per vehicle per day as the ICEV it is replacing, as determined from EMFAC2021. Thus, in each scenario, as ICEVs are replaced with other vehicle technologies, the population and corresponding VMT of ICEVs is reduced and allocated to the replacement vehicles in a one-to-one ratio.¹⁶ Similarly, Ramboll's analysis assumes that the vehicle lifetime (i.e., retirement rate) for ICEVs obtained from EMFAC2021 remains the same for any replacement vehicle technology. Therefore, Ramboll's analysis does not alter the total vehicle

¹⁴ Natural gas vehicles are excluded as they are not included in the default EMFAC2021 LDA fleet. Diesel vehicles are not included in this analysis because they comprise less than 0.3% of the total LDA population in EMFAC2021.

¹⁵ This analysis uses EMFAC2021 v1.0.1. A newer version of EMFAC2021 v1.0.2 was released on May 2, 2022 (after completion of this analysis) that reflects the revocation of the Safe Affordable Fuel-Efficient or SAFE vehicles rule. While this update increases the fuel economy, methane (CH₄), and nitrous oxide (N₂O) tailpipe emission factors by <5% and <0.5% for 2025+ model year ICEVs and PHEVs, respectively, it does not change the overall conclusions of the analysis.

¹⁶ For PHEVs replacing ICEVs, total VMT from the ICEV is allocated to eVMT and cVMT for the replacement PHEV according to the EMFAC2021 default split between eVMT and cVMT for the replacement vehicle. Additional details are provided in **Section 3.1.3** and **Appendix A**.

population and VMT projections in EMFAC2021, even as vehicle technologies change in each scenario.

3.1.2 Battery Electric Vehicles

BEVs are vehicles that use energy from batteries to attain propulsion power. BEVs have larger batteries than PHEVs and HEVs and are plugged in and charged using electricity from the grid. BEVs have no ICE, do not use gasoline fuel, and have zero tailpipe emissions. BEVs comprise a small but increasing percentage of the EMFAC2021 default fleet mix and are the primary vehicle technology assumed to replace ICEVs under the proposed ACC II regulation. Fuel economy for BEVs was calculated using energy consumption and VMT data from EMFAC2021. Unlike fuel economy for ICEVs, which varies by model year and calendar year, fuel economy for all model year BEVs in EMFAC2021 is fixed at 0.386 kilowatt-hour per mile (kWh/mi) (~86 miles per gallon equivalent (MPGe))¹⁷ irrespective of the calendar year in which they operate. Although VMT per vehicle for BEVs is not used in this analysis because any BEV replacing a ICEV is assumed to travel the same number of miles as the ICEV it is replacing, EMFAC2021 assumes that BEVs generally travel a similar number of miles per vehicle per day as ICEVs.

3.1.3 Plug-In Hybrid Electric Vehicles

PHEVs are vehicles that use energy from a battery, an ICE fueled by gasoline, or a combination of the two to attain propulsion power. PHEVs have smaller batteries than BEVs but can operate solely on energy from the battery and can be plugged in and charged using electricity from the grid. PHEVs comprise a small but increasing percentage of the EMFAC2021 default fleet mix and are the only vehicle technology considered in this analysis that is capable of both electric-only trips and trips using an ICE.

In order to account for the two potential operational modes of a PHEV (i.e., propulsion using only energy from the battery or propulsion with use of the ICE), total VMT in EMFAC2021 is resolved by combustion VMT (cVMT), for miles traveled by vehicles powered by an ICE, and electric VMT (eVMT), for miles traveled by vehicles powered by energy from a battery.¹⁸ Similarly, EMFAC2021 accounts for electric energy consumption separate from gasoline fuel consumption. In EMFAC2021, eVMT is defined as miles traveled during a pure electricity powered trip, and energy consumption is determined based on only pure electric trips during which an ICE does not turn on.¹⁹ Thus, only PHEVs have both cVMT and eVMT and both energy consumption and fuel consumption in EMFAC2021. The remaining vehicle technologies in EMFAC2021 have either cVMT and fuel consumption (e.g., ICEVs), or eVMT and energy consumption (e.g., BEVs). Throughout this analysis, we utilize the term “fuel

¹⁷ Non-liquid fuels, like electricity and hydrogen, are not measured in gallons, so using conversion factors allows them to be displayed on an energy-equivalent basis using the familiar MPG measurement. MPGe, or miles per gallon of gasoline equivalent, is calculated based on the energy content of gasoline, 119.53 MJ/gal for CARBOB, which is then converted to kWh to derive a conversion factor of 33.203 kilowatt-hours/gallon of gasoline equivalent. Available at: https://ww2.arb.ca.gov/sites/default/files/2022-05/quarterlysummary_043022.xlsx. Accessed: May 2022.

¹⁸ CARB. 2021. EMFAC2021 Volume I – User's Guide. January 15. Available at: https://ww2.arb.ca.gov/sites/default/files/2021-01/EMFAC202x_Users_Guide_01112021_final.pdf. Accessed: May 2022.

¹⁹ CARB. 2021. EMFAC2021 Volume III Technical Document - Version 1.0.0. March 31. Available at: https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf. Accessed: May 2022.

economy” as a fuel-neutral description of miles traveled per unit of fuel or energy consumed, whether the fuel is gasoline, hydrogen, or electricity. For example, fuel economies for all vehicles considered in this analysis are shown in **Appendix A, Tables A-8, A-11, A-14, A-17, A-20, and A-23.**

Based on these distinctions, Ramboll used EMFAC2021 data to derive electric and gasoline fuel economy, and the split between eVMT and cVMT for PHEVs. Gasoline fuel economy was determined based on fuel consumption and cVMT while electric fuel economy was determined based on energy consumption and eVMT. Gasoline fuel economy values for PHEVs in EMFAC2021 vary by model year and calendar year, ranging from 23 MPG to 29 MPG. In contrast, electric fuel economy values for PHEVs are constant in EMFAC2021 at 0.302 kWh/mi (~110 MPGe) for all model years in all calendar years. For PHEVs, the split between eVMT and cVMT varies by model year and calendar year. The eVMT fraction of total VMT increases from 46% in the earlier model years to 59% in the later model years, while the cVMT fraction decreases from 54% to 41%. These percentages are used to allocate total VMT to eVMT and cVMT when a PHEV replaces a ICEV in the scenario analysis. Although total VMT per vehicle for PHEVs is not used in this analysis because any PHEV replacing a ICEV is assumed to travel the same number of miles as the ICEV it is replacing, EMFAC2021 data shows that PHEVs generally travel a similar number of miles per vehicle per day as ICEVs. The methodology used to estimate tailpipe emissions for PHEVs is discussed in **Section 3.3.** See **Tables A-8 through A-25 in Appendix A** for PHEV fuel economy, tailpipe emission factors, and eVMT and cVMT percentages.

3.1.4 Hybrid Electric Vehicles (HEVs)

HEVs operate similar to ICEVs and obtain propulsion power primarily from an ICE, but incorporate a small battery and electric motor to improve overall fuel economy. Unlike BEVs and PHEVs, HEVs are not able to be plugged in and charged using electricity from the grid, nor are they capable of electric-only trips. Because of these operational characteristics, HEVs were analyzed similar to ICEVs in this analysis. HEVs are not included in the EMFAC2021 default fleet mix but were considered as replacements for ICEVs in some of the scenarios described in **Section 2.**

Fuel economy for HEVs was calculated based on the fuel economy of ICEVs obtained from EMFAC2021 and the relative fuel economies of the average model year 2020 HEV and ICEV as obtained from the United States Environmental Protection Agency’s (USEPA’s) 2020 EPA Automotive Trends Report (“EPA Report”).²⁰ The EPA Report shows that, as a production-weighted average, hybrid cars had a fuel economy about 41% higher than the average non-hybrid car in model year (MY) 2020. This factor was assumed to remain constant in future years and was used to estimate fuel economies for MY 2026 to 2050 HEVs. Using this factor, HEVs are estimated to have gasoline fuel economies ranging from about 43 MPG to 50 MPG. The methodology used to calculate tailpipe emissions for HEVs is discussed in **Section 3.3** and HEV fuel economies are shown in **Appendix A.**

²⁰ United States Environmental Protection Agency (USEPA). 2021. The 2020 EPA Automotive Trends Report. EPA-420-R-21-003. January. Available at: <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P1010U68.pdf>. Accessed: May 2022.

3.1.5 Fuel Cell Electric Vehicles

FCEVs use an electric propulsion system similar to that of BEVs but use an on-board fuel cell to convert energy stored as hydrogen to electricity rather than utilizing energy only from a battery. Thus, FCEVs are fueled with hydrogen stored in a tank on the vehicle. Similar to BEVs, FCEVs produce zero tailpipe emissions. FCEVs are not included in the EMFAC2021 default fleet mix but were considered as replacements for ICEVs in some of the scenarios described in **Section 2**. Fuel economy for FCEVs was calculated based on the fuel economy of ICEVs and the Energy Economy Ratio (EER) of a FCEV relative to an ICEV. EERs are dimensionless values that represent the efficiency of a fuel as used in a powertrain as compared to a reference fuel used in the same powertrain. Ramboll used an EER of 2.5 based on the value for a FCEV used as a replacement for a gasoline-fueled ICEV in light/medium-duty applications as reported in CARB's LCFS Regulation.²¹ This EER was applied to ICEV fuel economies as described in **Section 3.1.1** to determine FCEV fuel economies by model year and calendar year for MY 2026-2050 FCEVs. Using this methodology, FCEV energy economies range from about 0.366 to 0.374 kWh/mi (89 to 91 MPGe) as shown in **Appendix A**.

3.2 Fuel Cycle Emissions

An accurate assessment of future vehicle/fuel technology pathways requires a complete fuel-cycle analysis, commonly called a well-to-wheels analysis. A well-to-wheels analysis considers energy use and emissions associated with fuel production and distribution activities ("well-to-tank" or "upstream") as well as energy use and emissions associated with vehicle operation ("tank-to-wheels" or "tailpipe") activities.²² The following sub-sections describes the methodology used to estimate upstream and tailpipe emissions for the vehicle/fuel technologies that are considered in this analysis.

3.2.1 Upstream (Well-to-Tank) Emissions

Upstream emissions are generated from feedstock-related processes (recovery, processing, storage, and transportation of feedstocks) and fuel-related processes (production, transportation, storage, and distribution of fuels).²³

Ramboll estimated well-to-tank GHG emission factors for each analyzed fuel type (CaRFG, low-CI gasoline, electricity, and hydrogen) using carbon intensities obtained from the CA-GREET3.0 model,²⁴ LCFS Lookup Pathways Tables,²⁵ LCFS Quarterly Summary data,²⁶

²¹ CARB. 2020. Unofficial Electronic Version of the Low Carbon Fuel Standard. May 27. Available at: https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf. Accessed: May 2022.

²² Brinkman, Norman, Michael Wang, Trudy Weber, and Thomas Darlington. 2005. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. May. Available at: <https://greet.es.anl.gov/files/4mz3q5dw>. Accessed: May 2022.

²³ Ibid.

²⁴ CA-GREET 3.0 Model. Available at: <https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet30-corrected.xlsm>. Accessed: January 2021.

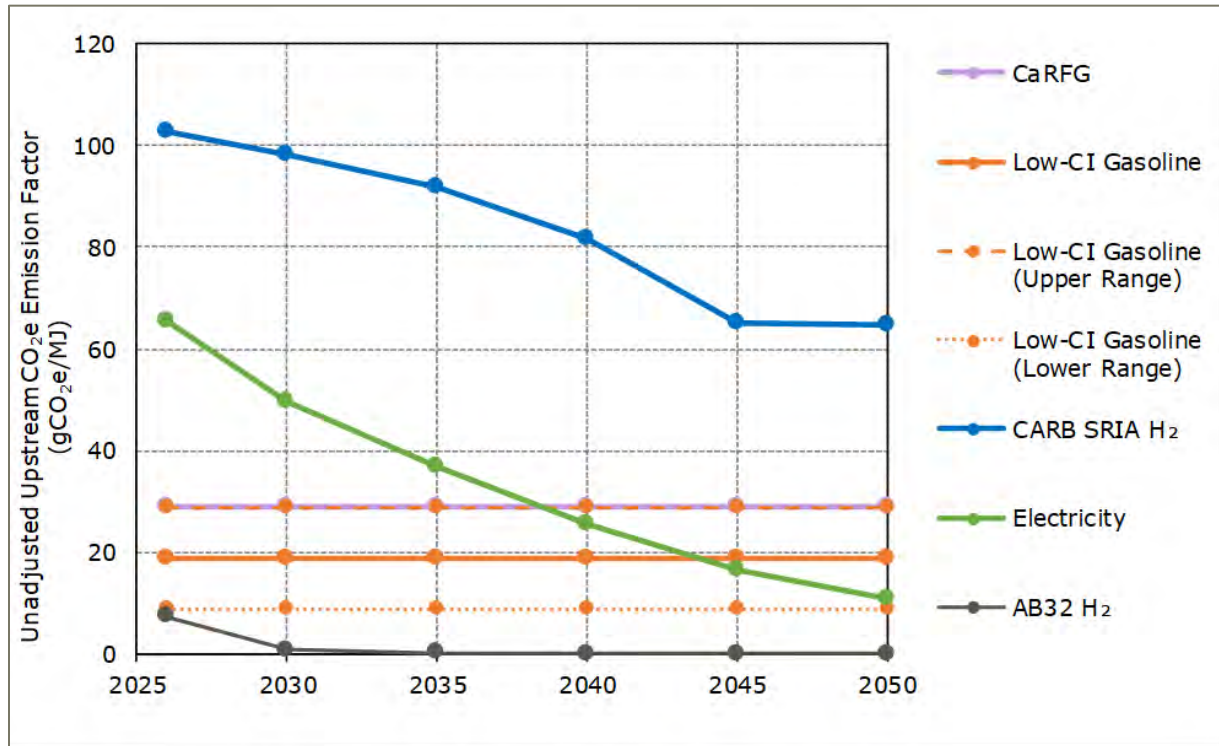
²⁵ CARB. 2018. CA-GREET3.0 Lookup Table Pathways Technical Support Documentation. August 13. Available at: <https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/lut-doc.pdf>. Accessed: May 2022.

²⁶ CARB. LCFS Quarterly Summaries. Available at: <https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries>. Accessed: May 2022.

and assumptions used in CARB's ACC II SRIA,²⁷ and AB 32 Initial Modeling.²⁸ Upstream GHG emission factors are typically represented as carbon intensities, i.e., the mass of GHG emissions in carbon dioxide equivalent (CO₂e) per unit of energy consumed in mega joules (MJ) for each fuel type. Carbon intensities for all fuel pathways considered in this analysis with and without EER adjustment are shown in **Figure 3-2** and **Figure 3-3** respectively. Additional details on the methodology used to estimate upstream GHG emission factors or CIs are provided in **Sections 3.2.1.1** through **3.2.1.4**.

Ramboll estimated the total upstream GHG emissions for each analysis year in each modeled scenario as a sum-product the upstream CI for each fuel type (**Figure 3-2**) and the total amount of each fuel consumed for each fuel type across all vehicle technologies (**Tables A-26** through **A-91** in **Appendix A**). The total amount of each fuel consumed was calculated using the VMT and fuel economy of the vehicle technologies included in each scenario. Fuel economies and VMT are determined as described in **Section 3.1**. This methodology accounts for the differences in EER between vehicle technologies because the conventional gasoline fuel energy derived from EMFAC2021 for the proportion of ICEVs replaced by other vehicle technologies was adjusted by the relative fuel economy of the replacement vehicles.

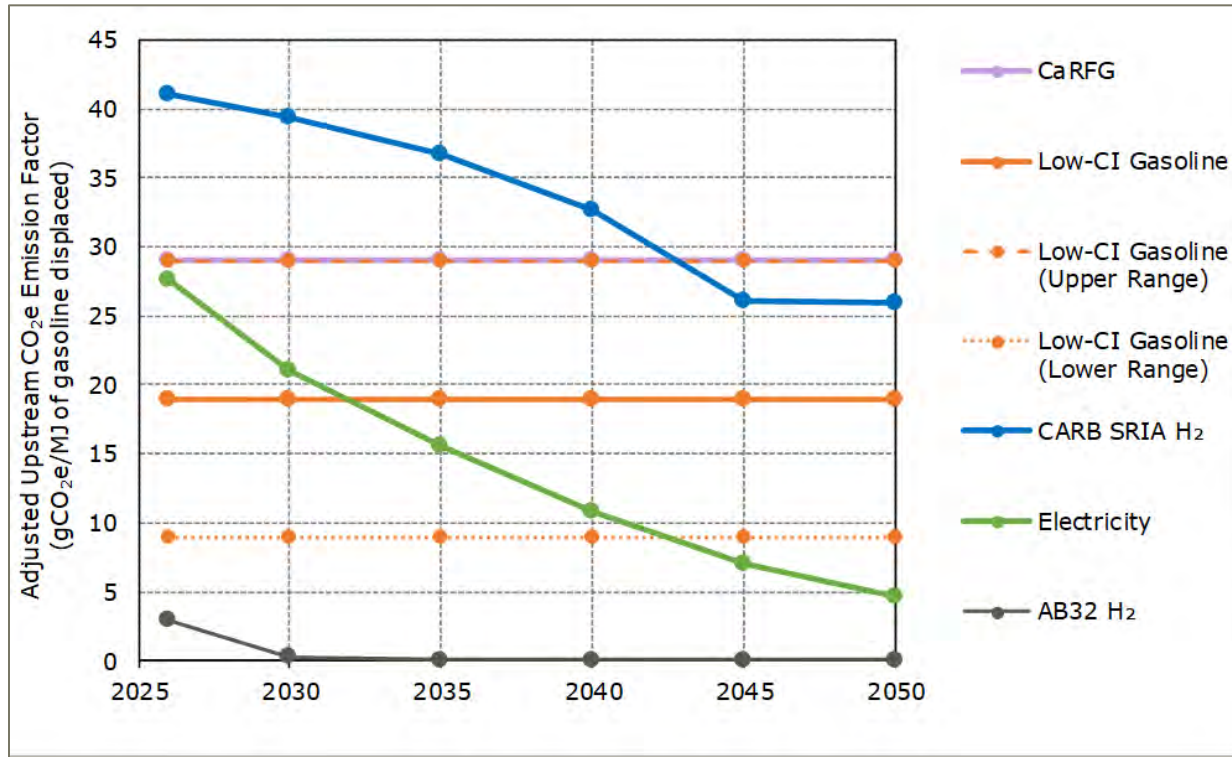
Figure 3-2. Upstream (EER-unadjusted) GHG Emission Factors by Fuel Type



²⁷ CARB. 2022. Appendix C-1: Standardized Regulatory Impact Assessment (SRIA). April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appc1.pdf>. Accessed: May 2022.

²⁸ E3. 2022. AB 32 Initial Model Results. March 15. Available at: <https://ww2.arb.ca.gov/sites/default/files/2022-03/SP22-Model-Results-E3-ppt.pdf>. Accessed: May 2022.

Figure 3-3. Upstream (EER-adjusted) GHG Emission Factors by Fuel Type



3.2.1.1 California Reformulated Gasoline

Ramboll estimated the upstream CI of CaRFG as an energy-weighted average value of the upstream CIs of the two components that make up CaRFG: California reformulated gasoline blendstock for oxygenate blending (CARBOB), and ethanol.

The upstream CI values used in this calculation include:

- 26.9 g CO₂e/MJ for CARBOB obtained from the CA-GREET3.0 Lookup Table Pathways,²⁹ and
- 59.8 g CO₂e/MJ for ethanol calculated as an average of the ethanol CIs available in the LCFS Quarterly Reports³⁰ for the most recent period (2020 Q1 to 2021 Q3) at the time of this analysis.

The blend ratio applied to these CI values to obtain a CI of 29.1 g CO₂e/MJ for CaRFG is 6.61% ethanol and 93.39% CARBOB on an energy basis, which is consistent with the 9.5% ethanol blend by volume assumed in the GREET model.³¹

²⁹ CARB. 2018. CA-GREET3.0 Lookup Table Pathways Technical Support Documentation. August 13. Available at: <https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/lut-doc.pdf>. Accessed: May 2022.

³⁰ CARB. LCFS Quarterly Summaries. Available at: <https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries>. Accessed: May 2022.

³¹ CA-GREET3.0 Model. Available here: https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet30-corrected.xlsm?_ga=2.255823756.582239942.1645477627-990540269.1603987774. Accessed: May 2022. Available under the tab 'Petroleum' under 'Energy % Ethanol in CaRFG'.

Finally, Ramboll estimated the upstream GHG emissions for CaRFG consumed by LDVs in each scenario using this CI value and the total consumption of CaRFG across all vehicle technologies in each analysis year.

3.2.1.2 Low-CI Gasoline

To estimate a carbon intensity for the low-CI gasoline considered in this analysis, a review of currently available and documented carbon intensities for low-CI renewable gasoline drop-in fuels was performed, as documented in **Table 3-1**. Sources for low-CI drop-in renewable gasoline fuels included the USEPA lifecycle GHG results, LCFS fuel pathways, Argonne National Laboratory (ANL) state-of-technology research, CARB-driven research, and a research paper published by the University of Chicago ANL. While the research yielded multiple pathways that spanned both renewable gasoline (e.g., bio-based feedstocks) as well as lower-CI gasoline alternatives, we chose to represent them as a single category due to their similar function as a drop-in replacement fuel. The average of these values was taken in order to find a representative carbon intensity for the low-CI gasoline fuel considered in this analysis, resulting in a CI of 19.0 g CO₂e/MJ, which is about 35% lower than the upstream CI for CaRFG.

Upstream GHG emissions associated with the use of low-CI gasoline in LDAs with ICEs for Scenarios S2b - PHEV + Low -CI Gas, S2c – HEV + Low-CI Gas, S3a – Low-CI Gas, S3b – Low-CI Gas (Delayed) and Custom Fleet Mix scenarios (S4a, S4b, and S4c) were calculated using this CI value of 19 g CO₂e/MJ and the total consumption of low-CI gasoline across all vehicle technologies in each analysis year.

In order to understand the impact of this carbon intensity on upstream and life cycle emissions, we also considered two sensitivity scenarios:

- Scenario 3a-1 – Low-CI Gas (Upper Range): For this scenario the low-CI gasoline CI was increased by 10 g CO₂e/MJ to 29 g CO₂e/MJ. This value is similar to the upstream CI for CaRFG.
- Scenario 3a-2 – Low CI-Gas (Lower Range): For this scenario the low-CI gasoline CI was reduced by 10 g CO₂e/MJ to 9 g CO₂e/MJ. This value is about 69% lower than the upstream CI for CaRFG.

Table 3-1. Low-CI Fuel Carbon Intensity Summary			
Reference	Process	Feedstock	Upstream CI (g CO₂e / MJ)
USEPA Lifecycle GHG Results ¹	Direct biochemical fermentation	Cellulose from corn stover	-29.0
USEPA Lifecycle GHG Results ¹	Catalytic pyrolysis and upgrading	Cellulose from corn stover	28.7
USEPA Lifecycle GHG Results ¹	Biochemical fermentation and upgrading	Cellulose from corn stover	30.6
LCFS Fuel Pathways ²	Pyrolysis	Forest residue [transport by rail]	21.2
LCFS Fuel Pathways ²	Pyrolysis	Forest residue [transport by truck]	26.1
ANL state-of-technology research ³	Ex Situ Catalytic Fast Pyrolysis	Woody biomass	20.7
Biofuel Supply Module ⁴	Pyrolysis	Cellulosic	8.1
Biofuel Supply Module ⁴	Pyrolysis	Wood	24.7
University of Chicago ANL Research Paper ⁵	Fischer-Tropsch Fuel Synthesis	Solar/Nuclear/Wind Energy for Hydrogen and Corn Ethanol Production for CO ₂	37.1
Average Carbon Intensity			19.0
References: ¹ EPA. 2016. Lifecycle Greenhouse Gas Results. Available here: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results . Accessed: May 2022. ² CARB. 2022. LCFS Current Pathways. Available here: https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/currentpathways_all.xlsx . Accessed: May 2022. ³ Argonne National Laboratory. 2021. Supply chain sustainability analysis of renewable hydrocarbon fuels- update of the 2020 state-of-technology cases. Available here: https://greet.es.anl.gov/publication-2020_update_renewable_hc_fuel . Accessed: May 2022. ⁴ CARB. 2016. Biofuels Supply Module. Available here: https://www.arb.ca.gov/cc/scopingplan/meetings/090716/bfsmv83b.zip . Accessed: May 2022. ⁵ University of Chicago. 2021. Life Cycle Analysis of Electrofuels: Fischer–Tropsch Fuel Production from Hydrogen and Corn Ethanol Byproduct CO ₂ . Available here: https://pubs.acs.org/doi/10.1021/acs.est.0c05893 . Accessed: May 2022.			

3.2.1.3 Electricity

Ramboll estimated upstream GHG emissions associated with the production and distribution of electricity consumed by PHEVs and BEVs in each modeled scenario using emission factors obtained from the CA-GREET 3.0 model.³² Developed from Argonne National Laboratory's GREET 2016 model,³³ the CA-GREET 3.0 model is used by CARB to calculate well-to-wheel emissions from transportation fuels under the California LCFS Program. Hence, use of this model to estimate upstream emissions is consistent with the CARB methodologies.

For purposes of this analysis, Ramboll adjusted the electricity grid mix inputs to the CA-GREET 3.0 model based on California Energy Commission (CEC) projections for each of the modeled calendar years 2026, 2030, 2035, 2040, 2045, and 2050.³⁴ Further details regarding CA-GREET 3.0 model inputs and outputs can be found in **Appendix A**.

As shown in **Figure 3-2**, the electricity CI values estimated using CA-GREET 3.0 decrease from 65.3 g CO₂e/MJ in 2026 to 11.1 g CO₂e/MJ in 2050. Once adjusted for the differences in the efficiency of electricity in BEVs as compared to gasoline-fueled ICEVs, the electricity CI values range from 27.6 g CO₂e/MJ of gasoline displaced (5.1% lower than that for CaRFG) in 2026 to 4.7 g CO₂e/MJ of gasoline displaced (83.9% lower than that for CaRFG) in 2050 (**Figure 3-3**).

3.2.1.4 Hydrogen

The methodology used to derive the carbon intensity for the hydrogen fuel pathways modeled in this analysis are described in the following sub-sections.

CARB SRIA Hydrogen

Ramboll assumed that 40% of the hydrogen for the CARB SRIA H₂ fuel pathway would come from renewable feedstocks and the remaining 60% from fossil feedstocks based on the methodology used in the SRIA for the proposed ACC II³⁵ and discussions with CARB ACC II staff.³⁶ The fossil feedstock for hydrogen is assumed to be fossil natural gas which is processed via a steam methane reformation (SMR) process to produce Fossil Hydrogen per

³² CARB. 2019. CA-GREET3.0 Model - Current Version: Effective January 4, 2019 (released August 13, 2018). Available at: https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet30-corrected.xlsm?_ga=2.203396115.367263062.1651770761-1504446328.1547148412. Accessed: May 2022.

³³ Available at: <https://greet.es.anl.gov/publication-greet-model>. Accessed: January 2021.

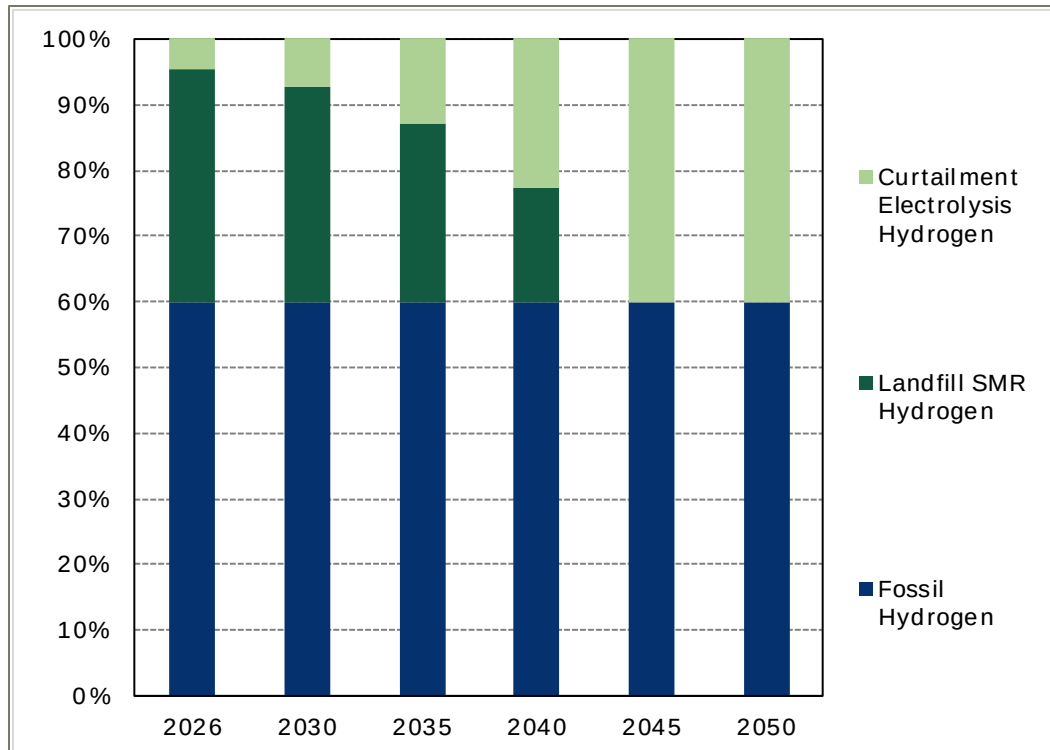
³⁴ CEC 2018. Deep Decarbonization in a High Renewables Future - Implications for Renewable Integration and Electric System Flexibility, Docket 18-IEPR-06 - 223869, Slide 10. Available at: <https://efiling.energy.ca.gov/GetDocument.aspx?tn=223869&DocumentContentId=54081>. Accessed: January 2021.

³⁵ CARB. 2022. Appendix C-1: Standardized Regulatory Impact Assessment (SRIA). April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appc1.pdf>. Accessed: May 2022.

³⁶ Based on e-mail communication between S. Moca, Ramboll US Consulting and CARB ACC II Staff on February 15, 2022. CARB staff indicated in their email that hydrogen fuel in the SRIA for the proposed ACC II consisted of 3 major blends of fuel types: fossil natural gas (NG) hydrogen, renewable hydrogen from renewable NG, renewable hydrogen from curtailments. CARB assumed that renewable hydrogen levels off at 40% of the total hydrogen used, and that renewable hydrogen gradually transitions from renewable NG hydrogen to renewable hydrogen from curtailments. CARB shared that this transition was modeled with a log function assuming a market share (%) of renewable hydrogen at specific time points which are 6% at 2020, 10% at 2025, and 100% at 2045. Additionally, they shared that the renewable natural gas feedstock was assumed to be 100% from landfill biogas. Lastly, for renewable hydrogen from curtailments, CARB staff assumed zero GHG emissions given transmission/distribution and refilling phases using renewable energy.

the 2020 Mobile Source Strategy³⁷ and as cited in the SRIA. The renewable feedstock is assumed to be Landfill Biogas with hydrogen production via SMR (Landfill SMR Hydrogen) and electrolysis using curtailment electricity (Curtailment Electrolysis Hydrogen).³⁸ Based on correspondence with CARB ACC II staff, the transition of hydrogen production from landfill biogas to curtailment electricity was modeled with a log function assuming specific feedstock shares at three points in time: 6% at 2020, 10% at 2025, and 100% at 2045.³⁹ The feedstock breakdown shown in **Figure 3-4** below illustrates this transition.

Figure 3-4: Feedstock Breakdown for CARB SRIA H₂⁴⁰



The upstream carbon intensity values for each feedstock were estimated as follows:

- **Fossil Hydrogen:** A CI of 117.67 g CO₂e/MJ for Fossil Hydrogen was obtained from the LCFS certified pathway for hydrogen production from SMR using fossil natural gas.⁴¹

³⁷ CARB. 2021. 2020 Mobile Source Strategy. October 28. Available here: https://ww2.arb.ca.gov/sites/default/files/2021-12/2020_Mobile_Source_Strategy.pdf. Accessed: May 2022.

³⁸ Curtailment is the reduction of output of a renewable resource below what it could have otherwise produced due to oversupply or other factors. Thus, the energy source for curtailment electrolysis hydrogen is envisioned to be electricity produced by an oversupply of a renewable resource. Reference: CAISO. 2017. Impacts of renewable energy on grid operations. Available here: <https://www.caiso.com/documents/curtailmentfastfacts.pdf>. Accessed: May 2022.

³⁹ Based on e-mail communications between S. Moca, Ramboll US Consulting and CARB ACC II Staff on February 15, 2022.

⁴⁰ Ibid.

⁴¹ CARB. 2018. CA-GREET3.0 Lookup Table Pathways Technical Support Documentation. August 13. Available at: <https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/lut-doc.pdf>. Accessed: May 2022.

Since the gaseous hydrogen compression and precooling processes in this pathway use California grid electricity, the CIs for Fossil Hydrogen SMR were adjusted over time to account for the increased renewables in the grid. Refer to **Table A-6** in **Appendix A** for further details.

- **Landfill SMR Hydrogen:** A CI of 99.48 g CO₂e/MJ for Landfill SMR Hydrogen was obtained from the LCFS certified pathway for hydrogen production from SMR using landfill biogas.⁴² Since the gaseous hydrogen compression and precooling processes in this pathway use California grid electricity, the CIs for Landfill SMR were adjusted over time to account for the increased renewables in the grid. Refer to **Table A-6** in **Appendix A** for further details.
- **Curtailment Electrolysis Hydrogen:** It was assumed that Curtailment Electrolysis Hydrogen would have a CI of zero, as the hydrogen is produced by electrolysis using curtailment electricity.⁴³

The resulting CIs for the CARB SRIA Hydrogen are estimated as a feedstock weighted average of the CIs for the individual feedstocks (Fossil Hydrogen, Landfill SMR, and Curtailment Electrolysis) based on the feedstock breakdown shown in **Figure 3-4** for each analysis year. As shown in **Figure 3-2**, these CIs reduce from 102.6 g CO₂e/MJ in 2026 to 64.8 g CO₂e/MJ in 2050. Once adjusted for the differences in the efficiency of electricity in FCEVs as compared to gasoline-fueled ICEVs, the CARB SRIA Hydrogen CI values range from 41.0 g CO₂e/MJ of gasoline displaced (41% greater than that for CaRFG) in 2026 to 25.9 g CO₂e/MJ of gasoline displaced (11% lower than that for CaRFG) in 2050 (**Figure 3-3**).

AB32 Hydrogen

The AB 32 Initial Modeling⁴⁴ for the draft 2022 Scoping Plan Update assumes that 100% of hydrogen production in the future would come from renewable sources, with the primary hydrogen production pathway being electrolysis using electricity generated by solar photovoltaic systems (Solar Electrolysis Hydrogen). To evaluate how hydrogen from a 100% renewable feedstock (AB32 Hydrogen) would impact the GHG inventory for the draft ACC II proposal, Ramboll modeled sensitivity scenario S1d-1 – ACC II (FCEV) + AB32 H₂ with this lower CI hydrogen. The following assumptions were used to develop the CI for AB32 Hydrogen:

- We assumed that AB32 Hydrogen would be a combination of hydrogen produced using the following pathways: Landfill SMR Hydrogen and Solar Electrolysis Hydrogen.
- The methodology used to estimate the CI for Landfill SMR Hydrogen is described in **Section 3.2.4.1**. As noted in that section, this CI reduces over time to account for the increased renewables in the California grid electricity that is used in the hydrogen compression and precooling processes. Refer to **Tables A-6** and **A-7** for further details.

⁴² Ibid.

⁴³ Based on e-mail communications between S. Moca, Ramboll US Consulting and CARB ACC II Staff on February 15, 2022

⁴⁴ E3. 2022. CARB Draft Scoping Plan: AB32 Source Emissions Initial Modeling Results. March 15. Available at: <https://ww2.arb.ca.gov/sites/default/files/2022-03/SP22-Model-Results-E3-ppt.pdf>. Accessed: May 2022.

- The upstream CI for Solar Electrolysis Hydrogen was assumed to be zero, as hydrogen is produced using electrolysis with zero CI electricity that is generated by solar photovoltaic systems.
- The volumes of Landfill SMR Hydrogen for the analysis years was assumed to not exceed the total renewable hydrogen volume (2,700,000 kg/year or 324,000,000 MJ/year) produced in 2021 per Annual Hydrogen Evaluation.⁴⁵ The remaining hydrogen demand in each analysis year was assumed to be met by Solar Electrolysis Hydrogen. Refer to **Table A-7** for further details.

The resulting CIs for the AB32 Hydrogen were estimated as a feedstock weighted average of the CIs for the individual feedstocks (Landfill SMR and Solar Electrolysis) are shown in **Figure 3-2** for each analysis year. These CIs reduce from 7.45 g CO₂e/MJ in 2026 to less than 1 g CO₂e/MJ in 2030 and beyond. Once adjusted for the differences in the efficiency of electricity in FCEVs as compared to gasoline-fueled ICEVs, the AB32 Hydrogen CIs values are even lower, ranging from 2.98 g CO₂e/MJ of gasoline displaced in 2026 to less than 0.5 g CO₂e/MJ of gasoline displaced in 2030 and beyond (**Figure 3-3**).

3.2.2 Tailpipe (Tank-to-Wheel) Emissions

Tailpipe emissions (tank-to-wheel) are generated from fuel consumption during vehicle operation.⁴⁶ **Table 3-2** summarizes the assumptions used to estimate the tailpipe GHG emissions from various vehicle/fuel technologies that are included in this analysis.

Table 3-2. Tailpipe Emission Assumptions	
Vehicle / Fuel Technology	Tailpipe GHG
ICEVs fueled by CaRFG	Default EMFAC emission factors adjusted for the ethanol content of CaRFG
ICEVs fueled by Low-CI Gasoline	Zero tailpipe CO ₂ emissions, default EMFAC emission factors for CH ₄ and N ₂ O emissions
PHEVs fueled by CaRFG and Electricity	cVMT: Default EMFAC emission factors adjusted for the ethanol content of CaRFG eVMT: Zero GHG tailpipe emissions
PHEVs fueled by Low-CI Gasoline and Electricity	cVMT: Zero tailpipe CO ₂ emissions, default EMFAC emission factors for CH ₄ and N ₂ O emissions eVMT: Zero GHG tailpipe emissions
HEVs fueled by CaRFG	Default EMFAC emission factors for ICEVs adjusted for the fuel economy of HEVs and the ethanol content of CaRFG
HEVs fueled by Low-CI Gasoline	Zero tailpipe CO ₂ emissions, default EMFAC emission factors for CH ₄ and N ₂ O emissions

⁴⁵ CARB. 2021 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development. September. Available at: https://ww2.arb.ca.gov/sites/default/files/2021-09/2021_AB-8_FINAL.pdf. Accessed: May 2022.

⁴⁶ Brinkman, Norman, Michael Wang, Trudy Weber, and Thomas Darlington. 2005. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. May. Available at: <https://greet.es.anl.gov/files/4mz3q5dw>. Accessed: May 2022.

Table 3-2. Tailpipe Emission Assumptions	
Vehicle /Fuel Technology	Tailpipe GHG
BEVs fueled by Electricity	Zero GHG tailpipe emissions
FCEVs fueled by Hydrogen	Zero GHG tailpipe emissions

Combustion of gasoline (CaRFG and Low-CI gasoline) in ICEs in ICEVs, PHEVs, and HEVs generate the following greenhouse gas emissions: carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Ramboll estimated tailpipe GHG emissions from gasoline fueled vehicle operation for each Scenario using data from EMFAC2021, as follows:

- EMFAC2021^{47,48} was queried at the statewide level for analysis years 2026, 2030, 2035, 2040, 2045 and 2050 to obtain daily total GHG exhaust emissions and gasoline fuel consumption data for ICEV and PHEV LDAs by model year.
- Tailpipe emission factors for CO₂, CH₄, and N₂O in mass of emissions per unit of gasoline fuel consumed (e.g., tons/gal and tons/MJ) were calculated for ICEVs and PHEVs as a ratio of the total exhaust emissions to gasoline fuel consumption obtained from EMFAC2021⁴⁹ for each model year vehicle in each analysis year. Refer to **Tables A-10, A-13, A-16, A-19, A-22, and A-25** in **Appendix A** for further details.
- Tailpipe GHG emission factors in mass of emissions per unit of gasoline fuel consumed (e.g., tons/gal and tons/MJ) for HEVs are assumed to be the same as ICEVs because of their operating characteristics, as described in **Section 3.1.4**.
- Tailpipe GHG emissions for ICEVs, PHEVs, and HEVs were then estimated using tailpipe GHG emission factors and the cVMT and gasoline fuel economies for these vehicle technologies in each Scenario (determined as described in **Section 3.1**). Specifically, gasoline fuel economies were used to calculate the average daily gasoline consumption for each vehicle type based on daily cVMT, and then the tailpipe emission factors for each vehicle type, were applied to the gasoline fuel consumption to estimate average daily tailpipe emissions of CO₂, CH₄, and N₂O for ICEVs, PHEVs, and HEVs.
- Total average daily tailpipe GHG emissions reported in units of carbon dioxide equivalent (CO₂e) were calculated by applying the global warming potentials (GWPs) from the International Panel on Climate Change (IPCC) Fourth Assessment Report⁵⁰ to the average daily emissions of CO₂, CH₄, and N₂O.

⁴⁷ CARB. 2021. EMFAC2021 Database v1.0.1. Available at: <https://arb.ca.gov/emfac/emissions-inventory>. Accessed: January 2022.

⁴⁸ This analysis uses EMFAC2021 v1.0.1. A newer version of EMFAC2021 v1.0.2 was released on May 2, 2022 (after completion of this analysis) that reflects the revocation of the Safe Affordable Fuel-Efficient or SAFE vehicles rule. While this update increases the fuel economy, methane (CH₄), and nitrous oxide (N₂O) tailpipe emission factors by <5% and <0.5% for 2025+ model year ICEVs and PHEVs, respectively, it does not change the overall conclusions of the analysis.

⁴⁹ Note, tailpipe emission factors for PHEVs are based only on *fuel* consumption, as *energy* consumption associated with pure electric trips has zero tailpipe emissions.

⁵⁰ Greenhouse Gas Protocol. Available at: https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf. Accessed January 2021.

- These average daily GHG emissions are scaled up to annual GHG emissions based on 347 days of operation per year for LDAs reported in EMFAC technical documentation.⁵¹
- Finally, since the CO₂ emissions generated by the combustion of the renewable ethanol content in CaRFG and Low-CI gasoline are considered biogenic, they are excluded from this analysis,⁵² using the following adjustments.
 - Adjustments for Tailpipe GHG Emissions Associated with CaRFG: EMFAC2021 calculates tailpipe emissions assuming gasoline vehicles are fueled by CaRFG. However, while tailpipe CO₂ emissions in EMFAC2021 account for the reduction in carbon content of CaRFG relative to CARBOB due to the 9.5 percent blend of ethanol by volume, CO₂ emissions from the renewable ethanol fraction in CaRFG are still included in EMFAC2021 default outputs. Thus, in order to account for the elimination of CO₂ emissions from the renewable ethanol content of CaRFG, Ramboll applied an emission reduction factor of 6.3 percent to all tailpipe CO₂ emissions resulting from the use of CaRFG. The emission reduction factor was derived based the 9.5 percent volume fraction of ethanol in CaRFG and the carbon content of ethanol, CARBOB, and CaRFG, assuming renewable ethanol has zero CO₂ tailpipe emissions. No adjustments were made to the tailpipe CH₄ and N₂O.
 - Adjustments for Tailpipe GHG Emissions Associated with Low-CI Gasoline: The low-CI gasoline included in this analysis is produced from renewable feedstocks (See **Section 3.2.1.2**) and tailpipe CO₂ emissions associated with the combustion of this fuel are biogenic and set to zero. No adjustments were made to tailpipe CH₄ and N₂O emissions for Low-CI Gasoline use.

Electricity consumption from batteries in PHEVs and BEVs does not produce tailpipe emissions. Hence, tailpipe GHG emissions for eVMT associated with PHEVs and BEVs was assumed to be zero. Similarly, hydrogen consumption in FCEVs does not generate GHG emissions, so tailpipe GHG emissions for FCEVs are assumed to be zero. Further details regarding tailpipe emission estimation methodology, including EMFAC2021 inputs and outputs, can be found in **Appendix A**.

3.3 Vehicle Cycle Emissions

Ramboll estimated vehicle cycle emissions using the Argonne National Laboratory (ANL) 2021 Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model.⁵³ GREET is a life cycle model developed by Argonne National Laboratory that evaluates the energy and environmental impacts of a range of vehicle technologies and transportation fuels, allowing users to model the effects of various vehicle-fuel type

⁵¹ CARB. 2018. EMFAC 2017 Volume III – Technical Documentation. July 20. Available at: <https://ww3.arb.ca.gov/msei/downloads/emfac2017-volume-iii-technical-documentation.pdf>. Accessed: May 2022.

⁵² This aligns CARB's methodology for estimating the statewide GHG emission inventory, as noted in the 2021 CARB Report on the *California Greenhouse Gas Emissions for 2000 to 2019*, which states that “carbon dioxide (CO₂) emissions from biofuels (the biofuel components of fuel blends) are classified as “biogenic CO₂”. They are tracked separately from the rest of the emissions in the inventory and are not included in the total emissions when comparing to California’s 2020 and 2030 GHG Limits.” Available at: https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2019/ghg_inventory_trends_00-19.pdf?msckid=9f56cab9d01611ec878dcdb49cca2c91. Accessed: May 2022.

⁵³ ANL. 2021. Greenhouse gases, Regulated Emissions, and Energy use in Technologies model. Available at: <https://greet.es.anl.gov/>. Accessed: May 2022.

combinations. GREET 1 focuses on fuel life cycle impacts and estimates the energy consumption and emissions associated with fuel production (“well-to-tank”) and vehicle operation (“tank-to-wheel”). GREET 2 is the vehicle life cycle model and evaluates the energy and emission impacts associated with vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling.⁵⁴

3.3.1 Vehicle Cycle Emission Factors

For this analysis, Ramboll used GREET 2 (and GREET 1 inputs as needed) to estimate vehicle life cycle emission factors for ICEV, HEV, BEV, and PHEV technologies. FCEVs were not included in the scope of Ramboll’s vehicle cycle emissions analysis.⁵⁵ The vehicles are evaluated as model year 2026 passenger vehicles; while vehicle cycle emissions may decrease over time with the increase in the renewable content of the electricity used for vehicle production, we do not expect the reduction to significantly alter the results or conclusions of the study.

Battery recycling for BEVs and PHEVs is not included in this assessment. This assumption is informed by current end-of-life recycling rate of <1% globally for lithium and rare earth minerals noted in the 2021 International Energy Association (IEA) Study on the *Role of Critical Minerals in Clean Energy Transition*.⁵⁶ Furthermore, it is likely that the vast majority of batteries produced in the future would require virgin material given the significant increase in demand under a mass vehicle electrification scenario.

The vehicle emission and electric grid mix data input to the model is based on the most current information available at the time of this study as the scope of this analysis does not include forecasting or projecting future energy demands from vehicle and battery manufacturing.

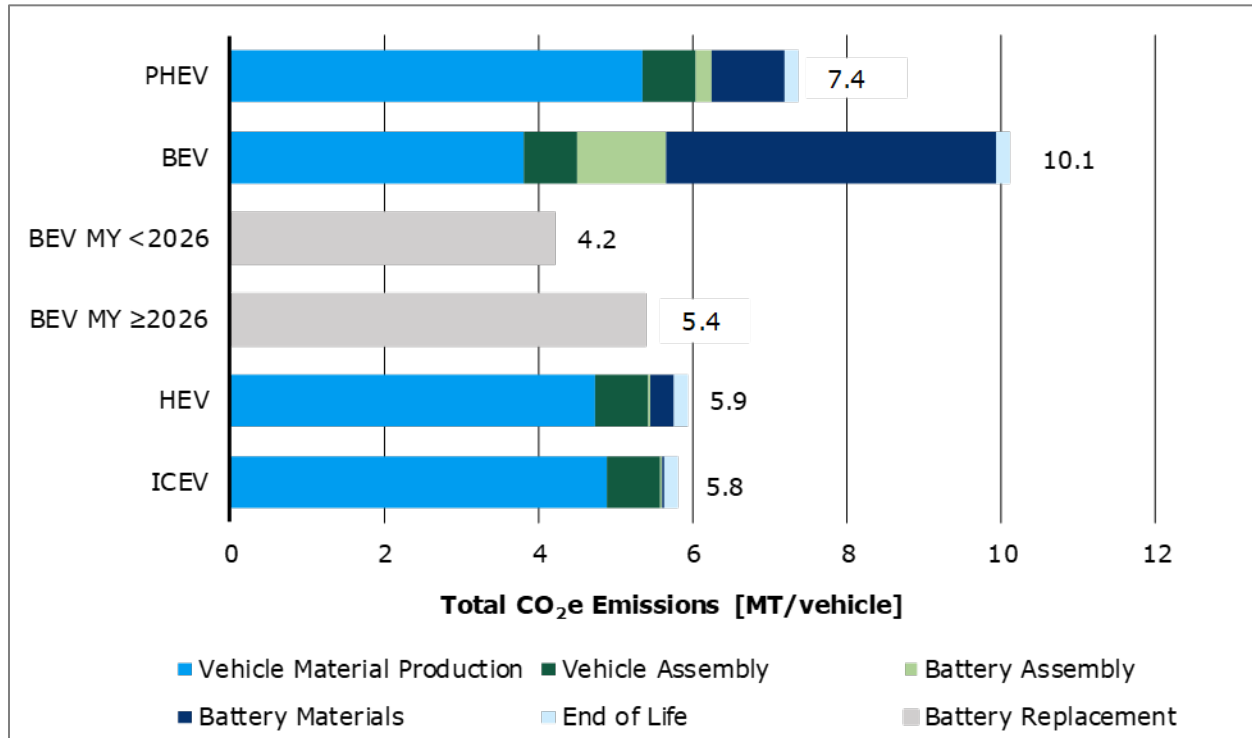
The resulting vehicle cycle emission factors in metric tons of CO_{2e} per vehicle for PHEVs, BEVs, HEVs, and ICEVs are shown in **Figure 3-5**. Additional details on the GREET model inputs used to estimate these emissions are described in the following sub-sections.

⁵⁴ ANL. 2021. GREET Model Platforms. Available at: <https://greet.es.anl.gov/greet.models>. Accessed: May 2022.

⁵⁵ FCEVs represented only a small fraction (<0.8%) of total 2020 ZEV sales and an even smaller fraction (<0.06%) of the total 2020 LDV sales in California. The vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling processes are still in the developmental stage, and it would be too speculative to estimate vehicle cycle emissions until the market for these vehicles mature. Sales data obtained from CEC data dashboard ‘New ZEV Sales in California’. Available here: <https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/new-zev-sales>. Accessed: May 2022.

⁵⁶ International Energy Agency (IEA). 2021. The Role of Critical Minerals in Clean Energy Transitions. May. Available at: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions?msclkid=fa519918d01f11ecbcf188dc9fbbf9f2>. Accessed: May 2022.

Figure 3-5: Vehicle Cycle and Battery Replacement GHG Emission Factors



3.3.1.1 GREET Inputs for ICEVs and HEVs

To model ICEVs and HEVs, Ramboll used default values in the GREET model for all vehicle production and assembly parameters except for the electricity mix used for material and fuel production. The US electric mix for stationary use in GREET 1 was updated with the 2020 national electricity mix published by the EPA's Emissions & Generation Resource Integrated Database (eGRID).⁵⁷ Ramboll also updated the GREET 1 electric grid mixes for fuel production for non-US countries where vehicle and battery components are produced or assembled. These grid mixes were updated using most recent available data from the IEA.⁵⁸ A full matrix of all non-default GREET inputs can be found in **Appendix A**.

3.3.1.2 GREET Inputs for BEVs and PHEVs

For BEVs, Ramboll modeled a lithium-ion (Li-ion) battery with a nickel manganese cobalt (NMC 622) cathode material, which per a 2021 study from the International Council on Clean Transportation (ICCT) is the most common cathode material used in BEVs globally.⁵⁹ The Li-ion peak battery energy for BEVs is modeled as 81 kWh. This value was calculated as a product of BEV fuel economy, range, and charge utilization. The fuel economy is 2.59-mi/kWh based on EMFAC2021 data (described in **Section 3.1.2**), the range is

⁵⁷ EPA. 2022. eGRID Summary Tables 2020. January 27. Available here: <https://www.epa.gov/egrid/summary-data>. Accessed: May 2022.

⁵⁸ IEA. 2022. Countries and regions. Available at: <https://www.iea.org/countries>. Accessed: May 2022.

⁵⁹ ICCT. 2021. A Global Comparison of The Life-Cycle Greenhouse Gas Emissions Of Combustion Engine And Electric Passenger Cars. Available here: <https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/>. Accessed: May 2022.

200 miles based on the minimum certified all-electric range in the draft ACC II regulation,⁶⁰ and the state of charge (SOC) utilization is 95% based on CARB's ZEV cost modeling worksheets.^{61,62} Battery production and assembly share by country is derived from the number of battery cells supplied to the US BEV market by production location, reported in an Argonne National Laboratory publication on the 2010-2020 Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States.⁶³ Production shares for 2020 were used in order to reflect the most current information available.

To model PHEVs, Ramboll assumed the NMC 111 cathode material (which is the GREET default) since NMC 622 is not an option provided in GREET 2 for PHEVs. The Li-ion peak battery energy for PHEVs is modeled as 14 kWh. This value was calculated as a product of PHEV fuel economy, range, and charge utilization. The fuel economy is 3.31 mi/kWh based on EMFAC2021 data (described in **Section 3.1.3**), the range is 40 miles based on the US-06 minimum certified all-electric range in the draft ACC II regulation,⁶⁴ and the SOC utilization is 85% based on CARB's ZEV cost modeling worksheets.^{65,66} Battery production and assembly shares by country are assumed to be equivalent to those used in the BEV model.

All other vehicle and battery parameters for BEVs and PHEVs were left unchanged from GREET default values, and a full matrix of all non-default inputs for these vehicles can be found in **Appendix A**.

3.3.2 Vehicle Cycle GHG Emissions in Scenario Analysis

Ramboll incorporated vehicle cycle GHG emissions for all ICEVs, PHEVs, BEVs, and HEVs in the scenario analysis by calculating GHG emissions for all vehicles of a given model year, and attributing those emissions to the corresponding calendar year (assumed to be the same as the model year) in which they were produced. The following steps were used to develop the vehicle cycle emissions and incorporate it into the scenario analysis:

⁶⁰ CARB. 2022. Appendix A-5: Proposed Regulation Order for Section 1962.4 Zero-Emission Vehicle Standards for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appa5.pdf>. Accessed: May 2022.

⁶¹ CARB. 2021. ZEV Cost Modeling Workbook October 2021. Available at: https://ww2.arb.ca.gov/sites/default/files/2021-11/ZEV_Cost_Modeling_Workbook_Update_October2021.xlsx. Accessed: January 2022.

⁶² The October 2021 version of CARB's ZEV Cost Modeling Workbook was referenced for this analysis. A newer version of this workbook was released in late April 2022 (after completion of this analysis), which assumed a lower SOC utilization for BEV batteries of 92.5%. However, this does not change the overall conclusions of the analysis.

⁶³ ANL. 2021. Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States: 2010-2020. March. Available at: <https://publications.anl.gov/anlpubs/2021/04/167369.pdf>. Accessed: May 2022.

⁶⁴ CARB. 2022. Appendix A-5: Proposed Regulation Order for Section 1962.4 Zero-Emission Vehicle Standards for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/appa5.pdf>. Accessed: May 2022.

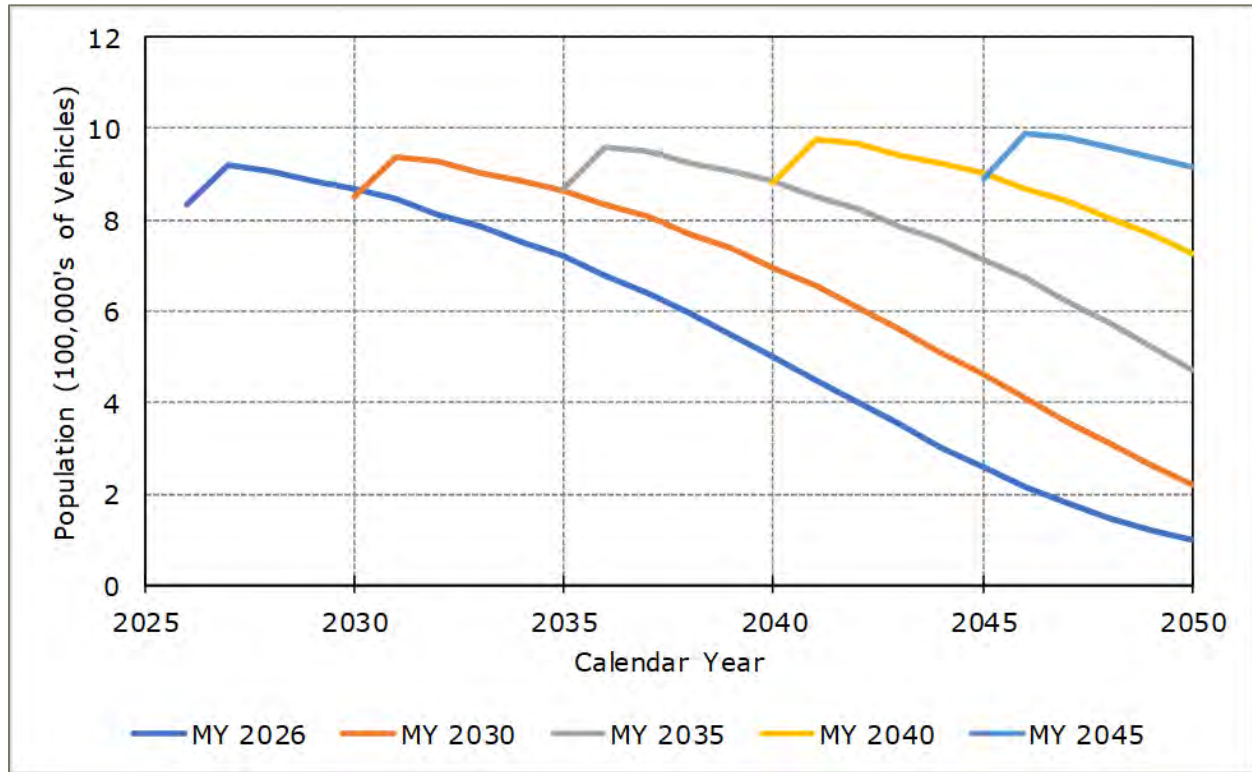
⁶⁵ CARB. 2021. ZEV Cost Modeling Workbook October 2021. Available at: https://ww2.arb.ca.gov/sites/default/files/2021-11/ZEV_Cost_Modeling_Workbook_Update_October2021.xlsx. Accessed: January 2022.

⁶⁶ The October 2021 version of CARB's ZEV Cost Modeling Workbook was referenced for this analysis. A newer version of this workbook was released in late April 2022 (after completion of this analysis), which assumed a lower SOC utilization for PHEV batteries of 80%. However, this does not change the overall conclusions of the analysis.

- Ramboll assumed that the total number of vehicles produced for a given model year is equal to the peak population of that model year in EMFAC2021. **Figure 3-6** shows that the peak vehicle population for any given model year in EMFAC2021 occurs one year after the corresponding calendar year (CY) in which they were first introduced to the fleet.⁶⁷
- GHG emissions from production of vehicles of a certain MY are assumed to occur in the calendar year the vehicles are produced (for example, MY 2026 vehicle population peaks in CY 2027, but vehicle cycle emission from vehicle production occur in CY 2026).
- Since EMFAC2021 does not output fleet data for CY 2051, Ramboll estimated the peak population of MY 2050 vehicles (which would occur in CY 2051) by applying the percentage increase in MY 2049 vehicles from CY 2049 to CY 2050 to the MY 2050 vehicle population in CY 2050.
- It is assumed that production patterns for different vehicle technologies would be similar to the pattern modeled in EMFAC2021. Therefore, the total number of vehicles produced for each vehicle technology in each model year is calculated based on the fleet mix percentage for that vehicle technology and the total peak population in the following calendar year. Fleet mixes for each scenario are shown in **Figure 2-3** and **Figure 2-4** and detailed tables showing fleet mix percentages and population data for each vehicle technology by model year in each calendar year are included in **Appendix A**.
- Finally, the total annual life cycle GHG emissions for each modeled scenario in the analysis years (2026, 2030, 2035, 2045, and 2050) were estimated as follows: The total number of vehicles produced for each vehicle technology in an analysis year was multiplied by the corresponding GREET vehicle life cycle emission factor (on a per-vehicle basis, see **Figure 3-5** for vehicle cycle emission factors) in order to generate vehicle life cycle GHG emissions. These emissions were then added to the upstream and tailpipe emissions for each analysis year in order to estimate total annual life cycle GHG emissions.

⁶⁷ Total LDA vehicle population reported in **Figure 3-6** is based on the EMFAC2021 queries performed for this analysis, as described in detail in Appendix A. Diesel vehicles are not included.

Figure 3-6: LDA Vehicle Population in EMFAC2021



3.3.3 GHG Emissions from Lithium Battery Replacement

In addition to GHG emissions from vehicle and battery production, Ramboll analyzed the GHG emissions associated with battery replacement for BEVs. Battery replacement for BEVs lithium-ion batteries is assumed to occur in the ninth year of use based on the 8-year warranty requirement proposed in the CARB ACC II Initial Statement of Reasons (ISOR) Staff Report.⁶⁸ Ramboll's scenario analysis assumes that one battery replacement occurs over the vehicle lifetime for all BEVs remaining in the vehicle fleet in the ninth year of operation (e.g., battery replacement emissions in CY 2026 are calculated based on the population of MY 2017 BEVs in CY 2026). This methodology accounts for the default retirement rate of vehicles in EMFAC2021, as illustrated in **Figure 3-6** above.

The emissions per vehicle associated with this battery replacement were estimated from the results of the GREET modelling described in **Section 3.4.1**. In particular, the emissions for battery production and assembly were combined to estimate battery replacement emissions on a per vehicle basis. For MY 2026-2050 BEVs, BEV battery replacement is assumed to occur for an 81-kWh battery as described in **Section 3.4.1**. However, for pre-2026 BEVs, a peak battery energy of 62.5 kWh was assumed a weighted average of the battery sizes and cumulative sales of various BEV models from 2010-2020 in the United States.⁶⁹ Thus,

⁶⁸ CARB. 2022. Staff Report: Initial Statement of Reasons. April 12. Available at: <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf>. Accessed: May 2021.

⁶⁹ Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States: 2010-2020. March. Available at: <https://publications.anl.gov/anlpubs/2021/04/167369.pdf>. Accessed: May 2022.

battery replacement emission factors for BEVs MY <2026 and BEVs MY $\geq$ 2026 were estimated separately, as represented by the gray bars in **Figure 3-5**.

Battery replacement emissions were calculated by multiplying the remaining population of BEVs in the vehicle fleet in the ninth year of operation by the emission factors per vehicle shown in **Figure 3-5**. The resulting emissions associated with BEV mid-life battery replacements were incorporated into the multi-technology scenario analysis by adding battery replacement emissions to life cycle emissions.

While batteries in PHEVs and HEVs deteriorate over time, for purposes of this analysis Ramboll has assumed that vehicle owners/operators would not replace the battery in these vehicle technologies. Instead, they would continue to operate these vehicles using the ICE and the underperforming battery till the end of the vehicle lifetime.

4. SCENARIO ANALYSIS EMISSIONS RESULTS

4.1 Fuel Cycle (Well-to-Wheel) Emissions

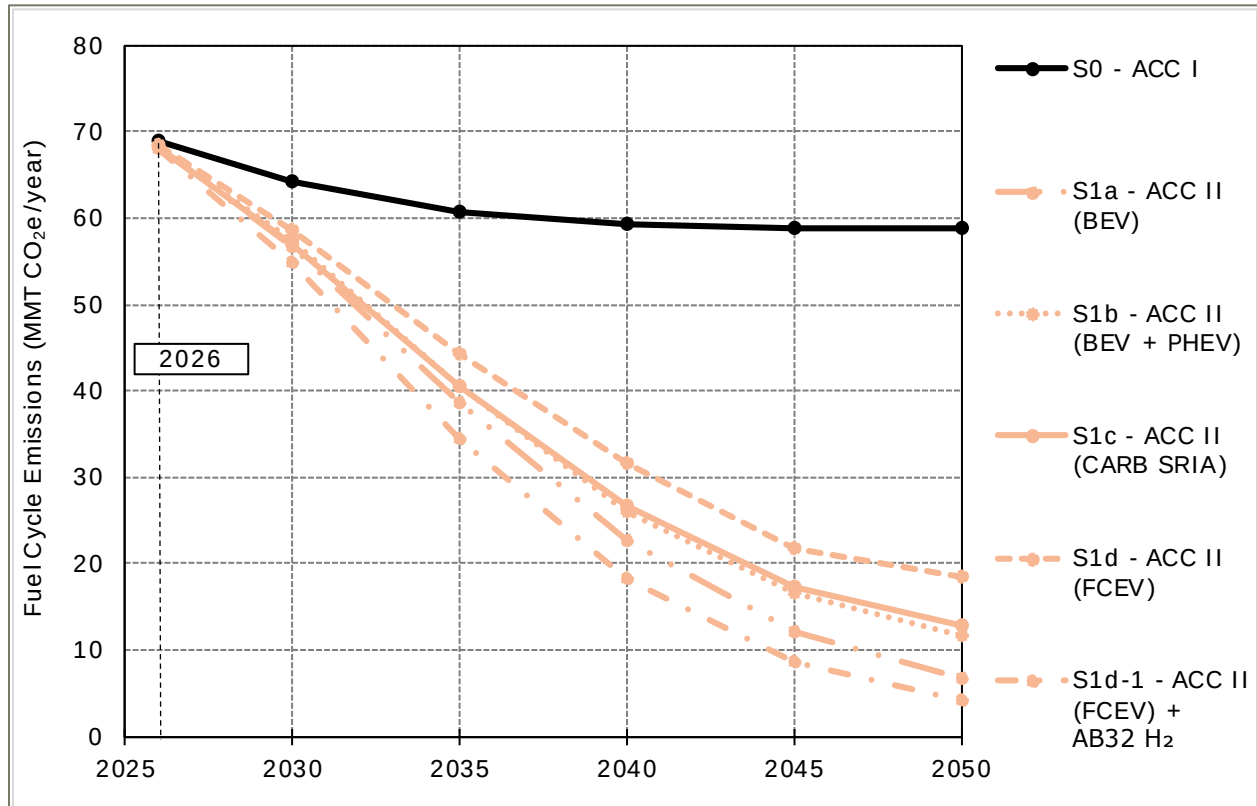
Fuel cycle emissions, also known as “well-to-wheel” emissions, include both upstream (well-to-tank) emissions and tailpipe (tank-to-wheel) emissions and represent overall emissions impacts of the fuel, including extraction of the raw materials for the fuel, fuel production and distribution, and use of the finished fuel during operation of the vehicle.⁷⁰

Figure 4-1 through **Figure 4-4** below present the estimated total GHG fuel cycle emissions for calendar years 2026 to 2050 for each modeled scenario: S0 – ACC I (represented by black line), S1 – Baseline ACC II Scenarios (represented by the pink lines and shaded pink region), S2 – Alternative Scenarios Part 1 (represented by blue lines), S3 – Alternative Scenarios Part 2 (represented by purple lines), S4 – Alternative Scenarios Part 3 (represented by green lines).

The results presented in **Figure 4-1** show that scenario S1d – ACC II (FCEV) achieves the fewest GHG emissions reductions of the S1 - Baseline ACC II Scenarios as compared to the S0 – ACC I Scenario. This result is driven by the relatively high CI of the CARB SRIA Hydrogen as compared to electricity and the AB32 Hydrogen that displace CaRFG used in scenario S0 – ACC I. On the other hand, scenario S1d-1 – ACC II (FCEV) + AB32 H₂ provides the greatest potential GHG emission reductions of the S1 - Baseline ACC II Scenarios, due to the significant reduction in upstream emissions for AB32 Hydrogen as compared to CaRFG.

⁷⁰ <https://www.epa.gov/renewable-fuel-standard-program/lifecycle-analysis-greenhouse-gas-emissions-under-renewable-fuel>

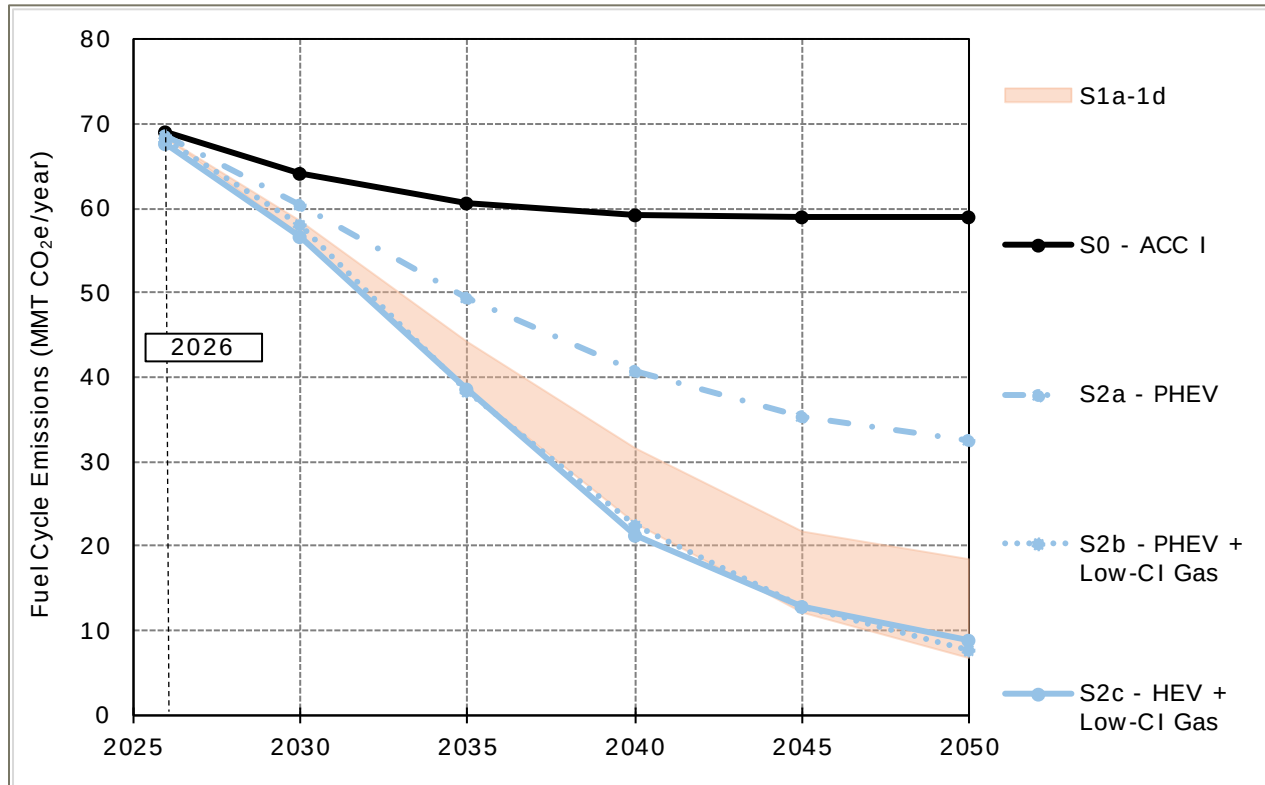
Figure 4-1: Fuel Cycle Emissions for Baseline Scenarios



As shown in **Figure 3-3**, AB32 Hydrogen pathway provides the lowest CI of all fuels considered, resulting in nearly carbon-free hydrogen with an upstream EER-adjusted CI less than 0.5 g CO₂e/MJ of gasoline displaced from 2030-2050. Aside from sensitivity scenario S1d-1 – ACC II (FCEV) + AB32 H₂, scenario S1a – ACC II (BEV), which assumes any additional ZEVs sales beyond those in the S0 – ACC I Scenario that are needed to meet the proposed ACC II ZEV sales requirements are met with BEVs, represents the lower bound of achievable GHG emissions under the draft ACC II proposal. Assuming the proposed ACC II sales requirements are met with the maximum allowable fraction of PHEVs in scenario S-1b – ACC II (BEV + PHEV) provides fewer fuel cycle GHG emission reductions than scenario S-1a – ACC II (BEV) in comparison to scenario S0 – ACC I. Results for S1c – ACC II (CARB SRIA) are similar to scenario S1b – ACC II (BEV + PHEV), although scenario S1c – ACC II (CARB SRIA) provides slightly lower fuel cycle GHG emission reductions in comparison to scenario S0 – ACC I in CY 2040-2050 due to the inclusion of FCEVs fueled by the CARB SRIA Hydrogen.

Figure 4-2 shows results for S2 - Alternative Scenarios Part 1, which estimate GHG emission reductions achievable from increased penetration of PHEVs or HEVs. Some of these scenarios include a phase-in of low-CI gasoline as a replacement for CaRFG that is used for ICEs in ICEVs, PHEVs, and HEVs.

Figure 4-2: Fuel Cycle Emissions for Alternative Scenarios Part 1



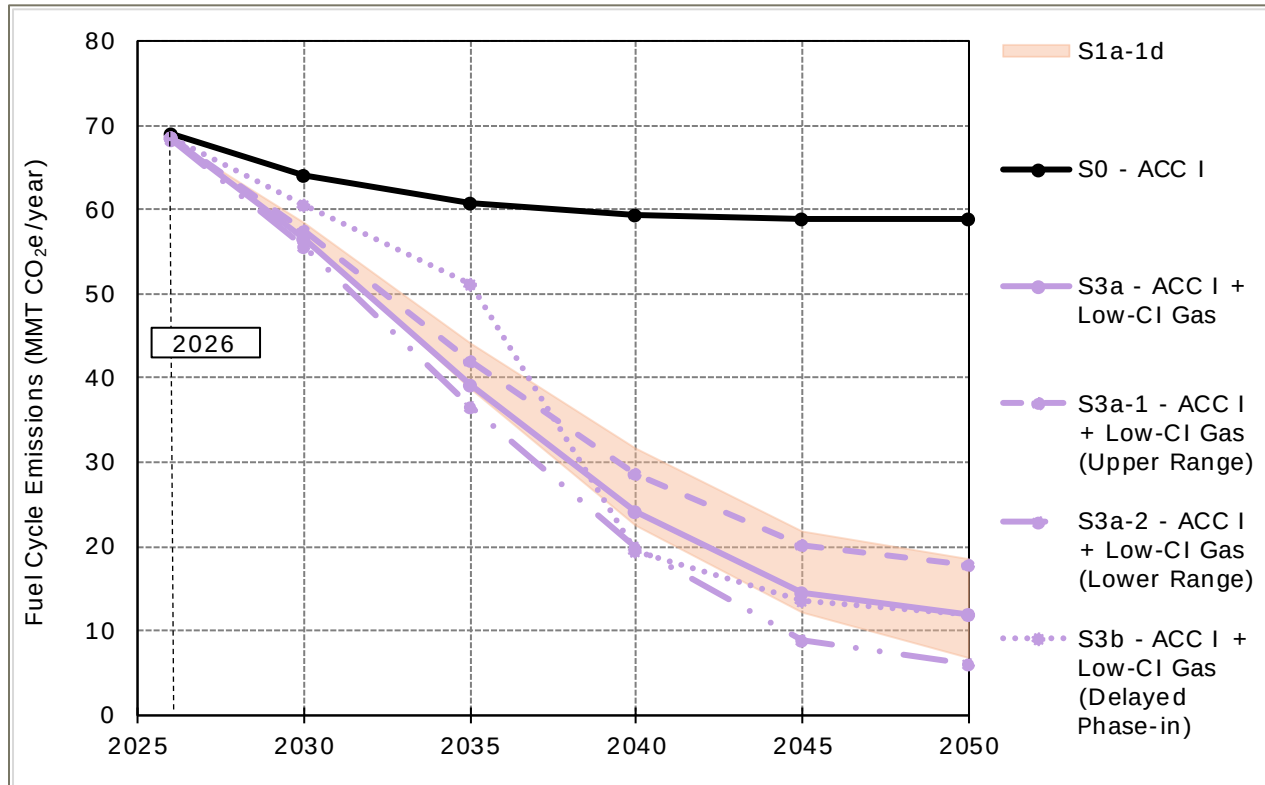
These results (**Figure 4-2**) show that we can achieve >50% of the estimated GHG reductions from the draft ACC-II proposal (scenarios S1a-1d, represented by the shaded pink region) as compared to S0 – ACC I (represented by the black solid line), by using PHEVs sales⁷¹ to meet the ACC II ZEV sales requirements (S2a – PHEV, represented by the blue dash-dot-dash line). Phasing in Low-CI gasoline (S2b – PHEV + Low-CI Gas, represented by the blue dotted line) with these PHEVs sales could increase the GHG reductions so they are comparable to the reductions achieved with draft ACC-II proposal (scenarios S1a through S1d, represented by the shaded pink region). Similarly, a combination of HEVs sales⁷² to meet the ACC II ZEV sales requirement and a phase-in of Low-CI gasoline to fuel ICEs in ICEVs, HEVs, and PHEVs (S2c – PHEV + Low-CI Gas, represented by the solid blue line) can also achieve GHG reductions that are comparable to the those from the draft ACC II proposal (scenarios S1a through S1d, represented by the shaded pink region) relative to Scenario S0 – ACC I.

Results for S3 - Alternative Scenarios Part 2, which explore the use of low-CI gasoline to generate GHG emission reductions needed to meet the State's long-term climate goals with no change in fleet mix, are shown in **Figure 4-3**.

⁷¹ Any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0 - ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with PHEVs.

⁷² Any additional ZEVs sales beyond those (BEVs and PHEVs) in the S0 - ACC I Scenario that are needed to meet the ZEV sales requirements in the draft ACC II proposal are met with HEVs.

Figure 4-3: Fuel Cycle Emissions for Alternative Scenarios Part 2



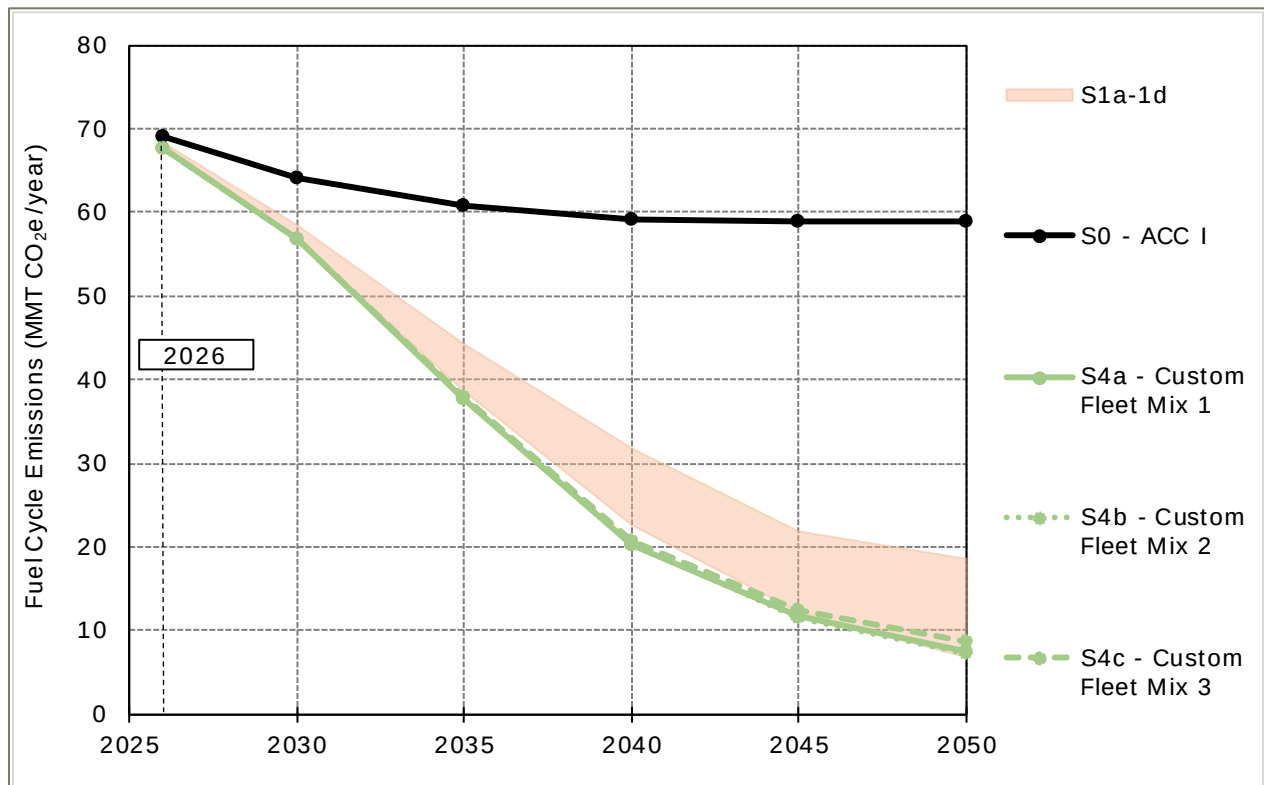
These results (**Figure 4-3**) show that a phase in of low-CI gasoline alone (represented by the purple lines) with no additional ZEV sales beyond those included in scenario S0 – ACC I (represented by the solid black line) can achieve fuel cycle GHG reductions similar to those achieved in the baseline ACC II scenarios (S1a through S1d, represented by the pink area) as compared to scenario S0 - ACC I. Results for scenario S3a-1 – Low-CI Gas indicate that phase in of low-CI gasoline (with a carbon intensity of 19 g CO₂e/MJ) could achieve similar or greater emission reductions than the lowest emission baseline ACC II scenario S1a - ACC II (BEV) through 2035, although emission reductions fall short of those estimated for Scenario S1a in 2040-2050. Reducing the carbon intensity of low-CI gasoline (S3a-2 – Low-CI Gas (Lower Range)) to 9 g CO₂e/MJ could generate further GHG emission reductions that exceed those estimated for the baseline ACC II scenarios relative to scenario S0 - ACC I. Even if the carbon intensity of low-CI gasoline was increased to 29 g CO₂e/MJ (S3a-1 – Low-CI Gas (Upper Range)), we can achieve GHG emission reductions (relative to S0 – ACC I) that are similar to the draft ACC II proposal (scenarios S1a through S1d).

The delayed phase in of low-CI gasoline considered in scenario S3b – Low-CI Gas (Delayed) decreases the emissions reductions (relative to S0 – ACC I) achieved through 2035 but achieves greater emission reductions from 2040-2050. Results for Alternative Scenarios Part 2 and Alternative Scenarios Part 3 show that low-CI gasoline could potentially achieve the State's long-term climate goals and decarbonize the transportation sector at a rate comparable to a ZEV-only regulation like the draft ACC II proposal.

Figure 4-4 shows results for Alternative Scenarios Part 3, which explore the potential emission reductions achievable from a diverse deployment of vehicle technologies. These

scenarios (S-4a through S-4c, represented by the green lines) all provide fuel cycle GHG emission reductions (relative to S0 – ACC I) that exceed those achieved in the baseline ACC II scenarios (S1a through S1d, represented by the pink area) for all calendar years except 2050. These results show that increased ZEV sales mandates are not the only way to achieve the State's climate goals and a combination of different vehicle technologies and fuel pathways could be utilized to meet California's GHG emission reduction targets.

Figure 4-4: Fuel Cycle Emissions for Alternative Scenarios Part 3



4.2 Life Cycle Emissions

Life cycle emissions include fuel cycle emissions and vehicle cycle emissions and provide a comprehensive life cycle-based assessment of the potential GHG emissions from all vehicle technologies. **Figure 4-5** through **Figure 4-8** below present the estimated total GHG life cycle emissions for calendar years 2026 to 2050 for each modeled scenario that does not include FCEVs,⁷³ using the same color scheme for each scenario described previously in **Section 4.1**.

The addition of vehicle cycle emissions to fuel cycle emissions increases the total GHG emissions in all calendar years in all scenarios relative to those shown in **Figure 4-1** through **Figure 4-4**. Additionally, because BEVs have the highest vehicle cycle GHG emissions (see **Figure 3-5** for vehicle cycle emissions for each vehicle type), scenarios with significant BEV penetration show the largest increase in life cycle GHG emissions relative to fuel cycle emissions. As a result, scenarios that focus on implementation of low-CI gasoline rather than

⁷³ As described in **Section 3.4**, life cycle emission results are not available for scenarios with FCEVs, so scenarios that include FCEVs are not shown in **Figure 4-5** through **Figure 4-8**.

increased penetration of BEVs generally achieve greater life cycle GHG emission reductions relative to scenario S0 – ACC I.

The results presented in **Figure 4-5** show that scenario S1a – ACC II (BEV) continues to provide greater GHG emission reductions (relative to S0 – ACC I) than scenario S1b – ACC II (BEV + PHEV), despite greater vehicle cycle emissions from more BEVs in scenario S1a – ACC II (BEV) than scenario S1b – ACC II (BEV + PHEV). Note that in **Figure 4-5** through **Figure 4-8**, life cycle emissions for Baseline ACC II Scenarios (pink shaded region) are bounded by scenarios S1a and S1b because scenarios with FCEVs (S1c, S1d, and S1d-1) are not included in the life cycle analysis.

Results for S3 - Alternative Scenarios Part 1 in **Figure 4-6** show that increased penetration of only PHEVs or HEVs combined with phase in of low-CI gasoline can provide greater life cycle GHG emission reductions than the draft ACC II proposal (scenarios S1a and S1b, represented by the shaded pink region). Similarly, GHG emission reductions from the phase in of low-CI gasoline (Alternative Scenarios Part 2, represented by purple lines in **Figure 4-7**) without any fleet mix changes from S0 – ACC I could exceed life cycle GHG emission reductions in the draft ACC II proposal (scenarios S1a and S1b, represented by the shaded pink region) in all years except 2050. Finally, **Figure 4-8** shows that a diverse mix of fuel and vehicle technologies (Alternative Scenarios Part 3, represented by green lines) can achieve greater life cycle GHG emission reductions relative to S0 – ACC I in all calendar years than the ZEV-centric approach in the draft ACC II proposal (scenarios S1a and S1b, represented by the shaded pink region).

Figure 4-5: Life Cycle Emissions for Baseline Scenarios

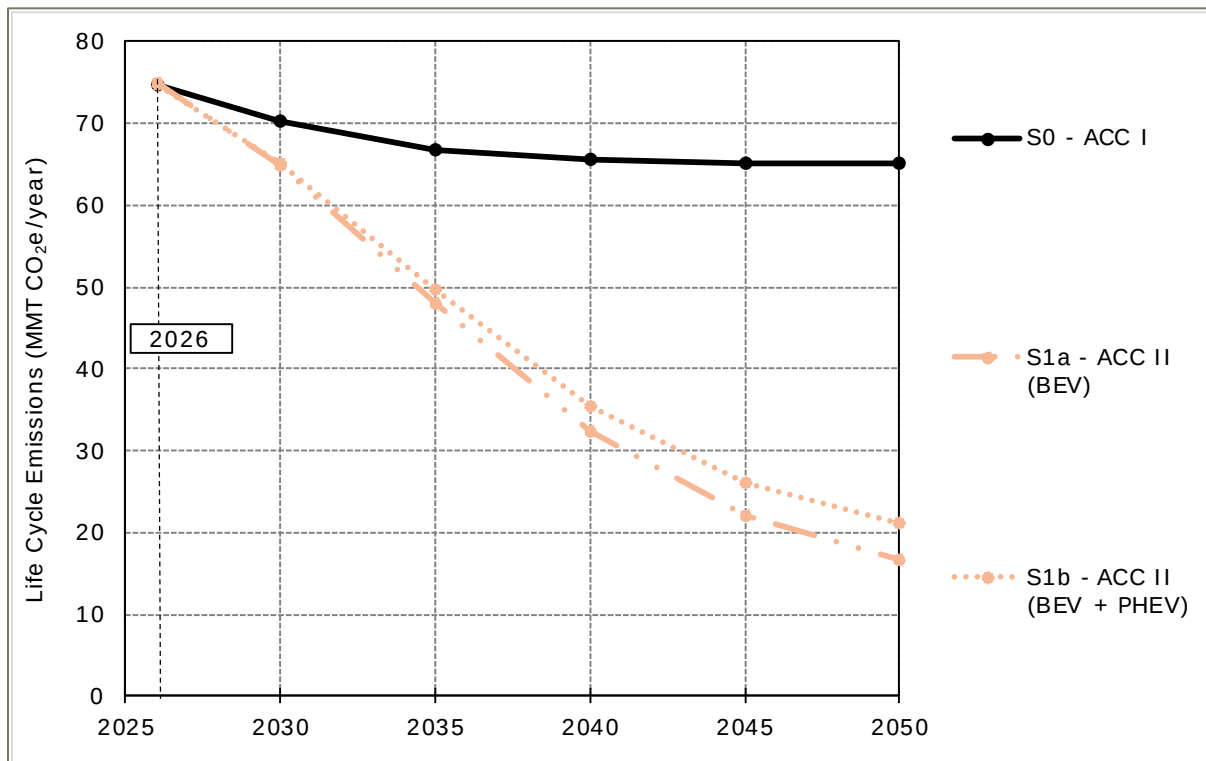


Figure 4-6: Life Cycle Emissions for Alternative Scenarios Part 1

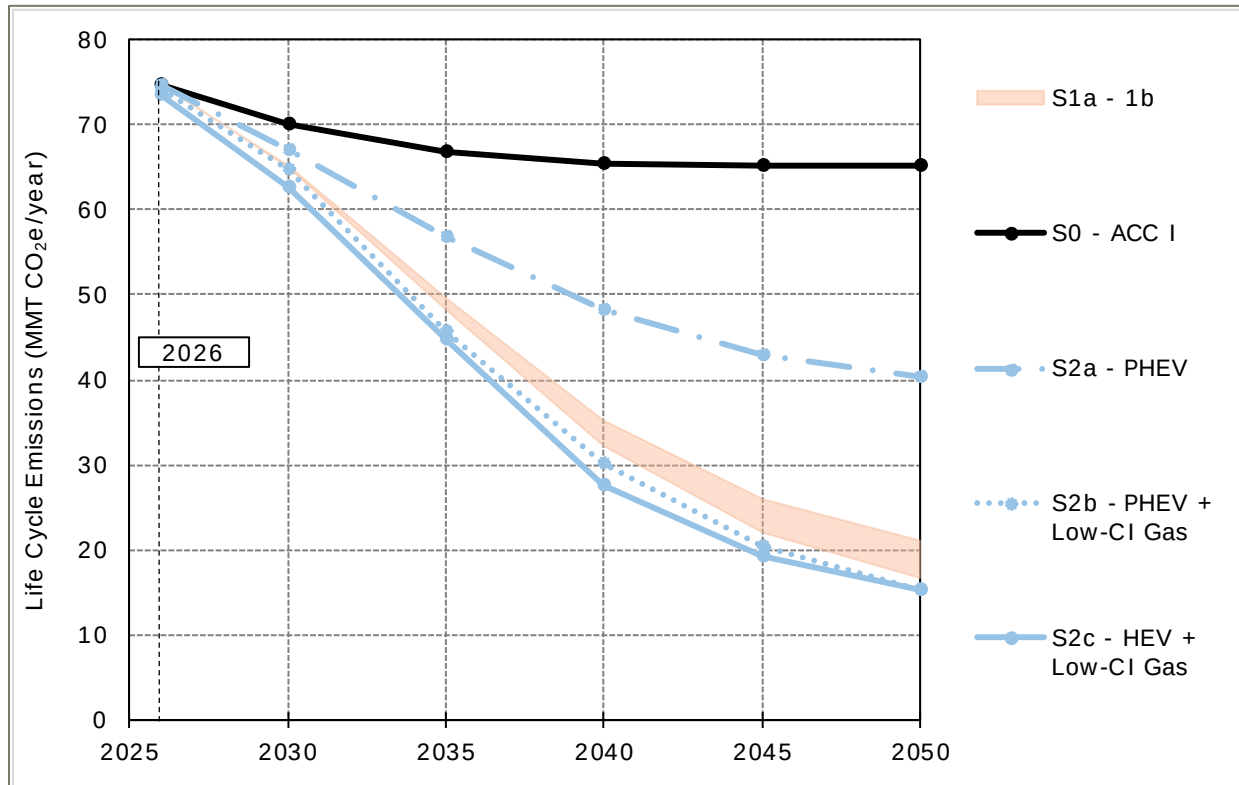


Figure 4-7: Life Cycle Emissions for Alternative Scenarios Part 2

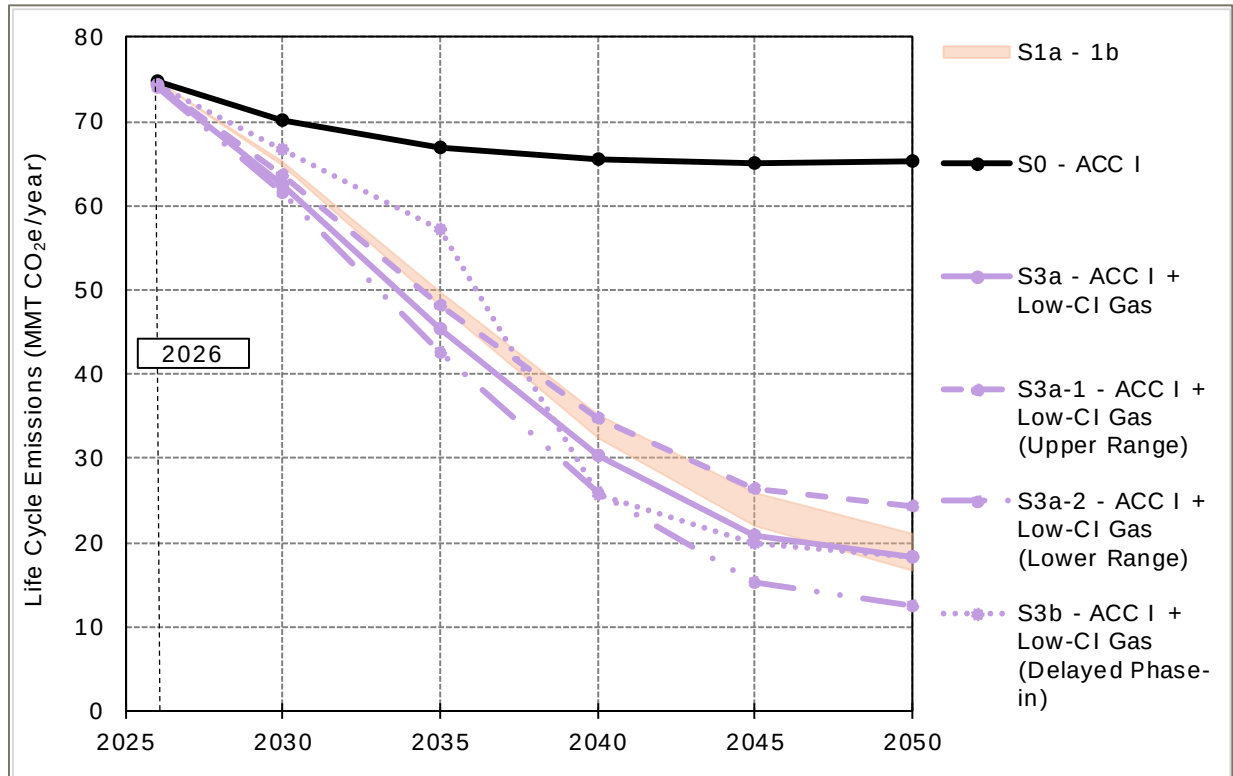
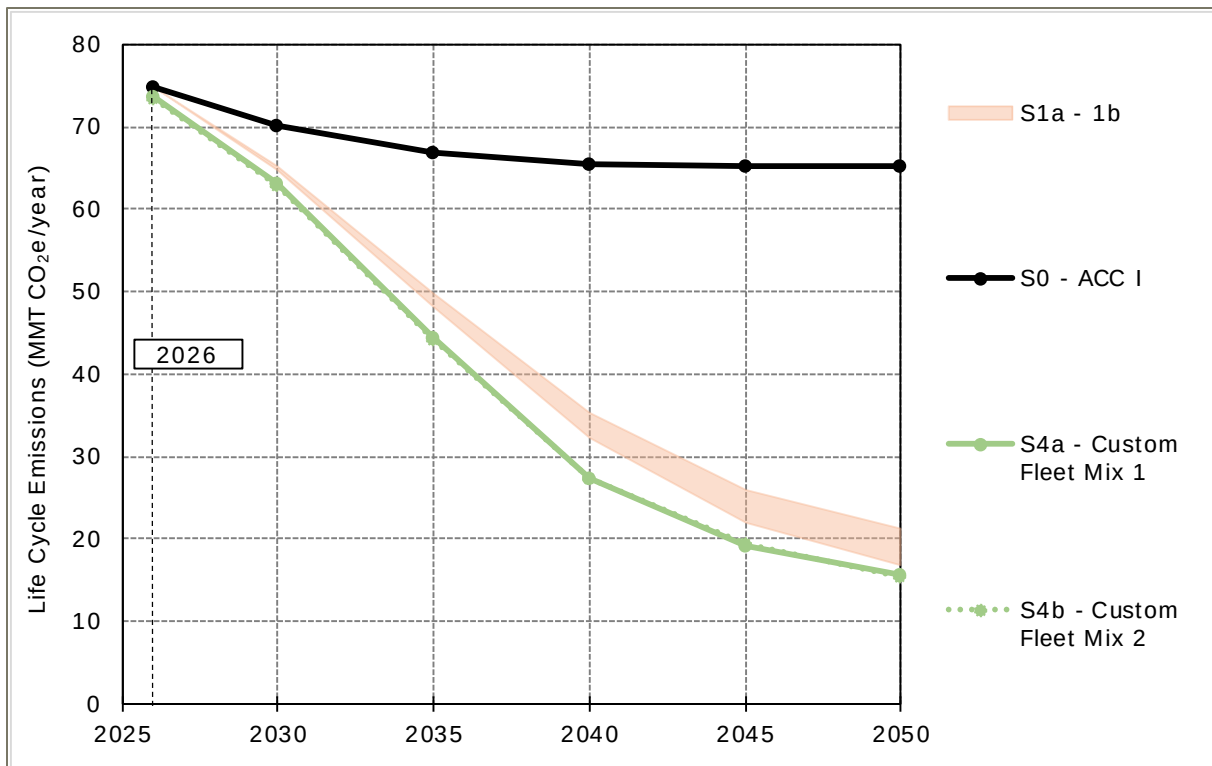


Figure 4-8: Life Cycle Emissions for Alternative Scenarios Part 3



4.3 Life Cycle Emissions with BEV Battery Replacement

Figure 4-9 through **Figure 4-12** show life cycle GHG emissions, including life cycle emissions associated with BEV battery replacement, for all scenarios without FCEVs⁷⁴ using the same color scheme for each scenario described previously. The inclusion of GHG emissions from BEV battery replacement increases the total GHG emissions in all calendar years for all scenarios with BEVs relative to the life cycle emission totals discussed in **Section 4.2**. As a result, scenarios that focus on implementation of low-CI gasoline rather than increased penetration of BEVs generally achieve greater GHG emission reductions relative to scenario S0 – ACC I.

Figure 4-9 shows that scenario S1a – ACC II (BEV) continues to provide greater GHG emission reductions (relative to S0 – ACC I) than scenario S1b – ACC II (BEV + PHEV), despite greater life cycle emissions from more BEV battery replacements in scenario S1a – ACC II (BEV) than scenario S1b – ACC II (BEV + PHEV). In **Figures 4-10** through **4-12**, the pink shaded region represents the range of life cycle emissions with BEV replacement for Baseline ACC II Scenarios S1a and S1b only, as other ACC II scenarios with FCEVs S1c, S1d, and S1d-a are not included in the life cycle analysis.

Results for S3 - Alternative Scenarios Part 1 in **Figure 4-10** show that increased penetration of only PHEVs or HEVs combined with phase in of low-CI gasoline provide even greater life cycle GHG emission reductions than the draft ACC II proposal (scenarios S1a and S1b, represented by the shaded pink region), when BEV replacement is included (compare with **Figure 4-6**, which does not include life cycle emissions for battery replacement). Similarly, phase in of low-CI gasoline alone (Alternative Scenarios Part 2, represented by purple lines in **Figure 4-11**), becomes a more attractive option to achieve similar to or greater GHG emission reductions (relative to S0 – ACC I) than those achieved by the draft ACC II proposal (S1a and S1b), when BEV battery replacement emissions are included. Finally, the mix of fuel and vehicle technologies in Alternative Scenarios Part 3 (represented by the green lines in **Figure 4-12**) provides even greater life cycle GHG emission reductions than the baseline ACC II scenarios when BEV battery replacement emissions are included (compare with **Figure 4-8**). Overall, inclusion of GHG emissions associated with the entire life cycle of the fuel and vehicle technologies including BEV battery replacement illustrates the importance of considering multiple vehicle technology and fuel pathways to achieve GHG emissions reductions rather than focusing on ZEV sales mandates as required in the draft ACC II proposal.

⁷⁴ As described in **Section 3.4**, life cycle emission results are not available for scenarios with FCEVs, so scenarios that include FCEVs are not shown in **Figure 4-9** through **Figure 4-12**.

Figure 4-9: Life Cycle Emissions with BEV Battery Replacement for Baseline Scenarios

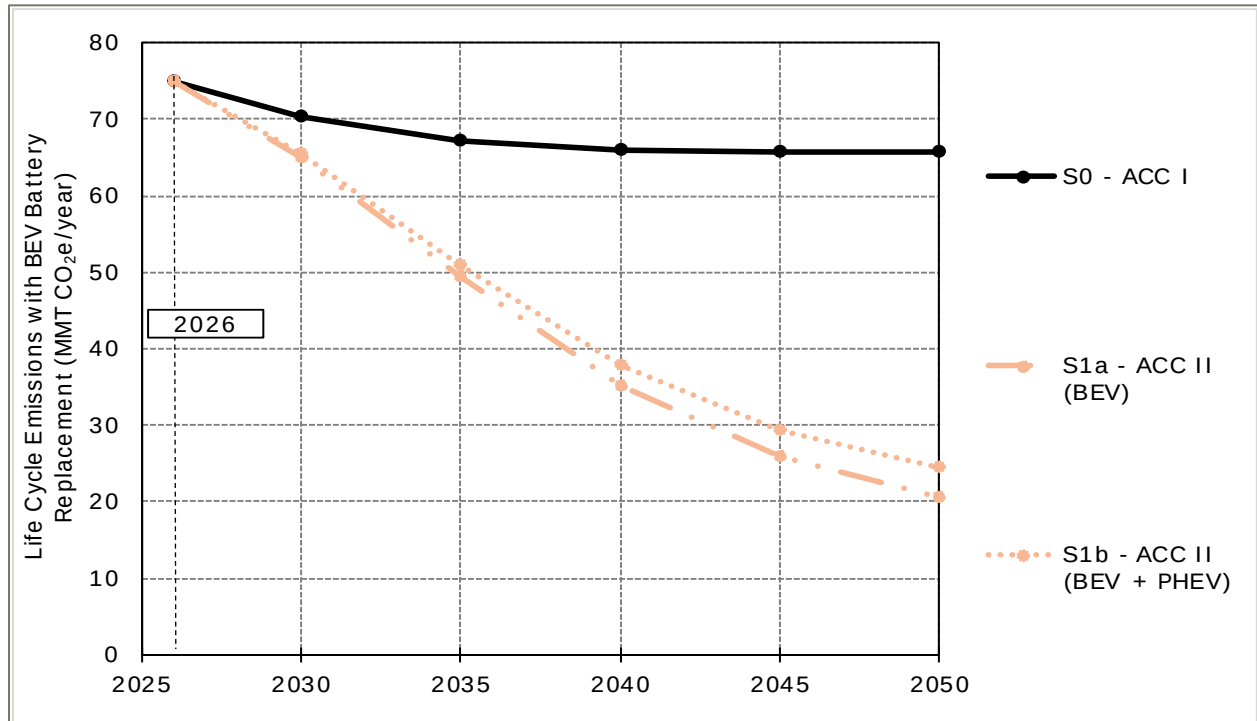


Figure 4-10: Life Cycle Emissions with BEV Battery Replacement for Alternative Scenarios Part 1

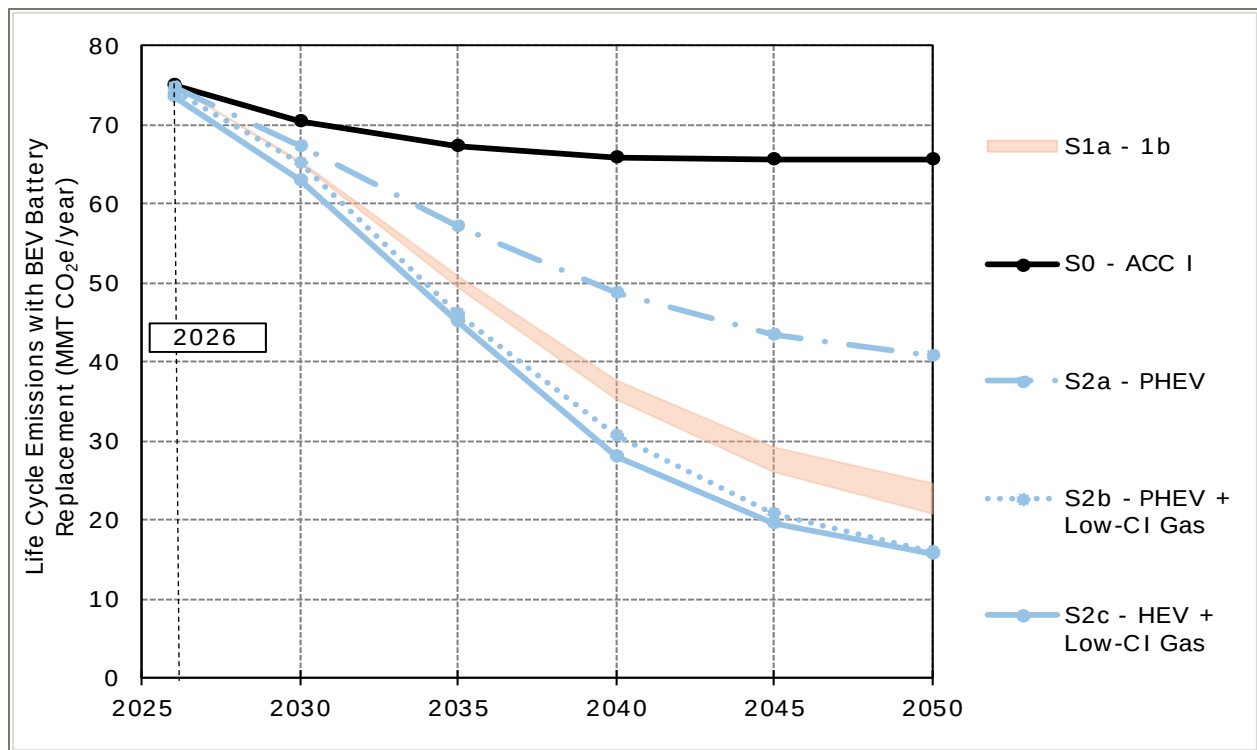


Figure 4-11: Life Cycle Emissions with BEV Battery Replacement for Alternative Scenarios Part 2

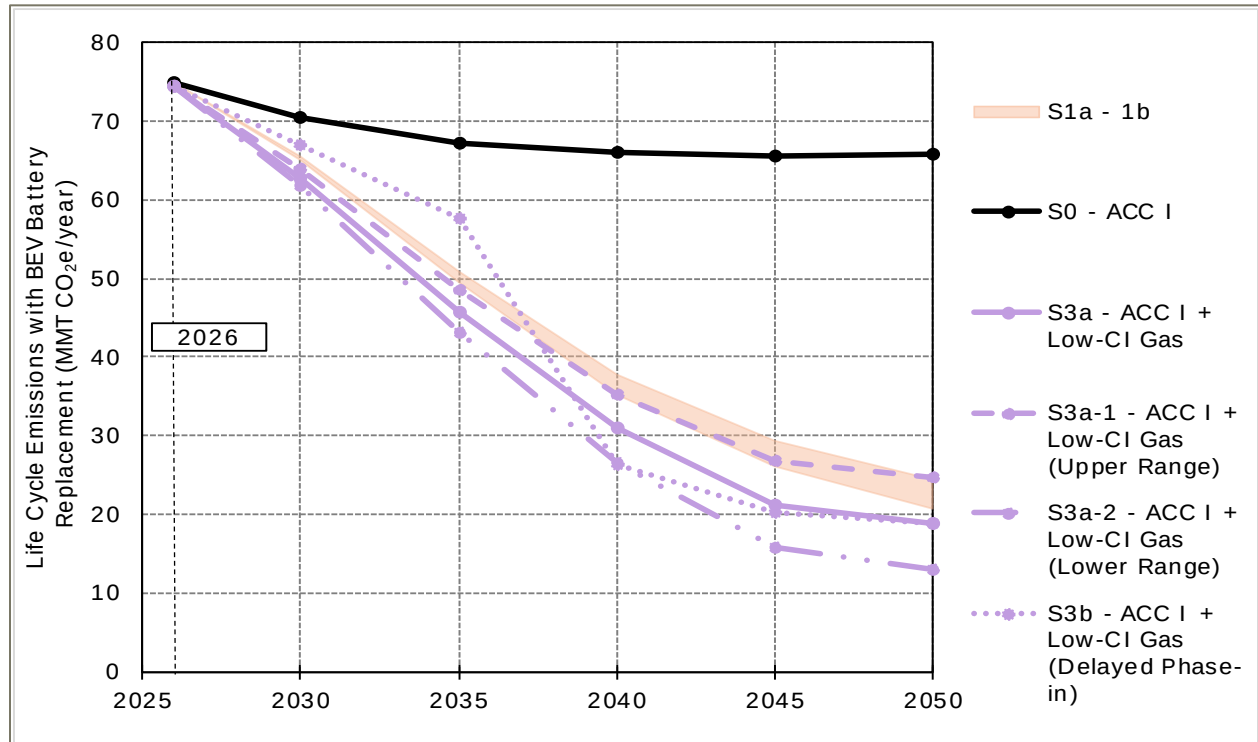
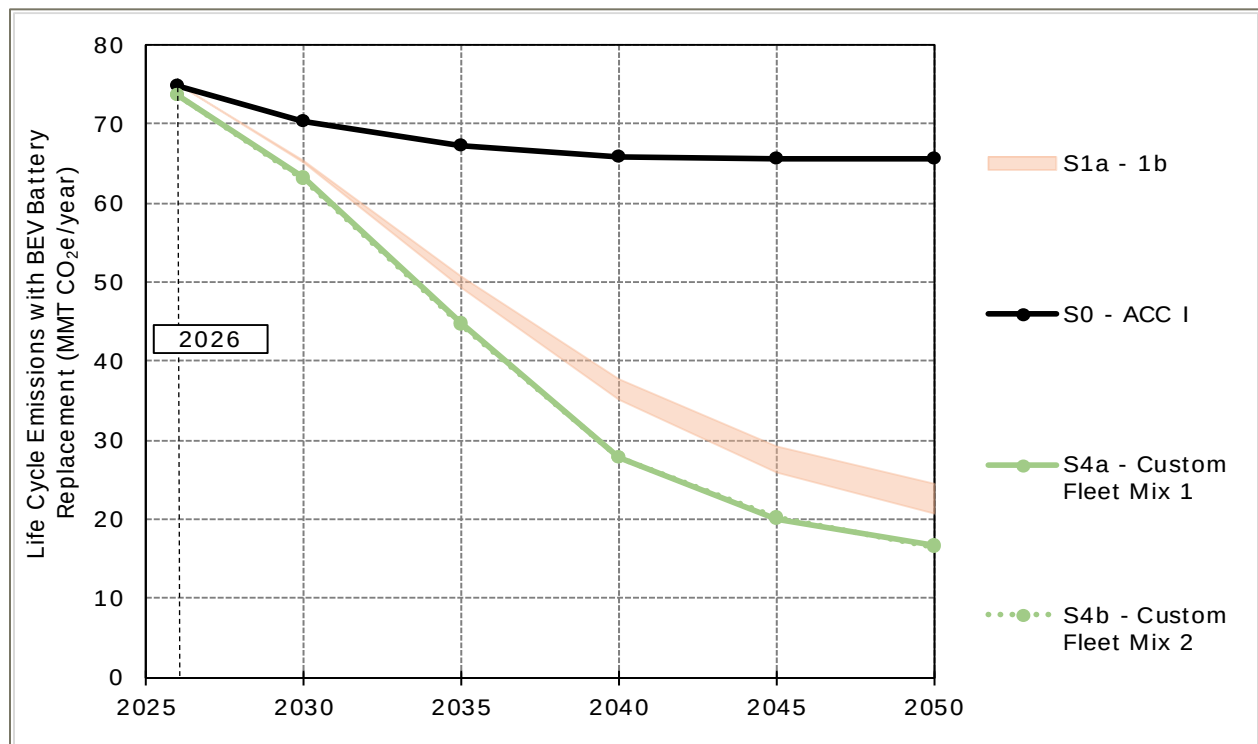


Figure 4-12: Life Cycle Emissions with BEV Battery Replacement for Alternative Scenarios Part 3



5. CONCLUSIONS

5.1 Summary of Analysis Conclusions

Ramboll's analysis demonstrates that there are a number of vehicle technology and fuel pathways that could achieve equal or greater GHG reductions as the proposed ACC II rulemaking. These alternative pathways would not require transformation of energy production and distribution infrastructure on an unprecedented short time scale, but they would allow battery, hydrogen, and low-CI gaseous and liquid fueled vehicles to compete to achieve the State's GHG targets in the quickest and most cost-effective manner. For example, a scenario that phases in low-CI gasoline as a drop-in fuel for ICEVs over a two-decade period could reduce GHG emission the same or more than the proposed ZEV-only mandate, when viewed on a life cycle basis. Other scenarios involving HEVs and PHEVs could be equally effective in providing GHG reductions when coupled with a phase in of low-CI gasoline. CARB could craft a regulation based on a GHG-reducing performance standard instead of instituting zero emission technology mandates, which is more consistent with traditional technology-forcing regulations that rely upon innovation within existing marketplaces. This study shows that such an approach could dramatically reduce GHG emissions without the systemic cost and delay risks associated with the current ZEV-centric strategy that include, but are not limited to, electric generation/infrastructure development, zero emission technology readiness, and cost.

The main conclusions of our analysis:

- Zero emission vehicle technology is only one of many different technology/fuel scenarios that could be utilized to meet California's GHG emission reduction targets;
- A full life cycle emission assessment is necessary if GHG reductions are a goal of the regulation, in order to understand the cradle-to-grave effects of a given vehicle/fuel technology pathway;
- BEV technology of the scope and schedule in ACC II would require technology and electrical generation/infrastructure developments that CARB has not analyzed and cannot mandate, control, or incentivize;
- There is a growing potential for renewable and low carbon fuels, including some with negative carbon intensity, to meet long-term GHG reductions;
- Low-CI gasoline could decarbonize the transportation sector at a rate comparable to a ZEV-only regulation; and
- Allowing the market flexibility to meet emission reduction targets could lead to a more diverse deployment of fuel and vehicle technologies to meet State targets.

These conclusions emphasize the need for CARB to conduct a similar analysis for the light and medium duty vehicle sector targeted in the draft ACC II proposal, to identify vehicle/fuel technology pathways that meet the emission reduction goals earlier and more cost effectively than the proposed ZEV-centric approach.

5.2 Next Steps – Technical

By focusing on a strategy that relies on ZEV sales mandates and not assessing the full life cycle GHG impacts of that strategy, CARB has overstated the potential emission benefits from PHEVs and BEVs while ignoring different vehicle/fuel pathways that could meet

California's GHG emission reduction targets. Finally, CARB has not demonstrated they have minimized leakage as required under AB32.

CARB should conduct a full life cycle GHG emission assessment to quantify the cradle-to-grave effects of the draft ACC II proposal and consider alternative GHG-reducing vehicle/fuel technologies in a technology-forcing (not technology mandating) rulemaking for California's LDV fleet that meets the State's emission goals. Such an analysis should build out and evaluate multiple scenarios beyond the singular ZEV-centric pathway proposed in the current ACC II regulation. These scenarios should be evaluated in the ACC II alternatives analyses presented in the SRIA and EA for technical feasibility, environmental impacts, and cost-effectiveness. These broader alternative analyses should include an assessment of the future availability of fueling (electric, hydrogen, and renewable and low carbon fuels) and related infrastructure to support this transition and help inform the final ACC II regulation.

The Role of Critical Minerals in Clean Energy Transitions

World Energy Outlook Special Report



INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

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Foreword

Ever since the International Energy Agency (IEA) was founded in 1974 in the wake of severe disruptions to global oil markets that shook the world economy, its core mission has been to foster secure and affordable energy supplies.

Today, the global energy system is in the midst of a major transition to clean energy. The efforts of an ever-expanding number of countries and companies to reduce their greenhouse gas emissions to net zero call for the massive deployment of a wide range of clean energy technologies, many of which in turn rely on critical minerals such as copper, lithium, nickel, cobalt and rare earth elements.

An evolving energy system calls for an evolving approach to energy security. As clean energy transitions accelerate globally and solar panels, wind turbines and electric cars are deployed on a growing scale, these rapidly growing markets for key minerals could be subject to price volatility, geopolitical influence and even disruptions to supply.

This *World Energy Outlook* special report on *The Role of Critical Minerals in Clean Energy Transitions* identifies risks to key minerals and metals that – left unaddressed – could make global progress towards a clean energy future slower or more costly, and therefore hamper international efforts to tackle climate change. The IEA is determined to play a leading role in enabling governments around the

world to anticipate and navigate possible disruptions and avoid damaging outcomes for our economies and our planet.

This special report is the most comprehensive global study of this subject to date, underscoring the IEA's commitment to ensuring energy systems remain as resilient, secure and sustainable as possible. Building on the IEA's detailed, technology-rich energy modelling tools, we have established a unique and extensive database that underpins our projections of the world's future mineral requirements under different climate and technology scenarios.

This is what energy security looks like in the 21st century. We must pay close attention to all potential vulnerabilities, as the IEA did in our recent series on electricity security for power systems, which covered challenges such as growing shares of variable renewables, climate resilience and cyber security.

Today's supply and investment plans for many critical minerals fall well short of what is needed to support an accelerated deployment of solar panels, wind turbines and electric vehicles. Many minerals come from a small number of producers. For example, in the cases of lithium, cobalt and rare earth elements, the world's top three producers control well over three-quarters of global output. This high geographical concentration, the long lead times to bring new mineral production on stream, the declining resource quality in some areas,

and various environmental and social impacts all raise concerns around reliable and sustainable supplies of minerals to support the energy transition.

These hazards are real, but they are surmountable. The response from policy makers and companies will determine whether critical minerals remain a vital enabler for clean energy transitions or become a bottleneck in the process.

Based on this special report, we identify the IEA's six key recommendations to ensure mineral security. An essential step is for policy makers to provide clear signals about their climate ambitions and how their targets will be turned into action. Long-term visibility is essential to provide the confidence investors need to commit to new projects. Efforts to scale up investment should go hand-in-hand with a broad strategy that encompasses technology innovation, recycling, supply chain resilience and sustainability standards.

There is no shortage of resources worldwide, and there are sizeable opportunities for those who can produce minerals in a sustainable and responsible manner. Because no single country will be able to solve these issues alone, strengthened international cooperation is essential. Leveraging the IEA's long-standing leadership in safeguarding energy security, we remain committed to helping governments, producers and consumers tackle these critical challenges.

Finally, I would like to thank the excellent team behind this ground-breaking report, led by Tae-Yoon Kim under the direction of Tim Gould, for their work in producing analysis of such high quality, and many other colleagues from across the Agency who brought their expertise to bear on this crucial topic.

Dr. Fatih Birol
Executive Director
International Energy Agency

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Executive summary

In the transition to clean energy, critical minerals bring new challenges to energy security

An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional hydrocarbon resources. Building solar photovoltaic (PV) plants, wind farms and electric vehicles (EVs) generally requires more minerals than their fossil fuel-based counterparts. A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen.

The types of mineral resources used vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies.

The shift to a clean energy system is set to drive a huge increase in the requirements for these minerals, meaning that the energy sector is emerging as a major force in mineral markets. Until the mid-2010s, the energy sector represented a small part of total demand for most minerals. However, as energy transitions gather pace, clean energy technologies are becoming the fastest-growing segment of demand.

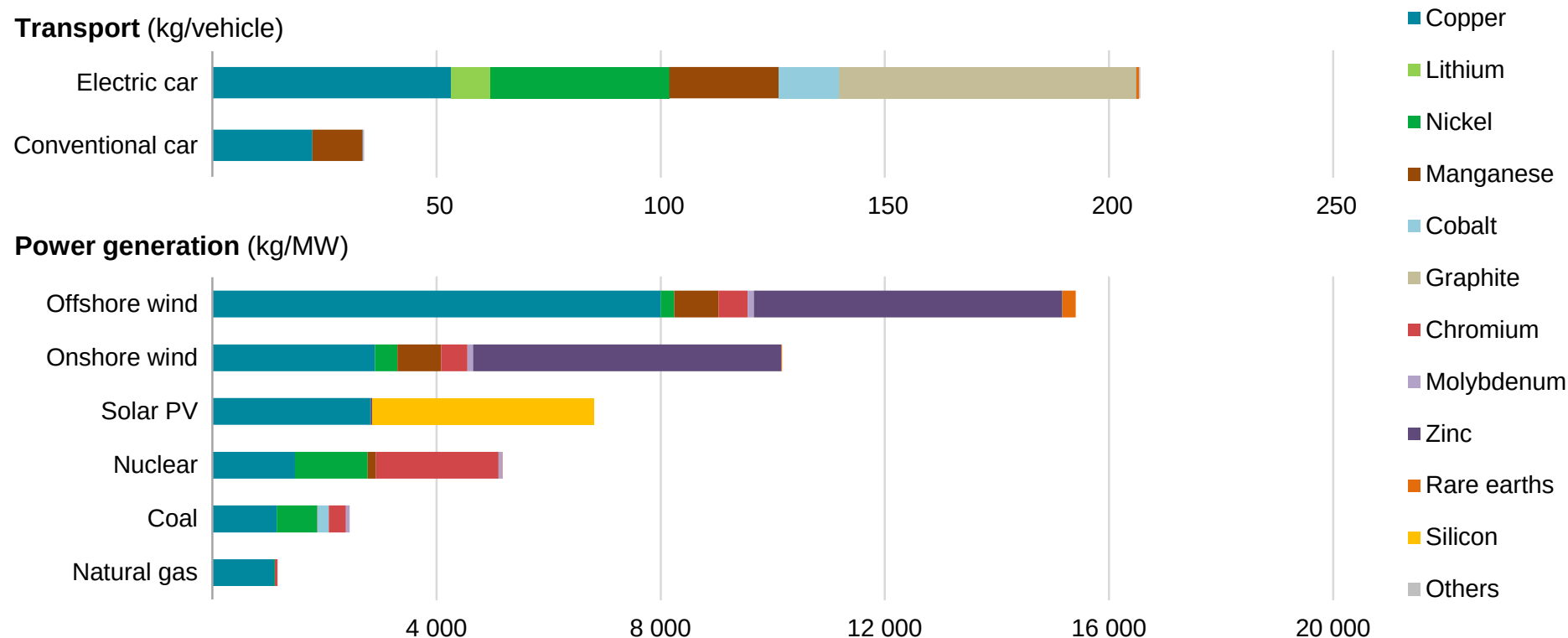
In a scenario that meets the Paris Agreement goals, clean energy technologies' share of total demand rises significantly over the next two decades to over 40% for copper and rare earth elements, 60-70% for nickel and cobalt, and almost 90% for lithium. EVs and battery storage have already displaced consumer electronics to become the largest consumer of lithium and are set to take over from stainless steel as the largest end user of nickel by 2040.

As countries accelerate their efforts to reduce emissions, they also need to make sure their energy systems remain resilient and secure. Today's international energy security mechanisms are designed to provide insurance against the risks of disruptions or price spikes in supplies of hydrocarbons, particularly oil. Minerals offer a different and distinct set of challenges, but their rising importance in a decarbonising energy system requires energy policy makers to expand their horizons and consider potential new vulnerabilities. Concerns about price volatility and security of supply do not disappear in an electrified, renewables-rich energy system.

This is why the IEA is paying close attention to the issue of critical minerals and their role in clean energy transitions. This report reflects the IEA's determination to stay ahead of the curve on all aspects of energy security in a fast-evolving energy world.

The rapid deployment of clean energy technologies as part of energy transitions implies a significant increase in demand for minerals

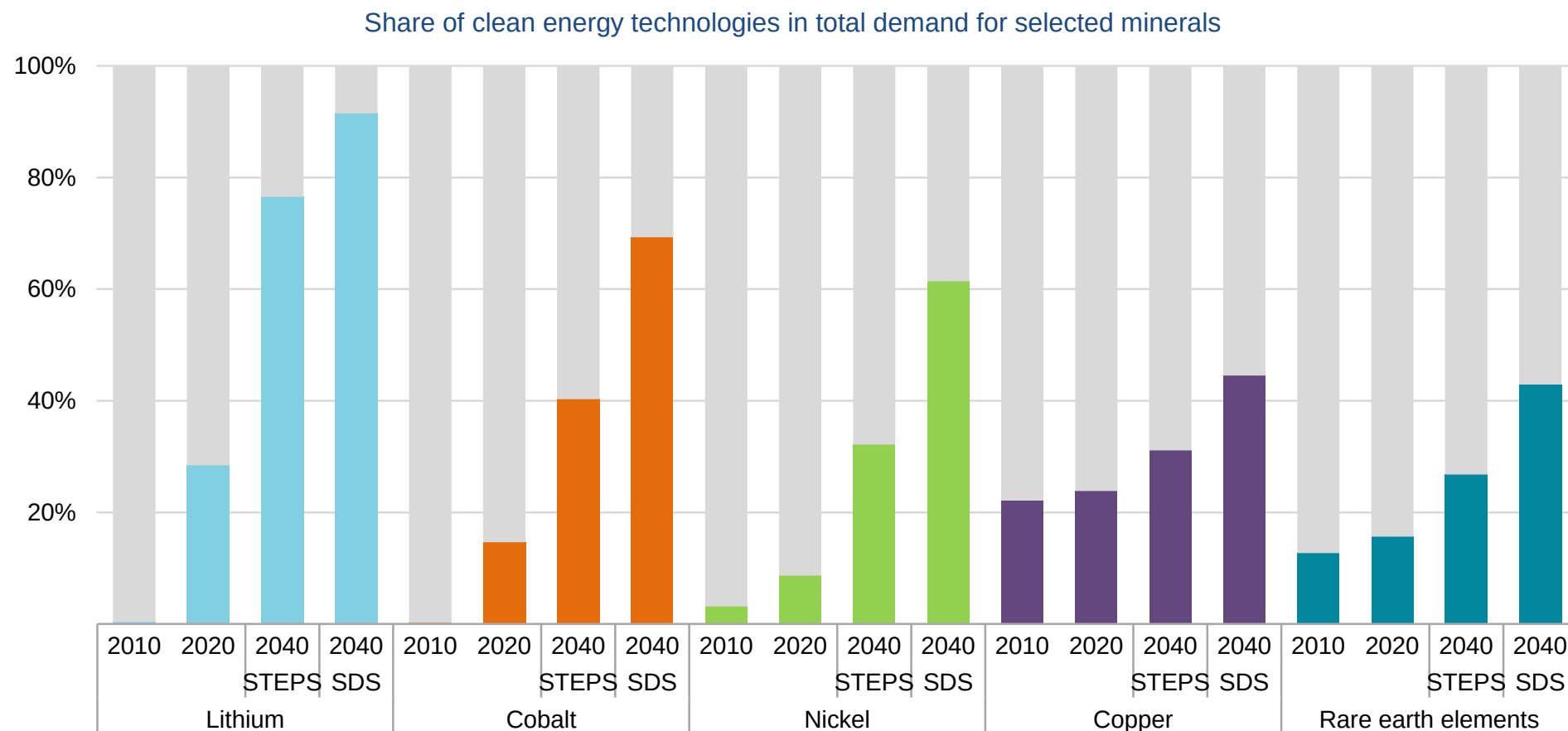
Minerals used in selected clean energy technologies



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Notes: kg = kilogramme; MW = megawatt. Steel and aluminium not included. See Chapter 1 and Annex for details on the assumptions and methodologies.

The energy sector becomes a leading consumer of minerals as energy transitions accelerate



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Notes: Demand from other sectors was assessed using historical consumption, relevant activity drivers and the derived material intensity. Neodymium demand is used as indicative for rare earth elements. STEPS = Stated Policies Scenario, an indication of where the energy system is heading based on a sector-by-sector analysis of today's policies and policy announcements; SDS = Sustainable Development Scenario, indicating what would be required in a trajectory consistent with meeting the Paris Agreement goals.

Clean energy transitions will have far-reaching consequences for metals and mining

Our bottom-up assessment suggests that a concerted effort to reach the goals of the Paris Agreement (climate stabilisation at “well below 2°C global temperature rise”, as in the IEA Sustainable Development Scenario [SDS]) would mean a quadrupling of mineral requirements for clean energy technologies by 2040. An even faster transition, to hit net-zero *globally* by 2050, would require six times more mineral inputs in 2040 than today.

Which sectors do these increases come from? In climate-driven scenarios, mineral demand for use in EVs and battery storage is a major force, growing at least thirty times to 2040. Lithium sees the fastest growth, with demand growing by over 40 times in the SDS by 2040, followed by graphite, cobalt and nickel (around 20-25 times). The expansion of electricity networks means that copper demand for power lines more than doubles over the same period.

The rise of low-carbon power generation to meet climate goals also means a tripling of mineral demand from this sector by 2040. Wind takes the lead, bolstered by material-intensive offshore wind. Solar PV follows closely, due to the sheer volume of capacity that is added. Hydropower, biomass and nuclear make only minor contributions given their comparatively low mineral requirements. In other sectors, the rapid growth of hydrogen as an energy carrier underpins major

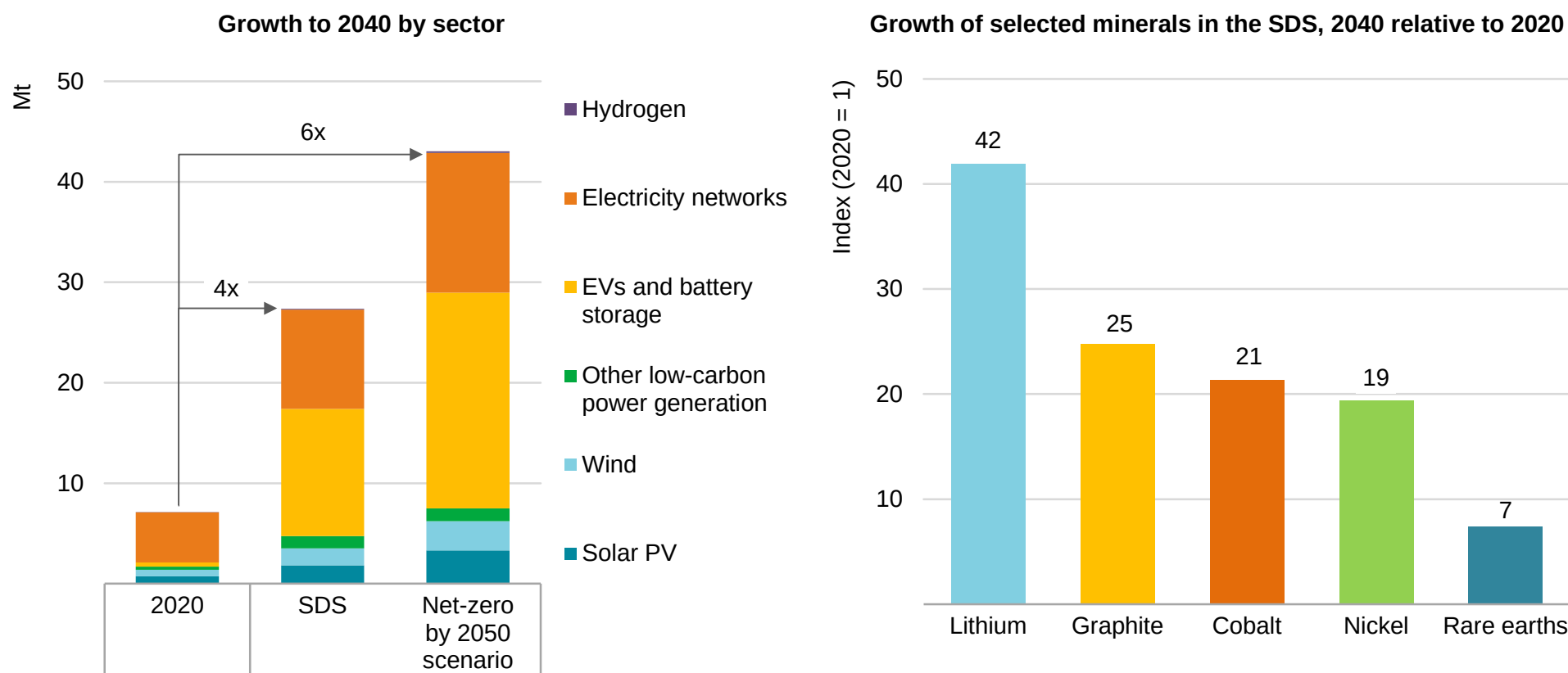
growth in demand for nickel and zirconium for electrolysers, and for platinum-group metals for fuel cells.

Demand trajectories are subject to large technology and policy uncertainties. We analysed 11 alternative cases to understand the impacts. For example, cobalt demand could be anything from 6 to 30 times higher than today’s levels depending on assumptions about the evolution of battery chemistry and climate policies. Likewise rare earth elements may see three to seven times higher demand in 2040 than today, depending on the choice of wind turbines and the strength of policy support. The largest source of demand variability comes from uncertainty around the stringency of climate policies. The big question for suppliers is whether the world is really heading for a scenario consistent with the Paris Agreement. Policy makers have a crucial role in narrowing this uncertainty by making clear their ambitions and turning targets into actions. This will be vital to reduce investment risks and ensure adequate flow of capital to new projects.

Clean energy transitions offer opportunities and challenges for companies that produce minerals. Today revenue from coal production is ten times larger than those from energy transition minerals. However, there is a rapid reversal of fortunes in a climate-driven scenario, as the combined revenues from energy transition minerals overtake those from coal well before 2040.

Mineral demand for clean energy technologies would rise by at least four times by 2040 to meet climate goals, with particularly high growth for EV-related minerals

Mineral demand for clean energy technologies by scenario

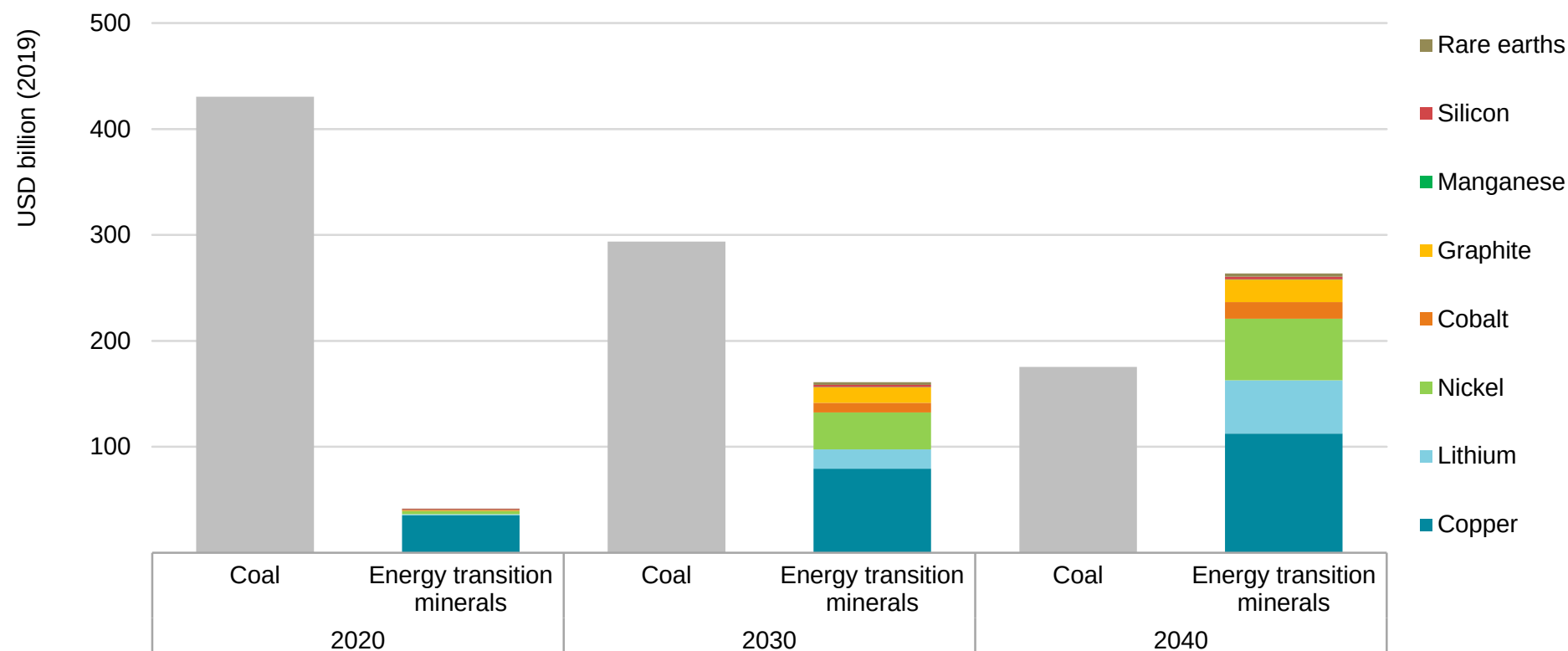


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Notes: Mt = million tonnes. Includes all minerals in the scope of this report, but does not include steel and aluminium. See Annex for a full list of minerals.

Changing fortunes: Coal vs energy transition minerals

Revenue from production of coal and selected energy transition minerals in the SDS



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Notes: Revenue for energy transition minerals includes only the volume required in clean energy technologies, not total demand. Future prices for coal are projected equilibrium prices in *WEO 2020* SDS. Prices for energy transition minerals are based on conservative assumptions about future price trends (moderate growth of around 10-20% from today's levels).

Today's mineral supply and investment plans fall short of what is needed to transform the energy sector, raising the risk of delayed or more expensive energy transitions

The prospect of a rapid increase in demand for critical minerals – well above anything seen previously in most cases – raises huge questions about the availability and reliability of supply. In the past, strains on the supply-demand balance for different minerals have prompted additional investment and measures to moderate or substitute demand. But these responses have come with time lags and have been accompanied by considerable price volatility. Similar episodes in the future could delay clean energy transitions and push up their cost. Given the urgency of reducing emissions, this is a possibility that the world can ill afford.

Raw materials are a significant element in the cost structure of many technologies required in energy transitions. In the case of lithium-ion batteries, technology learning and economies of scale have pushed down overall costs by 90% over the past decade. However, this also means that raw material costs now loom larger, accounting for some 50-70% of total battery costs, up from 40-50% five years ago. Higher mineral prices could therefore have a significant effect: a doubling of lithium or nickel prices would induce a 6% increase in battery costs. If both lithium and nickel prices were to double at the same time, this would offset all the anticipated unit cost reductions associated with a doubling of battery production capacity. In the case of electricity networks, copper and aluminium currently represent around 20% of

total grid investment costs. Higher prices as a result of tight supply could have a major impact on the level of grid investment.

Our analysis of the near-term outlook for supply presents a mixed picture. Some minerals such as mined lithium and cobalt are expected to be in surplus in the near term, while lithium chemical products, battery-grade nickel and key rare earth elements (e.g. neodymium and dysprosium) might face tight supply in the years ahead. However, looking further ahead in a scenario consistent with climate goals, expected supply from existing mines and projects under construction is estimated to meet only half of projected lithium and cobalt requirements and 80% of copper needs by 2030.

Today's supply and investment plans are geared to a world of more gradual, insufficient action on climate change (the STEPS trajectory). They are not ready to support accelerated energy transitions. While there are a host of projects at varying stages of development, there are many vulnerabilities that may increase the possibility of market tightness and greater price volatility:

- **High geographical concentration of production:** Production of many energy transition minerals is more concentrated than that of oil or natural gas. For lithium, cobalt and rare earth elements, the world's top three producing nations control well over three-

quarters of global output. In some cases, a single country is responsible for around half of worldwide production. The Democratic Republic of the Congo (DRC) and People's Republic of China (China) were responsible for some 70% and 60% of global production of cobalt and rare earth elements respectively in 2019. The level of concentration is even higher for processing operations, where China has a strong presence across the board. China's share of refining is around 35% for nickel, 50-70% for lithium and cobalt, and nearly 90% for rare earth elements. Chinese companies have also made substantial investment in overseas assets in Australia, Chile, the DRC and Indonesia. High levels of concentration, compounded by complex supply chains, increase the risks that could arise from physical disruption, trade restrictions or other developments in major producing countries.

- **Long project development lead times:** Our analysis suggests that it has taken on average over 16 years to move mining projects from discovery to first production. These long lead times raise questions about the ability of suppliers to ramp up output if demand were to pick up rapidly. If companies wait for deficits to emerge before committing to new projects, this could lead to a prolonged period of market tightness and price volatility.
- **Declining resource quality:** Concerns about resources relate to quality rather than quantity. In recent years, ore quality has continued to fall across a range of commodities. For example, the average copper ore grade in Chile declined by 30% over the past

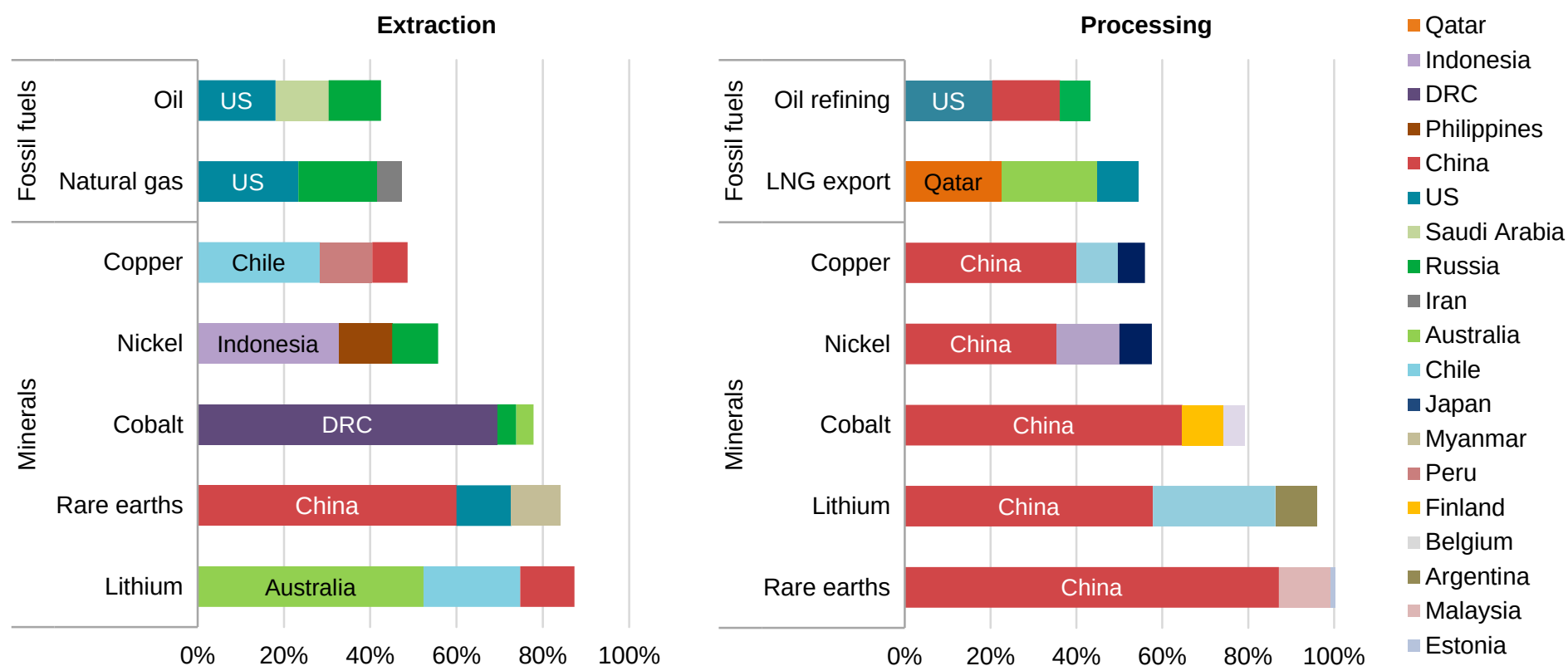
15 years. Extracting metal content from lower-grade ores requires more energy, exerting upward pressure on production costs, greenhouse gas emissions and waste volumes.

- **Growing scrutiny of environmental and social performance:** Production and processing of mineral resources gives rise to a variety of environmental and social issues that, if poorly managed, can harm local communities and disrupt supply. Consumers and investors are increasingly calling for companies to source minerals that are sustainably and responsibly produced. Without broad and sustained efforts to improve environmental and social performance, it may be challenging for consumers to exclude minerals produced with poor standards as higher-performing supply chains may not be sufficient to meet demand.
- **Higher exposure to climate risks:** Mining assets are exposed to growing climate risks. Copper and lithium are particularly vulnerable to water stress given their high water requirements. Over 50% of today's lithium and copper production is concentrated in areas with high water stress levels. Several major producing regions such as Australia, China, and Africa are also subject to extreme heat or flooding, which pose greater challenges in ensuring reliable and sustainable supplies.

These risks to the reliability, affordability and sustainability of mineral supply are manageable, but they are real. How policy makers and companies respond will determine whether critical minerals are a vital enabler for clean energy transitions, or a bottleneck in the process.

Production of many energy transition minerals today is more geographically concentrated than that of oil or natural gas

Share of top three producing countries in production of selected minerals and fossil fuels, 2019



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Notes: LNG = liquefied natural gas; US = United States. The values for copper processing are for refining operations.
Sources: IEA (2020a); USGS (2021), World Bureau of Metal Statistics (2020); Adamas Intelligence (2020).

New and more diversified supply sources will be vital to pave the way to a clean energy future

As energy transitions gather pace, security of mineral supply is gaining prominence in the energy security debate, a realm where oil has traditionally occupied a central role.

There are significant differences between oil security and mineral security, notably in the impacts that any disruption may have. In the event of an oil supply crisis, all consumers driving gasoline cars or diesel trucks are affected by higher prices. By contrast, a shortage or spike in the price of a mineral affects only the supply of *new* EVs or solar plants. Consumers driving existing EVs or using solar-powered electricity are not affected. In addition, the combustion of oil means that new supply is essential to the continuous operation of oil-using assets. However, minerals are a component of infrastructure, with the potential to be recovered and recycled.

Nonetheless, experience from oil markets may offer some valuable lessons for an approach to mineral security, in particular to underscore that supply-side measures need to be accompanied by wide-ranging efforts encompassing demand, technology, supply chain resilience and sustainability.

Rapid, orderly energy transitions require strong growth in investment in mineral supplies to keep up with the pace of demand growth. Policy makers can take a variety of actions to encourage new supply

projects: the most important is to provide clear and strong signals about energy transitions. If companies do not have confidence in countries' energy and climate policies, they are likely to make investment decisions based on much more conservative expectations. Given the long lead times for new project developments, this could create bottlenecks when deployment of clean energy technologies starts to grow rapidly. Diversification of supply is also crucial; resource-owning governments can support new project development by reinforcing national geological surveys, streamlining permitting procedures to shorten lead times, providing financing support to de-risk projects, and raising public awareness of the contribution that such projects play in the transformation of the energy sector.

Reducing material intensity and encouraging material substitution via technology innovation can also play major roles in alleviating strains on supply, while also reducing costs. For example, 40-50% reductions in the use of silver and silicon in solar cells over the past decade have enabled a spectacular rise in solar PV deployment. Innovation in production technologies can also unlock sizeable new supplies. Emerging technologies, such as direct lithium extraction or enhanced metal recovery from waste streams or low-grade ores, offer the potential for a step change in future supply volumes.

A strong focus on recycling, supply chain resilience and sustainability will be essential

Recycling relieves the pressure on primary supply. For bulk metals, recycling practices are well established, but this is not yet the case for many energy transition metals such as lithium and rare earth elements. Emerging waste streams from clean energy technologies (e.g. batteries and wind turbines) can change this picture. The amount of spent EV batteries reaching the end of their first life is expected to surge after 2030, at a time when mineral demand is set to still be growing rapidly. Recycling would not eliminate the need for continued investment in new supplies. But we estimate that by 2040, recycled quantities of copper, lithium, nickel and cobalt from spent batteries could reduce combined primary supply requirements for these minerals by around 10%. The security benefits of recycling can be far greater for regions with wider deployment of clean energy technologies due to greater economies of scale.

Regular market assessments and periodic stress tests, coupled with emergency response exercises (along the lines of the IEA's existing emergency response programmes), can help policy makers identify possible weak points, evaluate potential impacts and devise necessary actions. Voluntary strategic stockpiling can in some cases help countries weather short-term supply disruptions. Such programmes need to be carefully designed, and based on a detailed review of potential vulnerabilities. Some minerals with smaller markets have low pricing transparency and liquidity, making it difficult to manage price risks and affecting investment decisions.

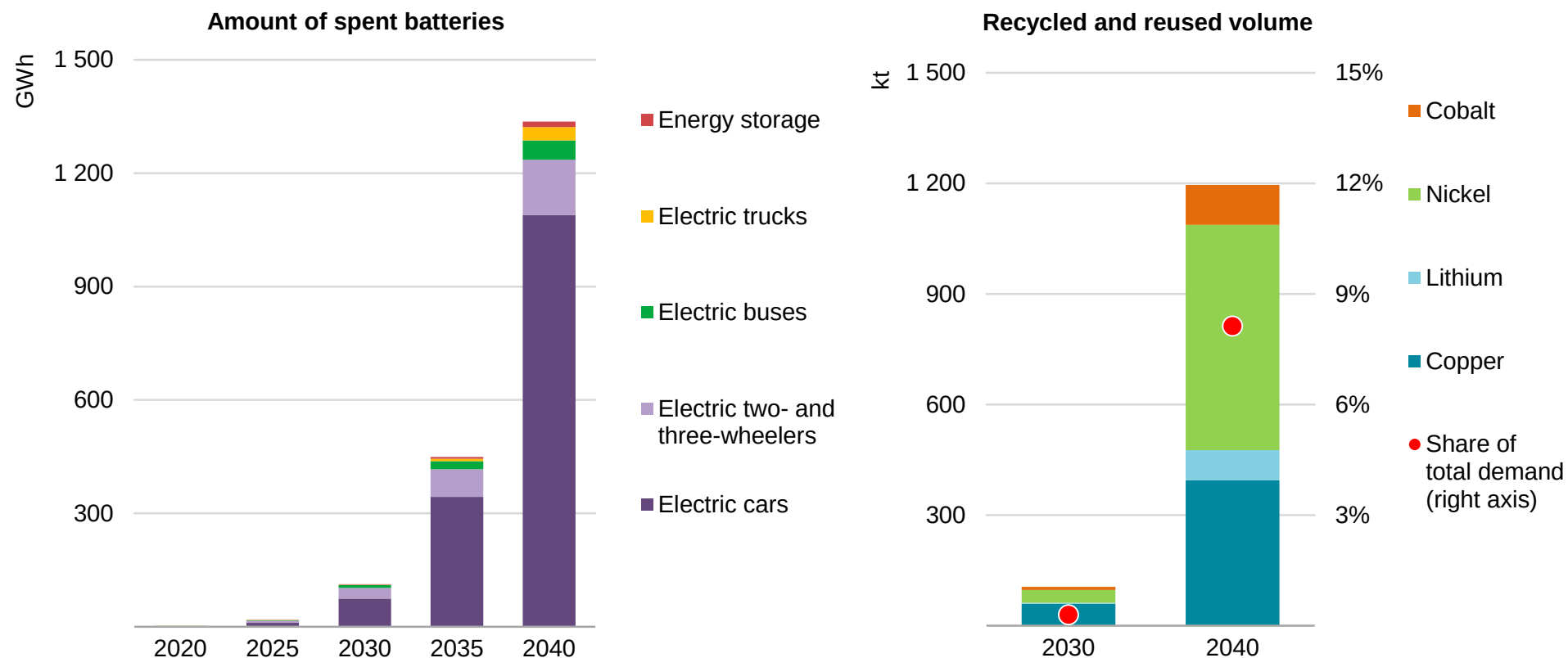
Establishing reliable price benchmarks will be a crucial step towards enhancing transparency and supporting market development.

Tackling the environmental and social impacts of mineral developments will be essential, including the emissions associated with mining and processing, risks arising from inadequate waste and water management, and impacts from inadequate worker safety, human rights abuses (such as child labour) and corruption. Ensuring that mineral wealth brings real gains to local communities is a broad and multi-faceted challenge, particularly in countries where artisanal and small-scale mines are common. Supply chain due diligence, with effective regulatory enforcement, can be a critical tool to identify, assess and mitigate risks, increasing traceability and transparency.

Emissions along the mineral supply chain do not negate the clear climate advantages of clean energy technologies. Total lifecycle greenhouse gas emissions of EVs are around half those of internal combustion engine cars on average, with the potential for a further 25% reduction with low-carbon electricity. While energy transition minerals have relatively high emission intensities, a large variation in the emissions footprint of different producers suggests that there are ways to minimise these emissions through fuel switching, low-carbon electricity and efficiency improvements. Integrating environmental concerns in the early stages of project planning can help ensure sustainable practices throughout the project life cycle.

The projected surge in spent battery volumes suggests immense scope for recycling

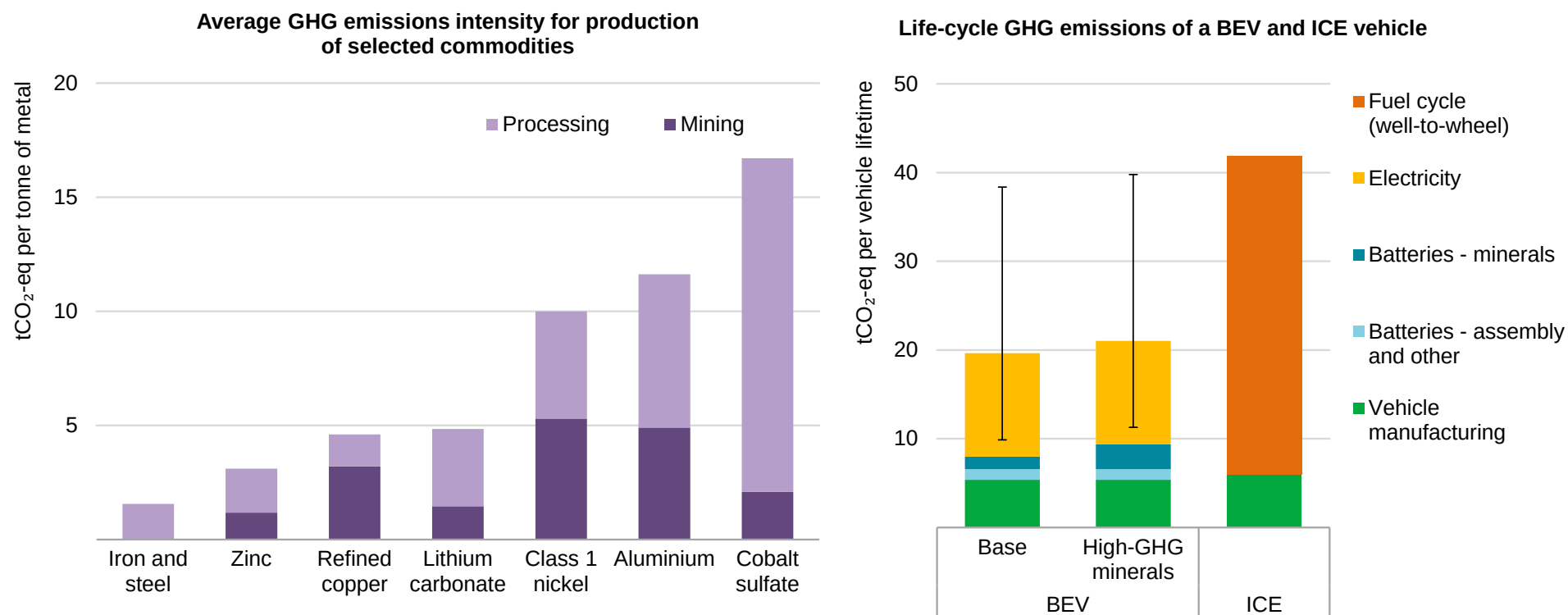
Amount of spent lithium-ion batteries from EVs and storage and recycled and reused minerals from batteries in the SDS



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Note: GWh = gigawatt hour.

Stronger actions are required to counter the upward pressure on emissions from mineral production, but the climate advantages of clean energy technologies remain clear



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Notes: BEV = battery electric vehicle; ICE = internal combustion engine. The “High-GHG minerals” case assumes double the GHG emissions intensity for battery minerals. Includes both Scope 1 and 2 emissions of all GHG from primary production. See Chapter 4 for more detailed assumptions.

Source: IEA analysis based on IEA (2020a); IEA (2020b); Kelly et al. (2020); Argonne National Laboratory (2020); Argonne National Laboratory (2019); Rio Tinto (2020); S&P Global (2021); Skarn Associates (2021); Marx et al. (2018).

IEA's six key recommendations for a new, comprehensive approach to mineral security

- 1. Ensure adequate investment in diversified sources of new supply.** Strong signals from policy makers about the speed of energy transitions and the growth trajectories of key clean energy technologies are critical to bring forward timely investment in new supply. Governments can play a major role in creating conditions conducive to diversified investment in the mineral supply chain.
- 2. Promote technology innovation at all points along the value chain.** Stepping up R&D efforts for technology innovation on both the demand and production sides can enable more efficient use of materials, allow material substitution and unlock sizeable new supplies, thereby bringing substantial environmental and security benefits.
- 3. Scale up recycling.** Policies can play a pivotal role in preparing for rapid growth of waste volumes by incentivising recycling for products reaching the end of their operating lives, supporting efficient collection and sorting activities and funding R&D into new recycling technologies.
- 4. Enhance supply chain resilience and market transparency.** Policy makers need to explore a range of measures to improve the resilience of supply chains for different minerals, develop response capabilities to potential supply disruptions and enhance market transparency. Measures can include regular market assessments and stress tests, as well as voluntary strategic stockpiles in some instances.
- 5. Mainstream higher environmental, social and governance standards.** Efforts to incentivise higher environmental and social performance can increase sustainably and responsibly produced volumes and lower the cost of sourcing them. If industry players with strong environmental and social standards are rewarded in the marketplace, this can also bring new suppliers to a more diversified market.
- 6. Strengthen international collaboration between producers and consumers.** An overarching international framework for dialogue and policy co-ordination among producers and consumers can play a vital role, an area where the IEA's energy security framework could usefully be leveraged. Such an initiative could include actions to (i) provide reliable and transparent data; (ii) conduct regular assessments of potential vulnerabilities of supply chains and potential collective responses; (iii) promote knowledge transfer and capacity building to spread sustainable and responsible development practices; and (iv) strengthen environmental and social performance standards to ensure a level playing field.

Introduction

Introduction

Clean energy transitions gained momentum in 2020, despite the major economic and social disruptions caused by the pandemic. Renewable electricity defied the Covid-19 crisis with record growth, and capacity additions are on course to reach fresh heights in the coming years (IEA, 2020). Electric car sales also charged ahead, with a remarkable 40% increase in 2020 amid a sluggish global market (IEA, 2021). Dozens of countries and many leading companies have announced plans to bring their emissions down to net zero by around the middle of this century.

The growing momentum behind clean energy transitions focuses attention on the importance of clean energy supply chains, and the adequate supply of minerals in particular. Minerals have played a vital role in the rise of many of the clean energy technologies that are widely used today – from solar panels and wind turbines to electricity networks and electric vehicles. But ensuring that these and other technologies can continue to draw on sufficient mineral supplies, and therefore support the acceleration of energy transitions, is a major challenge. Debates around energy security have traditionally been associated with oil and natural gas supplies, and more recently also with electricity, but as energy transitions gather pace policy makers need to expand their horizons to include new potential hazards.

With this *World Energy Outlook (WEO)* special report, we aim to: explain the complex links between clean energy technologies and

minerals; assess the mineral requirements under varying energy and technology scenarios; and identify the security, environmental and social implications of minerals supply for the energy transition. The report reflects the IEA's determination to ensure it stays ahead of the curve on all aspects of energy security in a decarbonising world.

Our analysis is based on two main IEA scenarios, drawn from *WEO-2020*. The **Sustainable Development Scenario (SDS)** charts a pathway that meets in full the world's goals to tackle climate change in line with the Paris Agreement, improve air quality and provide access to modern energy. The SDS relies on countries and companies hitting their announced net-zero emissions targets (mostly by 2050) on time and in full, which spurs the world as a whole to reach it before 2070. The range of technologies that are required in the SDS provides an essential benchmark for our discussion throughout the report. Reaching net-zero emissions globally by 2050 would demand a dramatic extra push for the deployment of various clean energy technologies.

The other scenario we refer to in the analysis is the **Stated Policies Scenario (STEPS)**, which provides an indication of where today's policy measures and plans might lead the energy sector. These outcomes fall far short of the world's shared sustainability goals. Comparison between the outcomes in these two scenarios provides an indication of the range of possible futures.

Scope

This report assesses the mineral requirements for a range of clean energy technologies, including renewable power (solar photovoltaic [PV], onshore and offshore wind, concentrating solar power, hydro, geothermal and biomass), nuclear power, electricity networks (transmission and distribution), electric vehicles, battery storage and hydrogen (electrolysers and fuel cells). Although this is not an exhaustive list of clean energy technologies, the technologies we cover represent the majority deployed in the SDS. We plan to expand the analysis to other technologies in future publications.

All these technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this report covers the entire mineral and metal value chain from mining to processing operations, we use “minerals” as a representative term for the sake of simplicity.

Minerals are not only used in the clean energy sector, but are also used widely across the entire energy system, in technologies that improve efficiency and reduce emissions. For example, the most efficient coal-fired power plants require a lot more nickel than the least efficient ones in order to allow for higher combustion

temperatures. Catalytic converters use platinum or palladium to help reduce harmful emissions from engines using petroleum. However, here we focus specifically on the use of minerals in clean energy technologies, given that they generally require considerably more minerals than fossil fuel counterparts. Our analysis also focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our report considers a wide range of minerals used in clean energy technologies, as indicated in the Annex. They include chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others. Steel is widely used across a broad range of technologies, but we have excluded it from the scope given that it does not have substantial security implications and the energy sector is not a major driver of growth in steel demand.

Aluminium also plays a crucial role in clean energy transitions, being widely used in applications such as solar cells, wind turbines and vehicle lightweighting. We have excluded it from demand projections as it is regularly assessed as part of the *WEO* and *Energy Technology Perspectives* series. However, we have assessed its use in electricity networks as the outlook for copper is inherently linked with aluminium use in grid lines.

Structure

We have structured this report in four chapters, as follows:

In **Chapter 1 (The State of Play)** we set out the linkages between critical minerals and energy transitions, and the reasons why they are rising up the policy agenda. We provide an overview of today's supply chains and examines their geographical concentration and other potential bottlenecks. We also describe the industry landscape, and recent investment and price dynamics.

In **Chapter 2 (Mineral Requirements for Clean Energy Technologies)** we analyse a range of possible trajectories for mineral requirements in various clean energy technologies. They include low-carbon power generation, batteries for electric vehicles and grid storage, electricity networks and hydrogen. We conducted the assessments using the detailed technology projections in IEA scenarios. We also address how and to what extent demand trajectories could evolve in different directions under a number of alternative technology evolution pathways.

In **Chapter 3 (Reliable Supply of Minerals)** we assess the prospects for supply of the main focus minerals – copper, lithium, nickel, cobalt and rare earth elements – that play a particularly important role in many clean energy technologies. We examine the contributions from existing mines and those under construction, and

shed light on specific vulnerabilities that could create pressures on future supply.

In this chapter we also discuss the potential contribution of secondary supply, especially via recycling. We assess how recycling could contribute to reducing requirements for primary supply, taking into account both conventional sources and emerging waste streams such as spent batteries from electric vehicles.

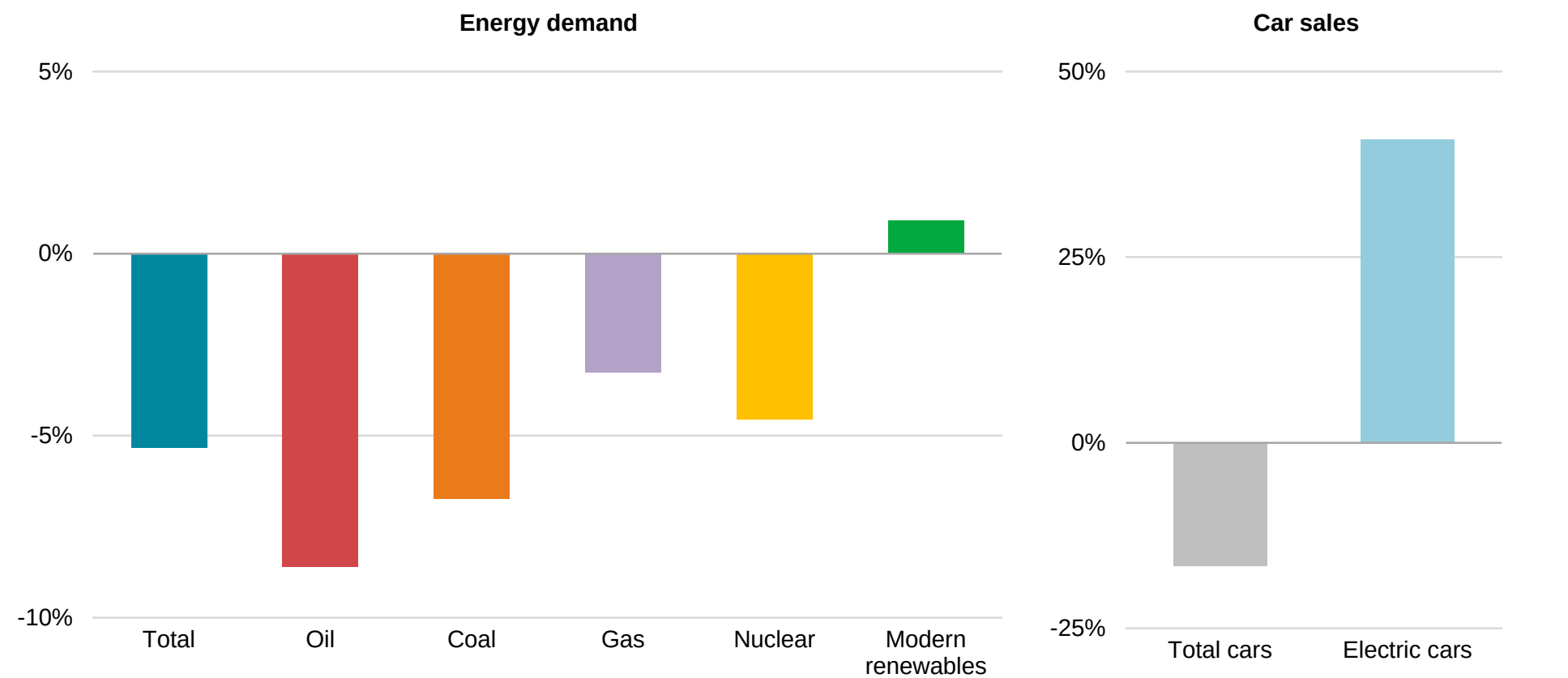
Using our analysis and lessons from historical episodes of disruption, we identify policy approaches to ensure reliable supply of minerals in an evolving market environment.

In **Chapter 4 (Sustainable and Responsible Development of Minerals)** we examine the environmental, social and governance implications of minerals development which, if improperly managed, could offset or negate their positive contributions to clean energy technologies. We assess potential hazards, spanning from emissions during production and processing, to inadequate waste and water management and extending to local community impacts such as corruption, human rights abuses and worker safety. We finally discuss potential policy approaches to mitigate these risks.

The state of play

Clean energy technologies defied the Covid-19 crisis with strong growth, making 2020 a pivotal year for clean energy transitions

Change in energy demand and car sales by type in 2020 relative to 2019

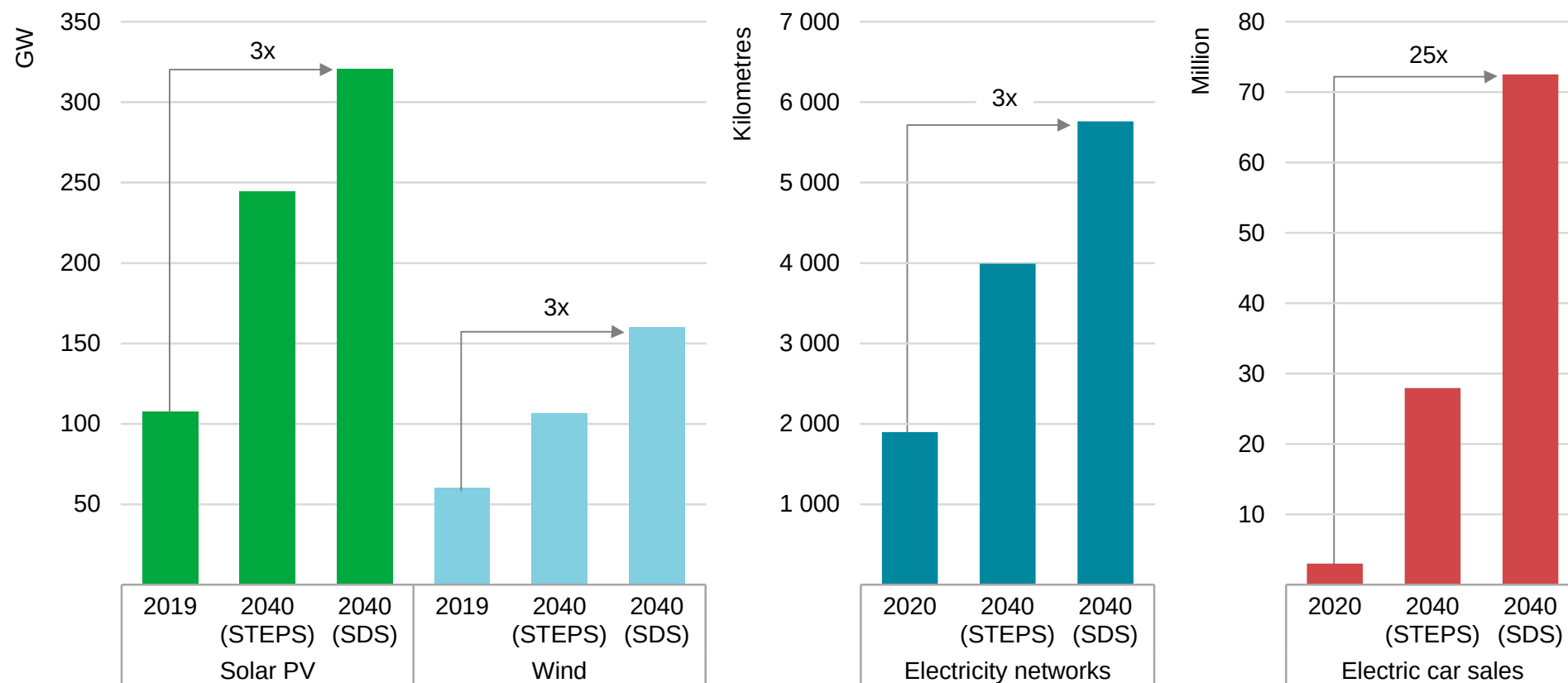


Sources: IEA (2020a) for energy demand; IEA (2021a) for car sales.

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But achieving climate goals requires a further rapid acceleration in clean energy deployment

Annual deployment of clean energy technologies by scenario



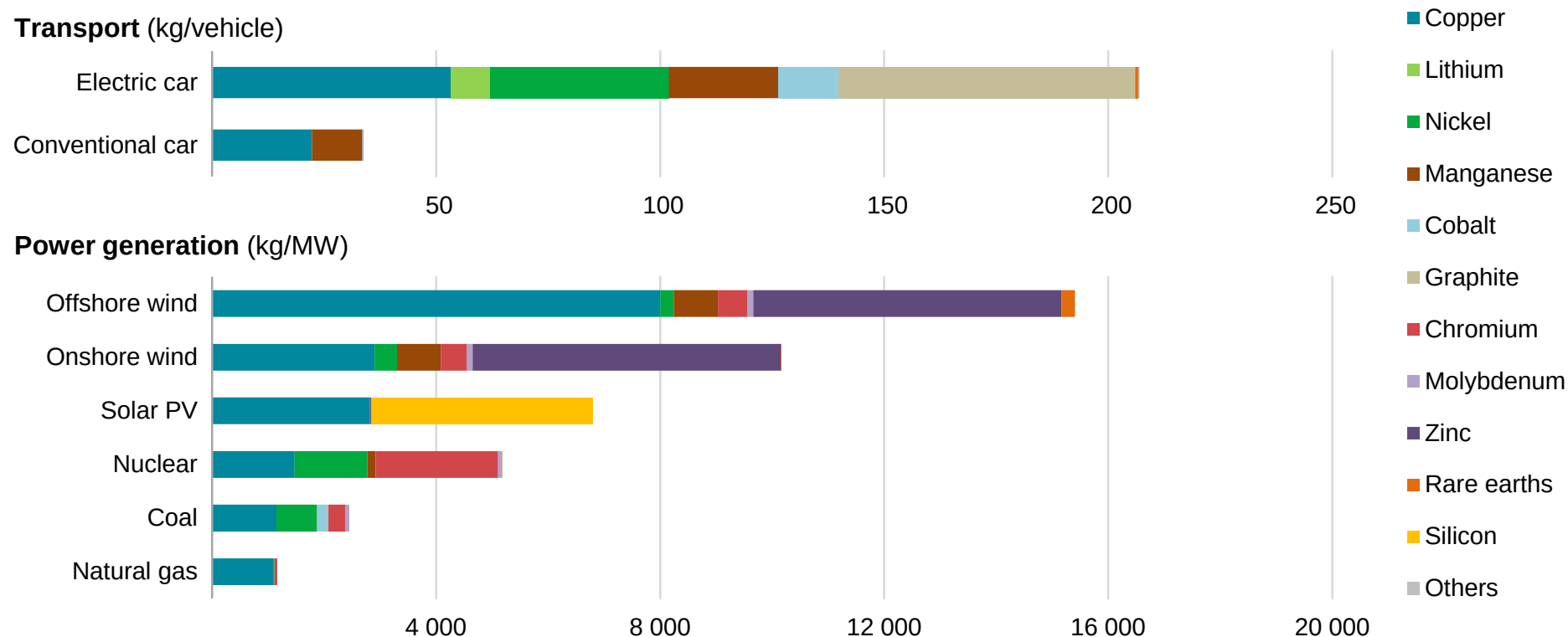
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Notes: PV = Photovoltaic; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

Sources: IEA (2021a); IEA (2020a).

The rapid deployment of these technologies as part of energy transitions implies a significant increase in demand for minerals

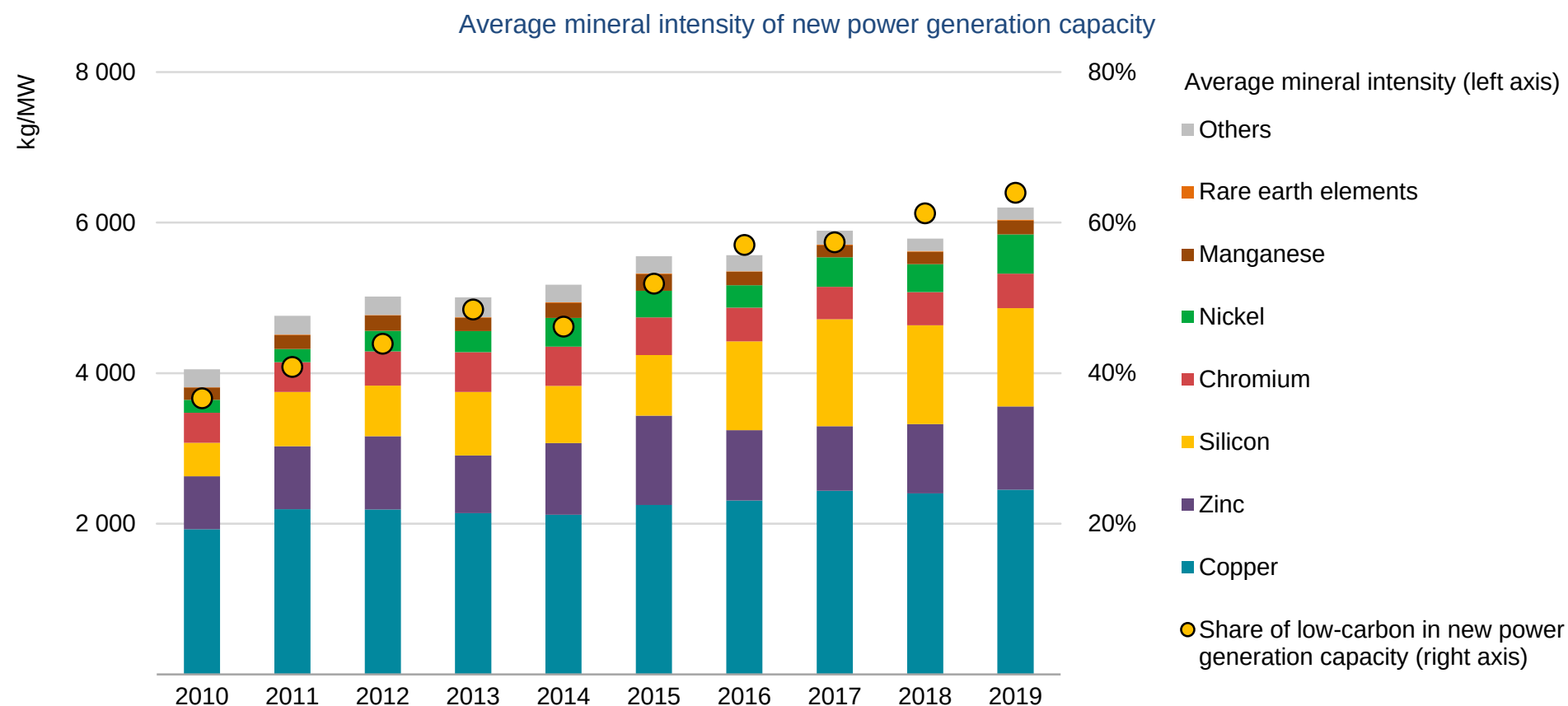
Minerals used in selected clean energy technologies



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Notes: kg = kilogramme; MW = megawatt. The values for vehicles are for the entire vehicle including batteries, motors and glider. The intensities for an electric car are based on a 75 kWh NMC (nickel manganese cobalt) 622 cathode and graphite-based anode. The values for offshore wind and onshore wind are based on the direct-drive permanent magnet synchronous generator system (including array cables) and the doubly-fed induction generator system respectively. The values for coal and natural gas are based on ultra-supercritical plants and combined-cycle gas turbines. Actual consumption can vary by project depending on technology choice, project size and installation environment.

The mineral requirement for new power generation capacity has increased by 50% since 2010 as low-carbon technologies take a growing share of investment



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Note: Low-carbon technologies include renewables and nuclear.

The shift from a fuel-intensive to a material-intensive energy system

The Covid-19 pandemic and resulting economic crisis have had an impact on almost every aspect of the global energy system. However, while fossil fuel consumption was hit hard in 2020, clean energy technologies – most notably renewables and electric vehicles (EVs) – remained relatively resilient. As a result, our latest estimates suggest that global energy-related CO₂ emissions fell by 6% in 2020, more than the 4% fall in energy demand (IEA, 2021b).

Nonetheless, as things stand, the world is far from seeing a decisive downturn in emissions – CO₂ emissions in December 2020 were already higher than their pre-crisis level one year earlier. Putting emissions on a trajectory consistent with the Paris Agreement, as analysed in the *World Energy Outlook* Sustainable Development Scenario (SDS), requires a significant scale-up of clean energy deployment across the board. In the SDS, the annual installation of solar PV cells, wind turbines and electricity networks needs to expand threefold by 2040 from today's levels, and sales of electric cars need to grow 25-fold over the same period. Reaching net-zero emissions globally by 2050 would demand an even more dramatic increase in the deployment of clean energy technologies over the same timeframe.

An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional hydrocarbon resources. While solar PV plants and wind farms do not require fuels to operate,

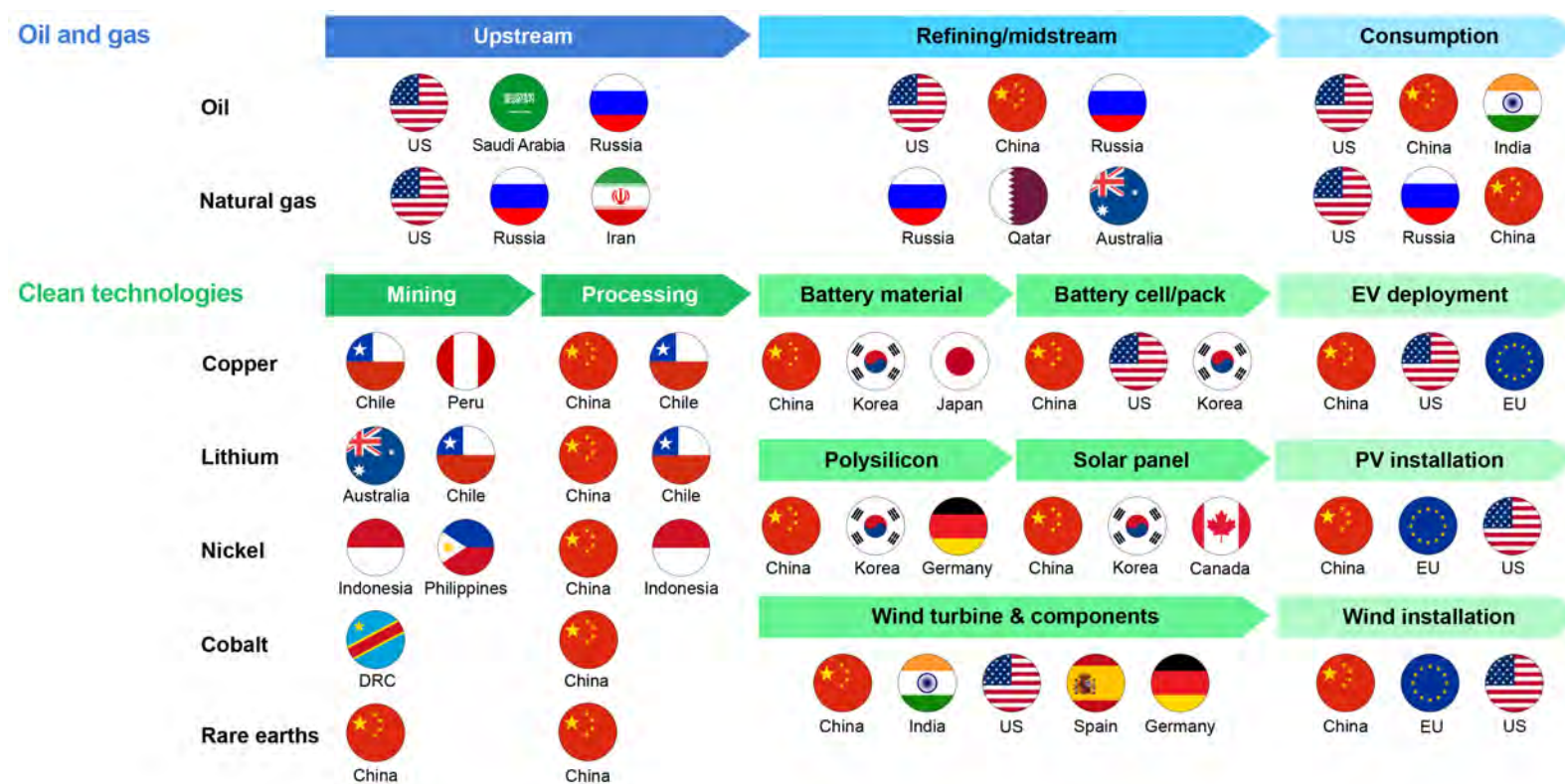
they generally require more materials than fossil fuel-based counterparts for construction. Minerals are a case in point. A typical electric car requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant of the same capacity. Since 2010 the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as renewables increase their share of total capacity additions. The transition to clean energy means a shift from a fuel-intensive to a material-intensive system.

The types of mineral resources used vary by technology. Lithium, cobalt and nickel play a central role in giving batteries greater performance, longevity and higher energy density. Rare earth elements are used to make powerful magnets that are vital for wind turbines and EVs. Electricity networks need a huge amount of copper and aluminium. Hydrogen electrolyzers and fuel cells require nickel or platinum group metals depending on the technology type. Copper is an essential element for almost all electricity-related technologies.

These characteristics of a clean energy system imply a significant increase in demand for minerals as more batteries, solar panels, wind turbines and networks are deployed. It also means that the energy sector is set to emerge as a major force in driving demand growth for many minerals, highlighting the strengthening linkages between minerals and clean energy technologies.

The transition to a clean energy system brings new energy trade patterns, countries and geopolitical considerations into play

Indicative supply chains of oil and gas and selected clean energy technologies

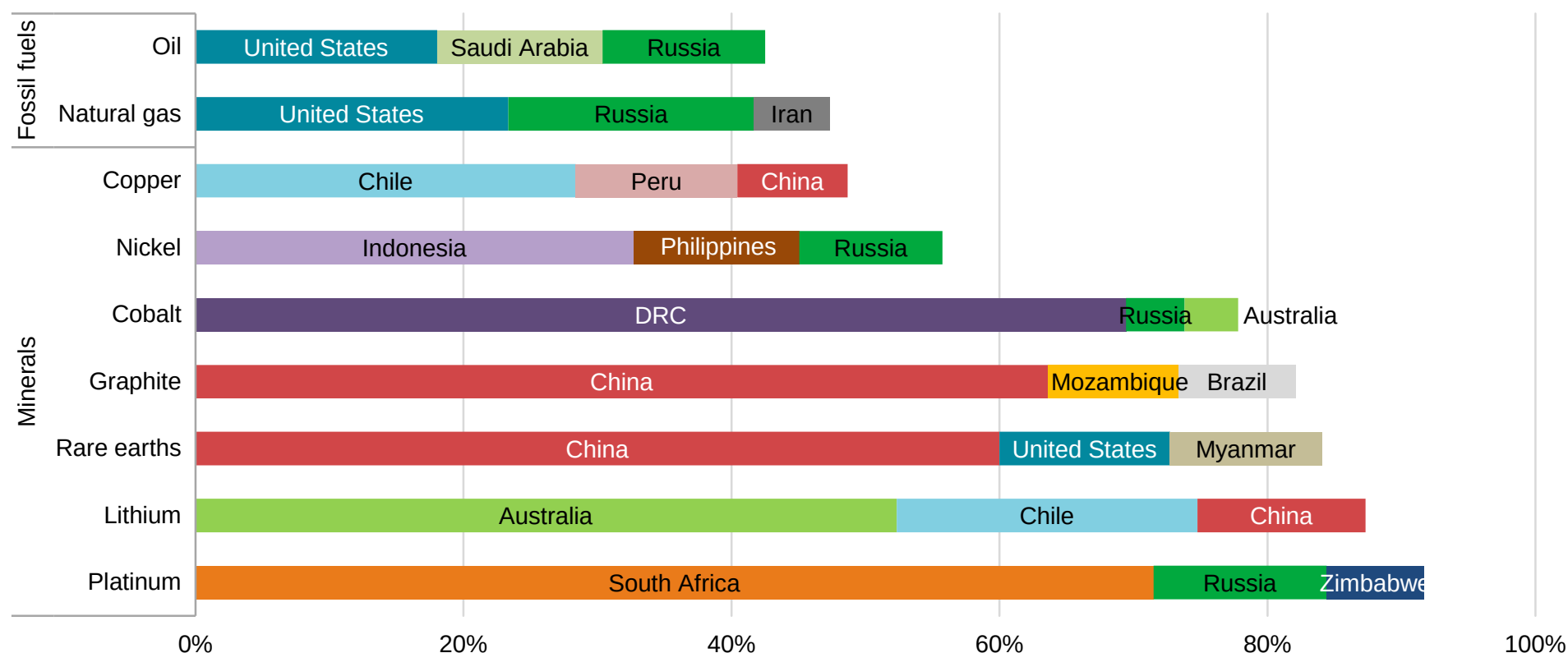


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Notes: DRC = Democratic Republic of the Congo; EU = European Union; US = United States; Russia = Russian Federation; China = People's Republic of China. Largest producers and consumers are noted in each case to provide an indication, rather than a complete account.

Current production of many energy transition minerals is more geographically concentrated than that of oil or natural gas

Share of top three producing countries in total production for selected minerals and fossil fuels, 2019

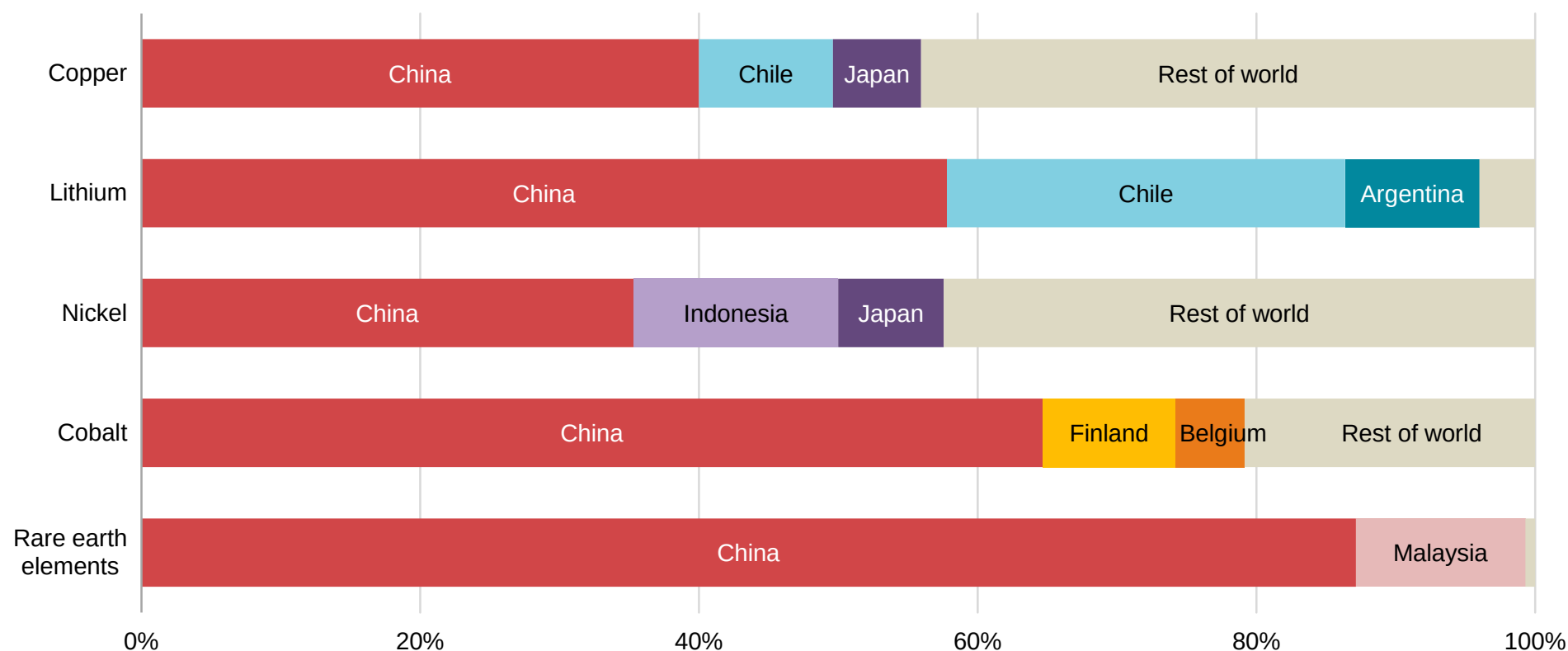


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Sources: IEA (2020b); USGS (2021).

The level of concentration is similarly high for processing operations, with China's significant presence across the board

Share of processing volume by country for selected minerals, 2019



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Note: The values for copper are for refining operations.

Sources: World Bureau of Metal Statistics (2020); Adamas Intelligence (2020) for rare earth elements.

Robust and resilient clean energy supply chains are essential, especially for critical minerals

Today's international energy security mechanisms are designed to provide some insurance against the risks of disruption, price spikes and geopolitical events in the supply of hydrocarbons, oil in particular. These concerns do not disappear during energy transitions as more solar panels, wind turbines and electric cars are deployed. However, alongside the many benefits of clean energy transitions, they also raise additional questions about the security and resilience of clean energy supply chains, which policy makers need to address.

Compared with fossil fuel supply, the supply chains for clean energy technologies can be even more complex (and in many instances, less transparent). In addition, the supply chain for many clean energy technologies and their raw materials is more geographically concentrated than that of oil or natural gas. This is especially the case for many of the minerals that are central to manufacturing clean energy technology equipment and infrastructure.

For lithium, cobalt and rare earth elements (REEs), the top three producing nations control well over three-quarters of global output. In some cases, a single country is responsible for around half of worldwide production. South Africa and the Democratic Republic of the Congo are responsible for some 70% of global production of platinum and cobalt respectively, and China accounted for 60% of global REE production in 2019 (albeit down from over 80% in the mid-

2010s). The picture for copper and nickel is slightly more diverse, but still around half of global supply is concentrated in the top three producing countries.

The level of concentration is even higher for processing and refining operations. China has gained a strong presence across the board. China's share of refining is around 35% for nickel (the figure becomes higher when including the involvement of Chinese companies in Indonesian operations), 50-70% for lithium and cobalt, and as high as 90% for REE processing that converts mined output into oxides, metals and magnets.

This creates sources of concern for companies that produce solar panels, wind turbines, electric motors and batteries using imported minerals, as their supply chains can quickly be affected by regulatory changes, trade restrictions or political instability in a small number of countries. The Covid-19 pandemic already demonstrated the ripple effects that disruptions in one part of the supply chain can have on the supply of components and the completion of projects.

The implications of any potential supply disruptions are not as widespread as those for oil and gas (see Box 1.1). Nonetheless, trade patterns, producer country policies and geopolitical considerations remain crucial even in an electrified, renewables-rich energy system.

Box 1.1. Oil security vs mineral security

Minerals are increasingly recognised as essential to the good functioning of an evolving energy system, moving into a realm where oil has traditionally occupied a central role. There are similarities, in that threats to reliable supply can have far-reaching consequences throughout the energy system. So traditional concerns over oil security (e.g. unplanned supply disruption or price spikes) are relevant for minerals as well.

However, fundamental differences exist in the impacts that disruption may have. An oil supply crisis, when it happens, has broad repercussions for all vehicles that run on it. Consumers driving gasoline cars or diesel trucks are immediately affected by higher prices.

By contrast, a shortage or spike in the price of a mineral required for producing batteries and solar panels affects only the supply of new EVs or solar plants. Consumers driving existing EVs or using solar-powered electricity are not affected. The main threats from supply disruptions are delayed and more expensive energy transitions, rather than disturbed daily lives.

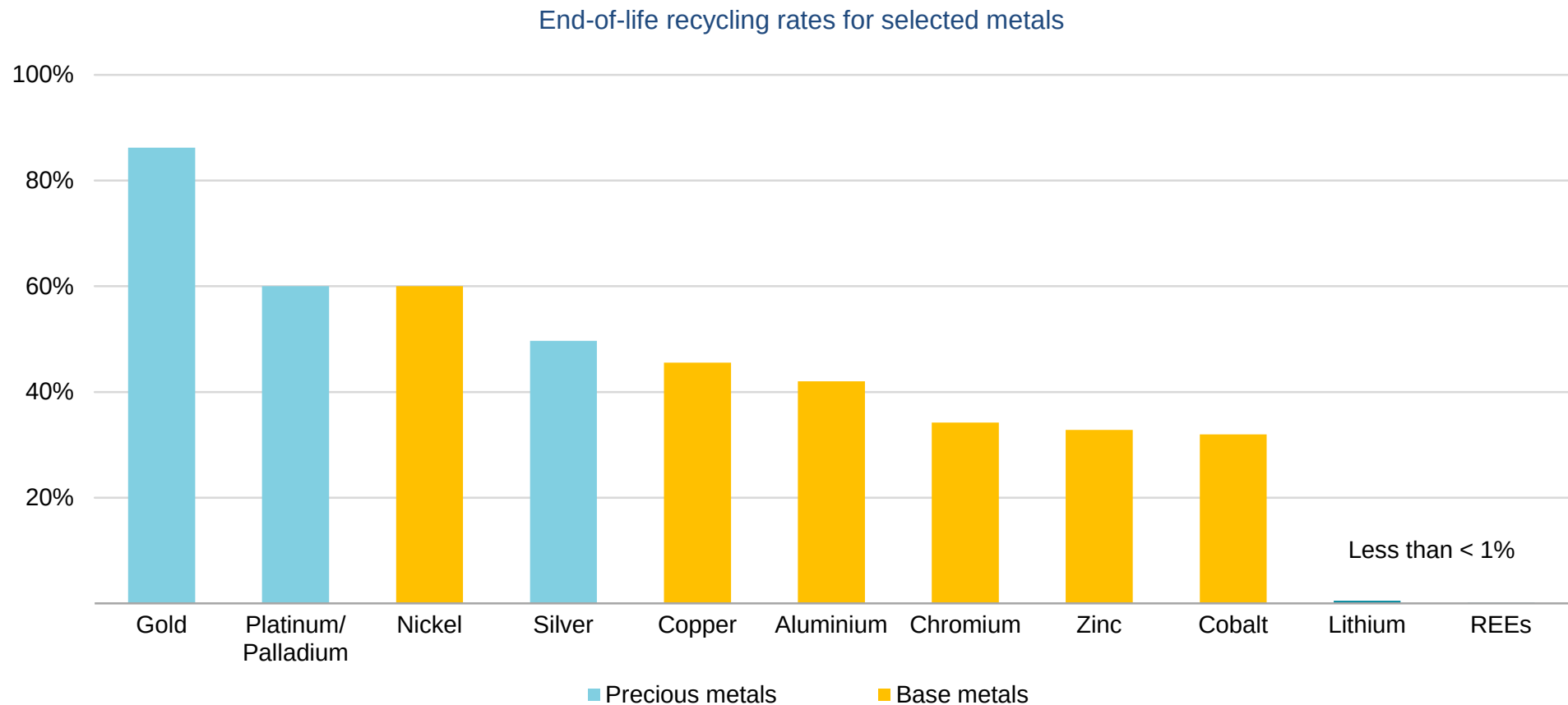
Notably, oil burns up when it is used, requiring continuous inputs to run assets. However, minerals are a component of infrastructure, with the potential to be recovered and recycled at the end of the infrastructure lifetime (Hastings-Simon and Bazilian, 2020).

Moreover, while oil is a single commodity with a large, liquid global market, there are multiple minerals now in play for the energy sector, each with its own complexities and supply dynamics. Individual countries may have very different positions in the value chain for each of the minerals that are now rising in prominence in the global energy debate.

Despite these differences, the experience of oil markets may offer a number of lessons for an approach to mineral security. The approach to safeguarding oil security tended to focus on supply-side measures. Strategic stockholding has long been at the centre of the IEA's efforts to ensure oil market security. However, the framework for oil security has evolved over time to encompass demand and resilience aspects, including efforts to identify immediate areas of demand restraint, improve fuel efficiency and review countries' preparedness against potential disruption.

This range of responses and measures provides valuable context for the discussion on minerals security. While supply-side measures (e.g. ensuring adequate investment in production) remain crucial, these need to be accompanied by efforts to promote more efficient use of minerals, assess the resilience of supply chains, and encourage wider use of recycled materials, to be more effective.

Today’s recycling rates vary by metal depending on the ease of collection, price levels and market maturity



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Sources: Henckens (2021); UNEP (2011) for aluminium; Sverdrup and Ragnarsdottir (2016) for platinum and palladium; OECD (2019) for nickel and cobalt.

Scaling up recycling can bring significant security benefits, although the need for continued investment in primary supply remains

One of the major differences between oil and minerals lies in the way that they are used and recovered in the energy system. Unlike oil, which is combusted on an ongoing basis, minerals and metals are permanent materials that can be reused and recycled continuously with the right infrastructure and technologies in place. Compared with oil, this offers an additional lever to ensure reliable supplies of minerals by keeping them in circulation as long as possible.

The level of recycling is typically measured by two indicators. End-of-life (EOL) recycling rates measure the share of material in waste flows that is actually recycled. Recycling input rates (also called recycled content rates) assess the share of secondary sources in total supply. EOL recycling rates differ substantially by metal. Base metals used in large volumes such as copper, nickel and aluminium have achieved high EOL recycling rates (Henckens, 2021). Precious metals such as platinum, palladium and gold have also achieved higher rates of recycling due to very high global prices encouraging both collection and product recycling. Lithium, however, has almost no global recycling capabilities due in part to limited collection and technical constraints (e.g. lithium reactivity in thermodynamic and metallurgic recycling), with a similar picture for REEs. There are also regional variances: around 50% of total base metal production in the European Union is supplied via secondary production, using recycled

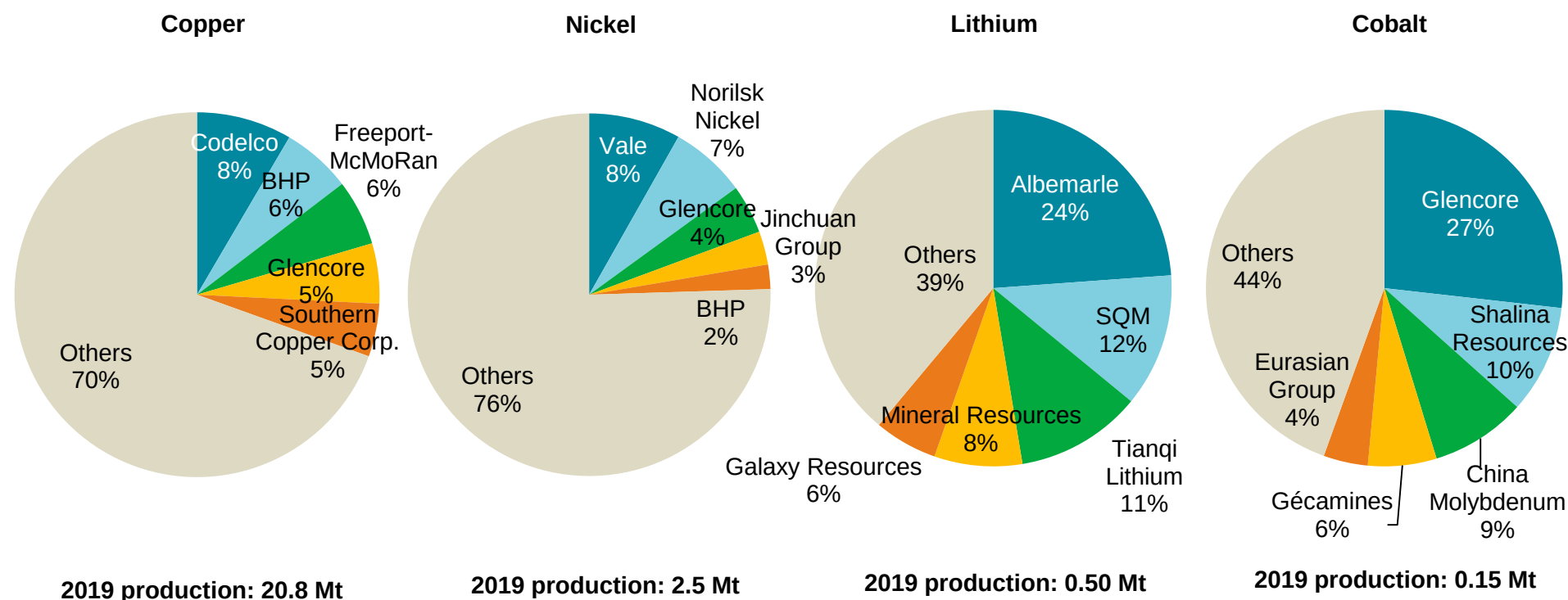
metals, as opposed to 18% in the rest of the world (Eurometaux, 2019).

Recycling does not eliminate the need for continued investment in primary supply of minerals. A World Bank study suggests that new investment in primary supply will still be needed even in the case that EOL recycling rates were to reach 100% by 2050. (World Bank, 2020). However, recycling can play an important role in relieving the burden on primary supply from virgin materials at a time when demand starts to surge. For example, the amount of spent EV batteries reaching the end of their first life is expected to grow exponentially after 2030 in the SDS, offering the potential to reduce the pressure on investment for primary supply (see Chapter 3).

Although various commercial and environmental challenges exist, the competitiveness of the recycling industry is set to improve over time with economies of scale and technology improvement as more players enter the field. Their relative advantages are likely to be further supported by potential upward pressure on production costs for virgin resources. Also, regions with greater deployment of clean energy technology stand to benefit from far greater economies of scale. This highlights the sizeable security benefit that recycling can bring to importing regions and underscores the need to incorporate a circular approach in the mineral security framework.

Companies that mine and process minerals have a major role to play in clean energy transitions

Major mining companies that produce selected energy transition minerals, 2019



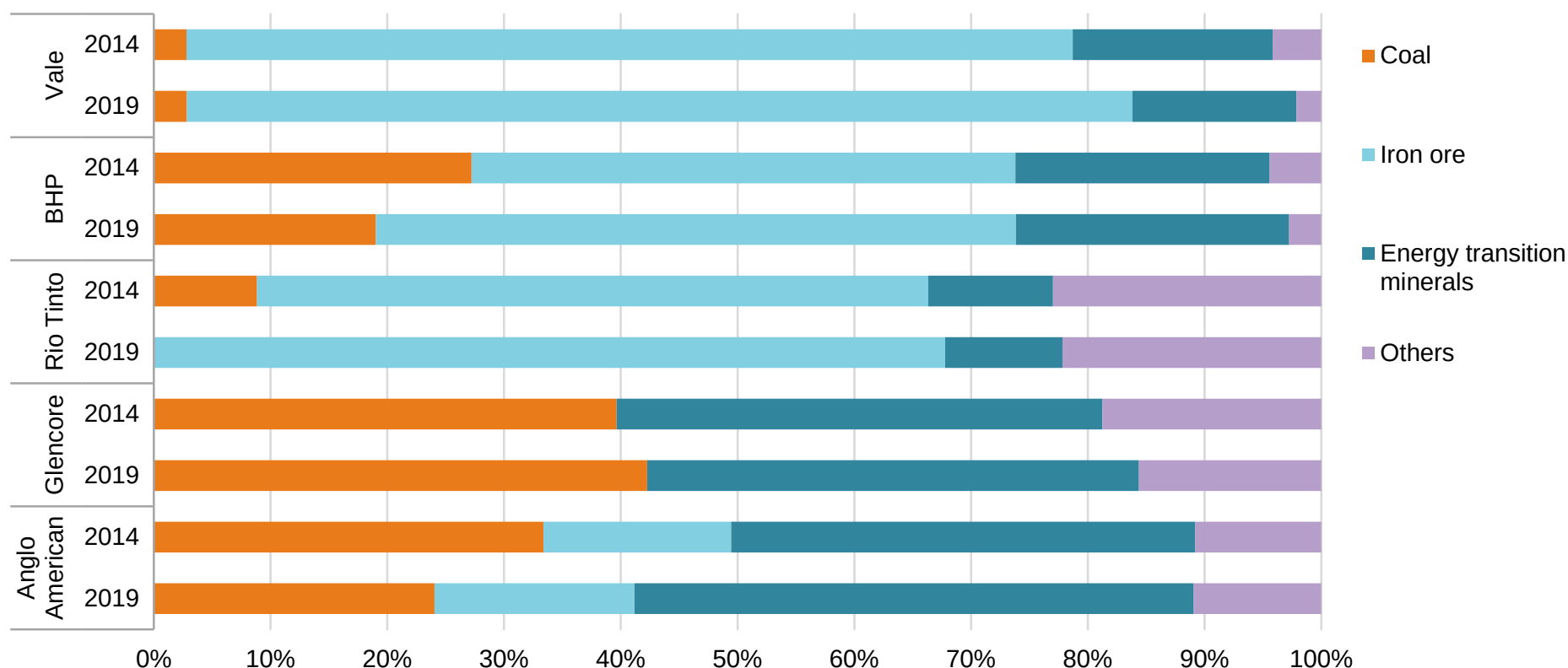
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Notes: Mt = million tonnes. Glencore's cobalt production volume includes output from Katanga Mining Ltd. Shalina Resources' cobalt production volume includes output of Chemaf. Lithium production volumes are denoted on a lithium carbonate-equivalent basis.

Source: S&P Global (2021).

Some mining majors have reduced coal exposure in recent years, although a decisive shift towards the minerals required for energy transitions is not yet visible

Production portfolio value of selected diversified major mining companies, 2014 and 2019

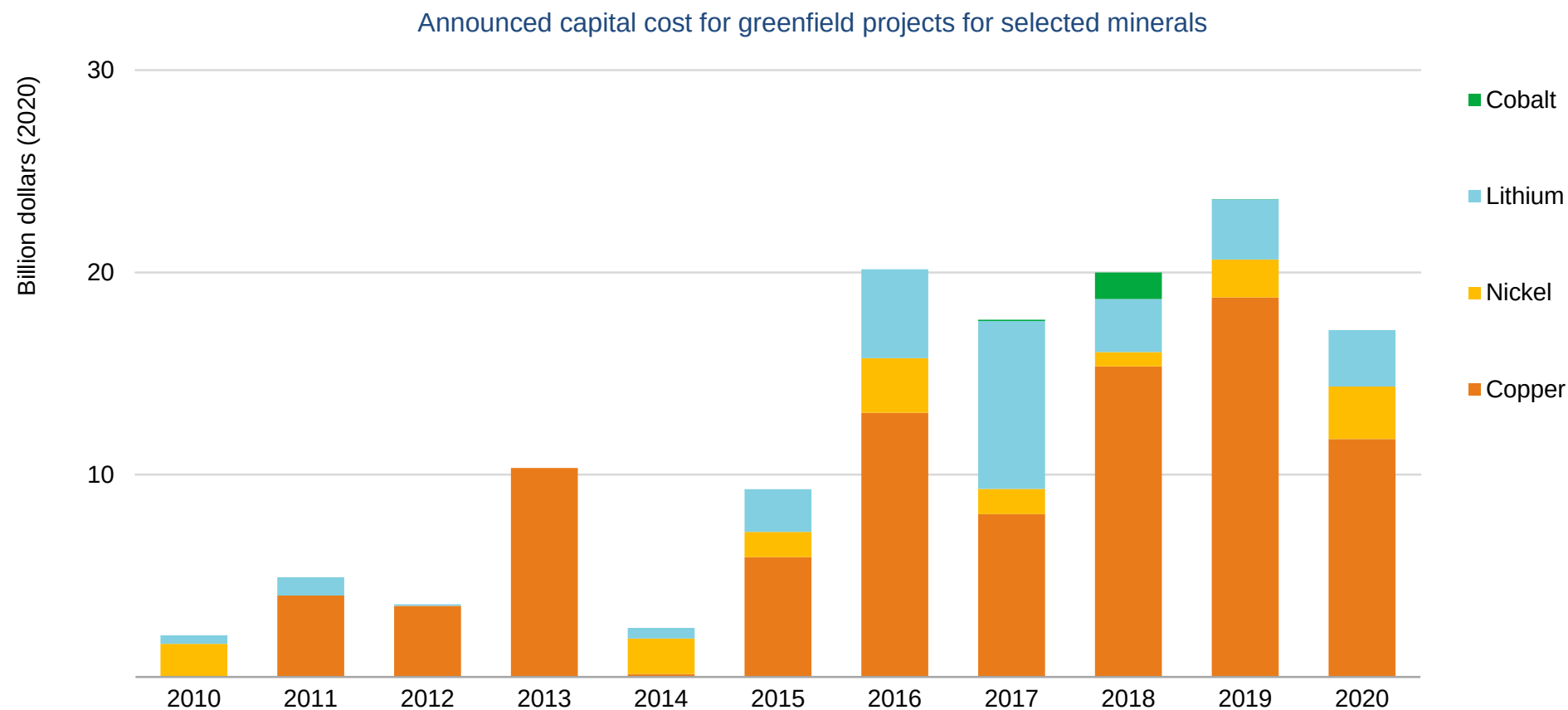


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Notes: Energy transition minerals include copper, lithium, nickel, cobalt, manganese, molybdenum and platinum-group metals. The value of the 2014 production portfolio was estimated using 2019 prices to remove price effects.

Source: IEA analysis based on companies' annual reports and S&P Global (2021).

Investment in new mineral supply projects has been on an upward path...



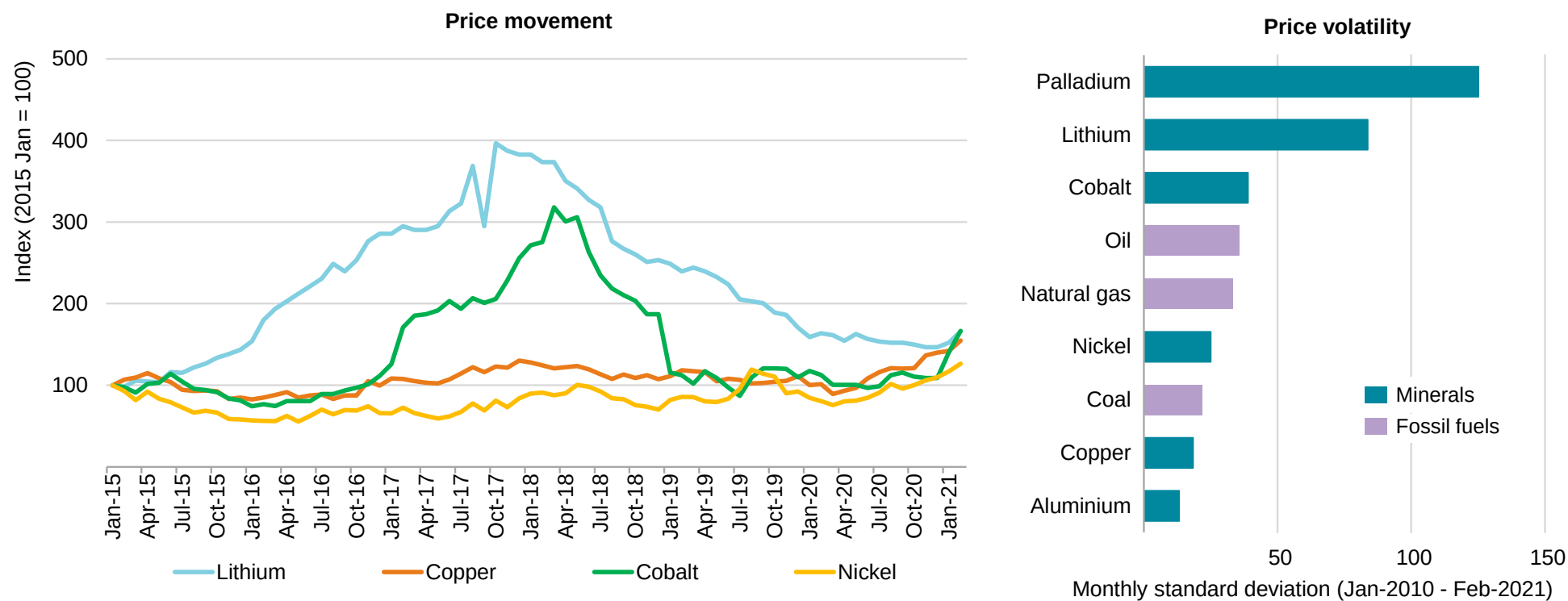
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Notes: Capital cost for cobalt includes only those projects whose primary commodity is cobalt. The figures do not include sustaining capital expenditure.

Source: S&P Global (2021).

...but continued investment is needed to manage new price cycles and volatility

Price movement and volatility of selected minerals



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Notes: Assessment based on Lithium Carbonate CIF Asia, LME Copper Grade A Cash, LME Cobalt Cash and LME Nickel Cash prices.
Source: IEA (2020a), S&P Global (2021).

Exploitation of mineral resources gives rise to a variety of environmental and social implications that must be carefully managed to ensure reliable supplies

Selected environmental and social challenges related to energy transition minerals

Areas of risks		Description
Environment	Climate change	<ul style="list-style-type: none"> With higher greenhouse gas emission intensities than bulk metals, production of energy transition minerals can be a significant source of emissions as demand rises Changing patterns of demand and types of resource targeted for development pose upward pressure
	Land use	<ul style="list-style-type: none"> Mining brings major changes in land cover that can have adverse impacts on biodiversity Changes in land use can result in the displacement of communities and the loss of habitats that are home to endangered species
	Water management	<ul style="list-style-type: none"> Mining and mineral processing require large volumes of water for their operations and pose contamination risks through acid mine drainage, wastewater discharge and the disposal of tailings Water scarcity is a major barrier to the development of mineral resources: around half of global lithium and copper production are concentrated in areas of high water stress
	Waste	<ul style="list-style-type: none"> Declining ore quality can lead to a major increase in mining waste (e.g. tailings, waste rocks); tailings dam failure can cause large-scale environmental disasters (e.g. Brumadinho dam collapse in Brazil) Mining and mineral processing generate hazardous waste (e.g. heavy metals, radioactive material)
Social	Governance	<ul style="list-style-type: none"> Mineral revenues in resource-rich countries have not always been used to support economic and industrial growth and are often diverted to finance armed conflict or for private gain Corruption and bribery pose major liability risks for companies
	Health and safety	<ul style="list-style-type: none"> Workers face poor working conditions and workplace hazards (e.g. accidents, exposure to toxic chemicals) Workers at artisanal and small-scale mine (ASM) sites often work in unstable underground mines without access to safety equipment
	Human rights	<ul style="list-style-type: none"> Mineral exploitation may lead to adverse impacts on the local population such as child or forced labour (e.g. children have been found to be present at about 30% of cobalt ASM sites in the DRC) Changes in the community associated with mining may also have an unequal impact on women

Clean energy transitions offer opportunities and challenges for companies

As the world moves from fuel-intensive systems to more material-intensive systems, companies that produce minerals and metals provide an essential bridge between resources in the ground and the energy technologies that consumers need. As such, there is large scope for mining and refining companies to contribute to orderly clean energy transitions by ensuring adequate supply of minerals. These projects will inevitably be subject to strong scrutiny of their social and environmental performance.

Many of the large mining companies are already involved in the energy sector, as producers of coal. Energy transitions therefore present a challenge, as well as an opportunity, as companies respond to rising stakeholder pressure to clarify the implications of energy transitions for their operations and business models. Some of these companies are already moving away from coal. Rio Tinto entirely exited the coal business in recent years and other companies are heading in a similar direction, largely through reducing thermal coal production. Although there has been growing participation in copper production in recent years, they have yet to make a concerted move into energy transition minerals.

Despite the prospects offered by energy transitions, until recently companies were quite cautious about committing significant capital to new projects; this is largely because of uncertainties over the timing and extent of demand growth (linked to questions about the

real commitment of countries to their climate ambitions) as well as the complexities involved in developing high-quality projects.

The picture is starting to change, as countries have sent stronger signals about their net-zero ambitions, and price signals for some minerals in 2017-2018 offered greater encouragement. Investment in new projects picked up in the latter part of the 2010s (although there was a Covid-induced fall in 2020). This trend would need to be sustained in order to support ample supply, although the risk of boom and bust cycles is ever-present for commodities that feature long lead-times from project planning to production (see Chapter 3).

Prices for minerals tend to be volatile, often more so than for traditional hydrocarbons, due to the mismatch between the pace of changes in demand patterns and that of new project development, and also to the opacity of supply chains. In the late 2010s, prices for minerals with relatively smaller markets – such as lithium and cobalt – recorded a dramatic increase in a short time as the adoption of EVs started to grow in earnest. Although prices have since dropped, as higher prices triggered a swathe of supply expansions (in the form of ASMs for cobalt), this has been a wake-up call about possible strains on supply and market balance. This provides additional reasons for policy makers to be vigilant about this critical aspect of a clean energy future.

Mineral requirements for clean energy transitions

Introduction

Minerals and metals¹ have played a critical role in the rise of many of the clean energy technologies that are widely used today – from wind turbines and solar panels to electric vehicles and battery storage. As the deployment of clean energy technology rises, the energy sector is also becoming a vital part of the minerals and metals industry. With clean energy transitions, the linkages between minerals and energy are set to strengthen.

However, this raises the question: will sufficient sustainable and responsibly sourced mineral supplies be available to support the acceleration of energy transitions? The first step to address this is to understand the potential requirements for minerals arising from clean energy transitions.

The type and volume of mineral needs vary widely across the spectrum of clean energy technologies, and even within a certain technology (e.g. wind turbine technologies; EV battery chemistries). In this chapter we assess the aggregate mineral demand from a wide range of clean energy technologies – low-carbon power generation (renewables and nuclear), electricity networks, electric vehicles (EVs), battery storage and hydrogen (electrolysers and fuel cells) –

under two main IEA scenarios: the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS).

For each of the clean energy technologies, we estimate overall mineral demand using four main variables: clean energy deployment trends under different scenarios; sub-technology shares within each technology area; mineral intensity of each sub-technology; and mineral intensity improvements.² The first two variables were taken from the projections in the *World Energy Outlook 2020*, complemented by the results in the *Energy Technology Perspectives 2020*.

We compiled the mineral intensity assumptions through extensive literature review, and expert and industry consultations, including with IEA [Technology Collaboration Programmes](#). The pace of mineral intensity improvements varies by scenario, with the STEPS generally seeing minimal improvement over time as compared to modest improvement (around 10% in the longer term) assumed in the SDS. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar photovoltaic [PV], platinum loading in fuel cells, rare earth element

¹ This report considers a wide range of minerals and metals used in clean energy technologies, including chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others (see Annex for the complete list). Steel and aluminium are not included in the scope for demand assessment, but

aluminium use in electricity networks is exceptionally assessed given that the outlook for copper is closely linked with aluminium use in grid lines (see Introduction).

² See Annex for methodologies and data sources.

[REE] use in wind turbines), we applied specific improvement rates based on the review of underlying drivers.

Projected mineral demand is subject to considerable uncertainty. It is highly dependent on the stringency of climate policies (reflected in the difference between the STEPS and SDS), but also on different technology development pathways. As such, in addition to our base assumptions for technology development pathways (“base case”) in both the STEPS and SDS, we identified key variables for each technology that could drive mineral demand in different directions. We then built 11 alternative cases under both scenarios to quantify the impacts of varying technology evolution trends.

Alternative technology evolution pathways explored

Technology	Alternative cases
Solar PV	<ul style="list-style-type: none"> • Comeback of high cadmium telluride • Faster adoption of perovskite solar cells • Wider adoption of gallium arsenide technology
Wind	<ul style="list-style-type: none"> • Constrained REE supply
Electricity networks	<ul style="list-style-type: none"> • Increased use of aluminium in underground cables • Wider adoption of direct-current systems

Technology	Alternative cases
EVs	<ul style="list-style-type: none"> • Delayed shift to nickel-rich cathodes • More rapid move towards a silicon-rich anode • Faster uptake of lithium metal anode all-solid-state batteries
Battery storage	<ul style="list-style-type: none"> • Rapid adoption of home energy storage • Early commercialisation of vanadium flow batteries

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While our report focuses on projecting mineral requirements for clean energy technologies, for the five focus minerals – copper, lithium, nickel, cobalt and neodymium (as a representative for REEs) – it also assesses demand from other sectors. This is to understand the contribution of clean energy technologies to overall demand and better assess supply-side challenges. We projected mineral demand for other sectors using historical consumption by end-use applications, relevant activity drivers (e.g. GDP, industry value added, vehicle activities, steel production) and material intensities (see Annex: Scope and methodology).

Mineral needs vary widely across clean energy technologies

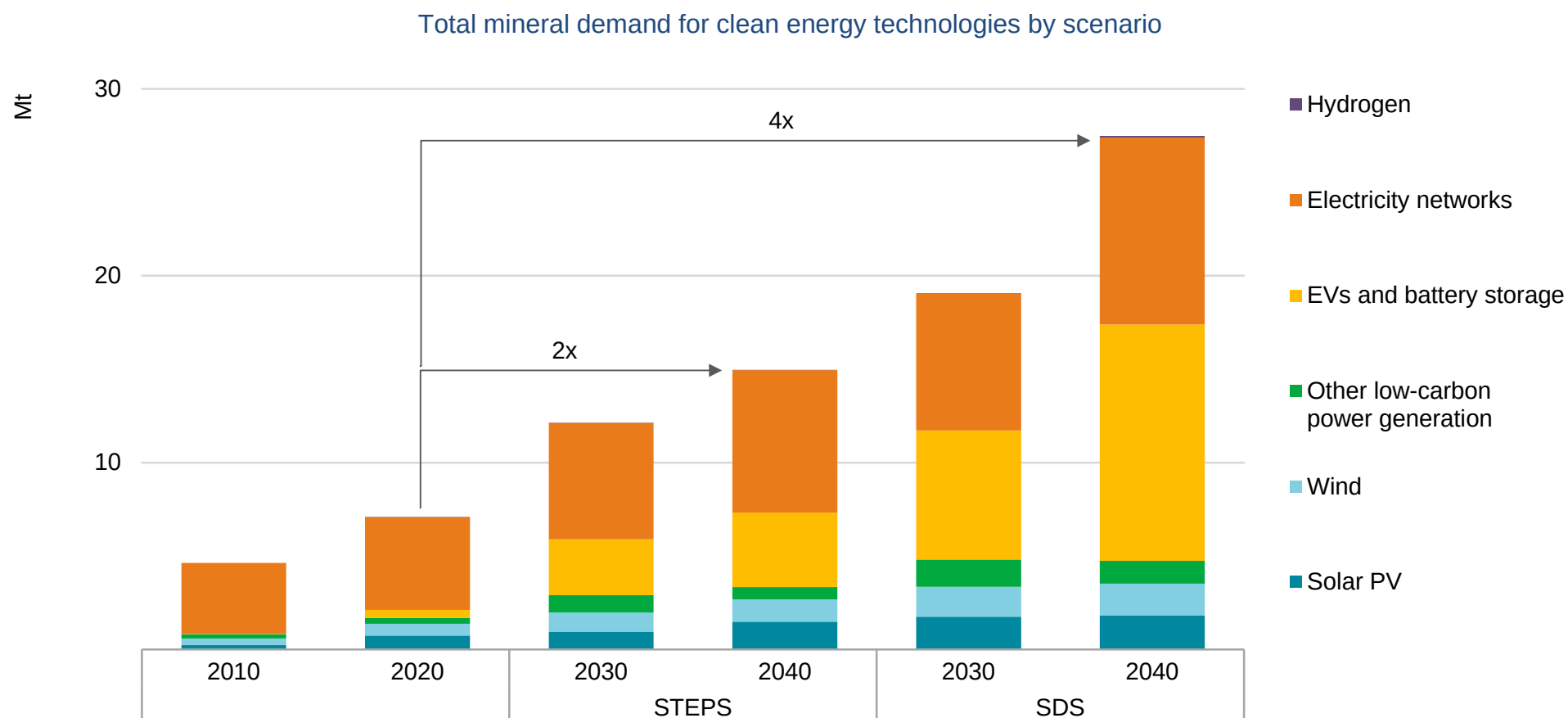
Critical mineral needs for clean energy technologies

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	●	○	●	●	●	○	●
Hydro	●	○	○	○	○	●	●	○	●
CSP	●	○	●	○	○	●	●	○	●
Bioenergy	●	○	○	○	○	○	●	○	●
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	●	○	●	○	○	●	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	●	○	○	●	●

Notes: Shading indicates the relative importance of minerals for a particular clean energy technology (● = high; ● = moderate; ○ = low), which are discussed in their respective sections in this chapter. CSP = concentrating solar power; PGM = platinum group metals.

* In this report, aluminium demand is assessed for electricity networks only and is not included in the aggregate demand projections.

Total mineral demand from clean energy technologies is set to double in the STEPS and quadruple in the SDS by 2040

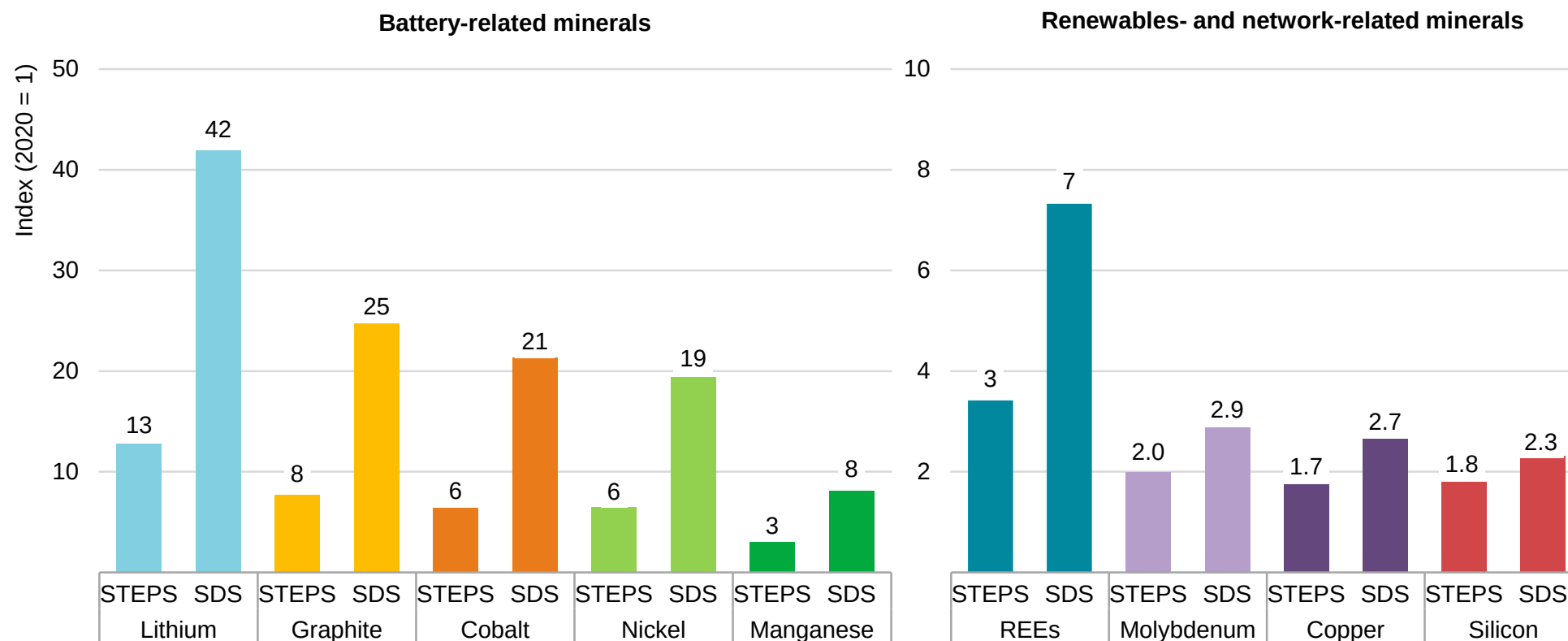


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Notes: Includes all minerals in the scope of this report, including chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, REEs and others, but does not include steel and aluminium (see Annex for a full list of minerals). Mt = million tonnes.

The relative demand growth is particularly high for battery-related minerals

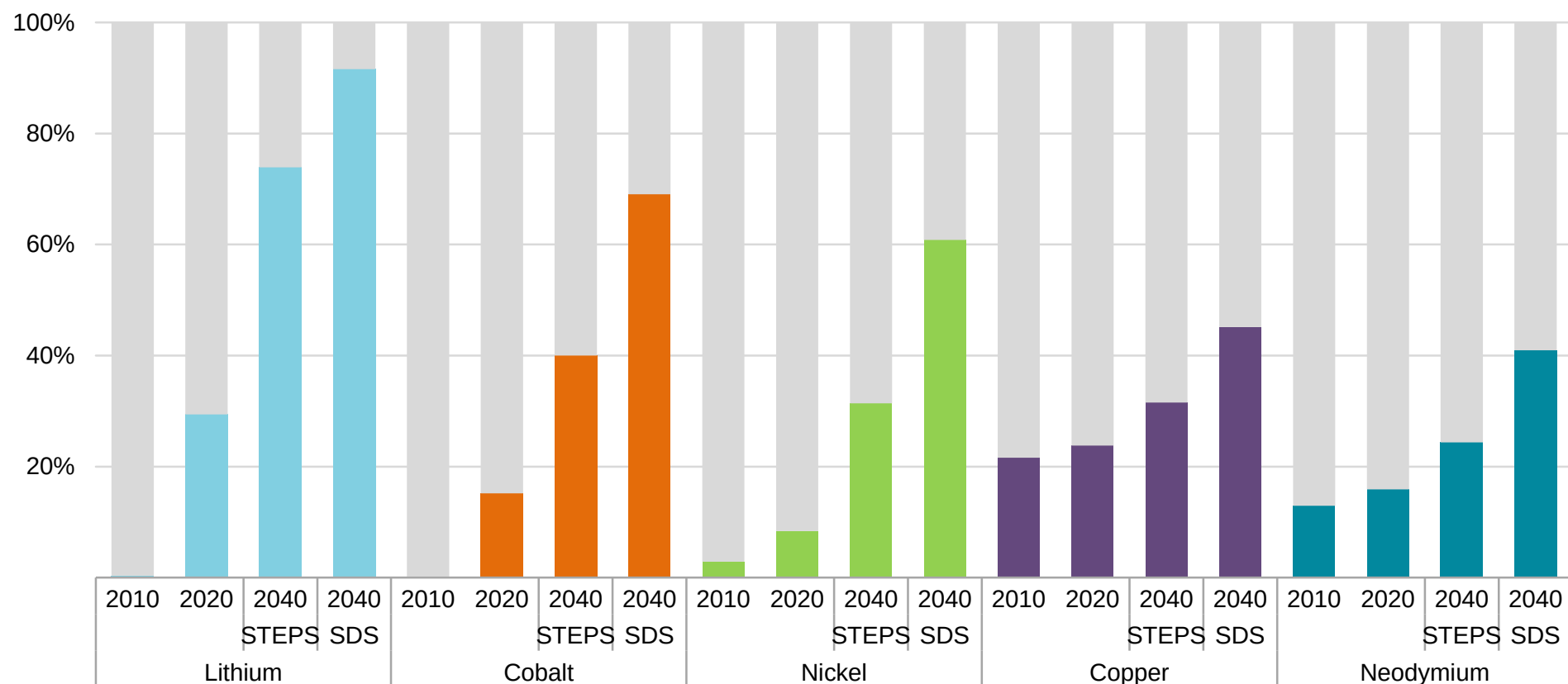
Growth in demand for selected minerals from clean energy technologies in 2040 relative to 2020 levels



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Clean energy technologies are set to emerge as a major force in driving demand growth for critical minerals

Share of clean energy technologies in total demand for selected minerals

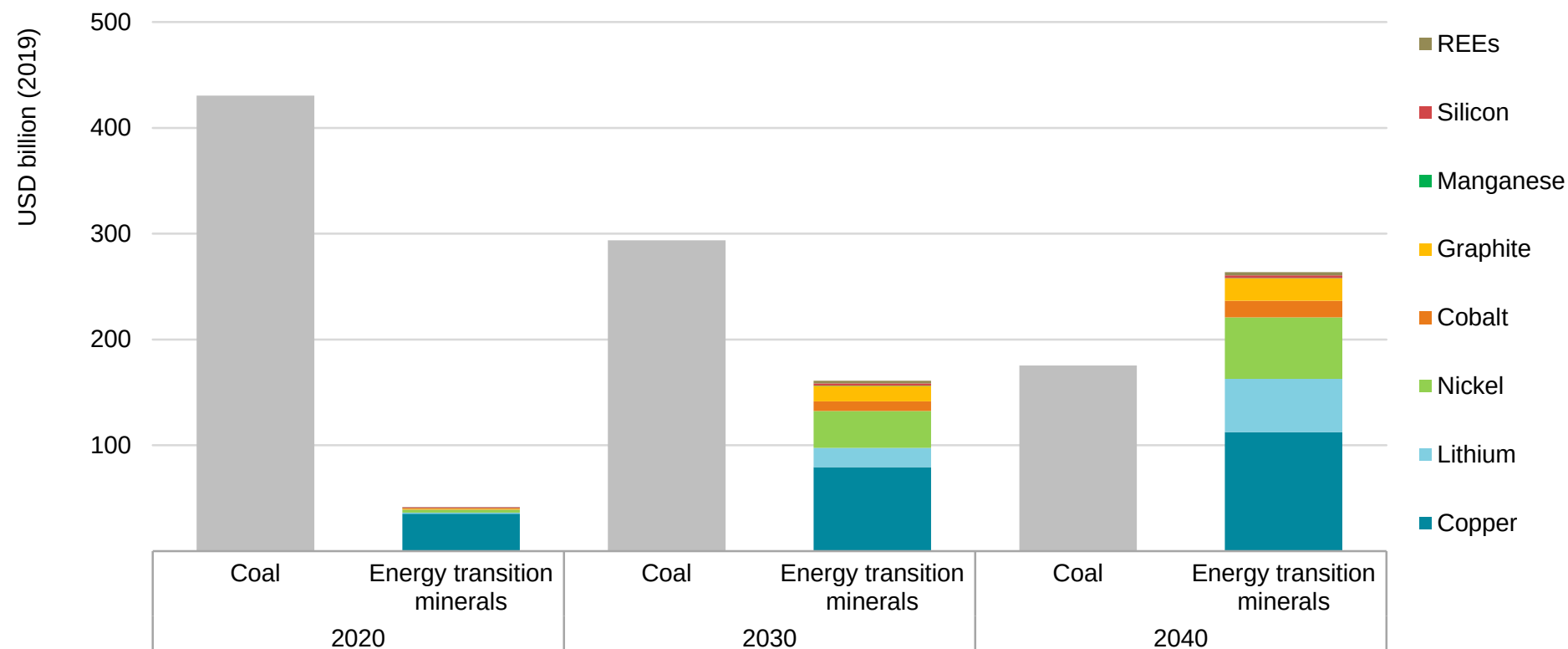


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Note: Demand from other sectors was assessed using historical consumption, relevant activity drivers and the derived material intensity.

Changing fortunes: Coal vs energy transition minerals

Revenue from production of coal and selected energy transition minerals in the SDS



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Notes: Revenue for energy transition minerals includes only the volume consumed in clean energy technologies, not total demand. Future prices for coal are projected equilibrium prices in *WEO 2020* SDS. Prices for energy transition minerals are based on conservative assumptions about future price trends (moderate growth of around 10-20% from today's levels).

Rising deployment of clean energy technologies is set to supercharge demand for critical minerals

The global clean energy transitions will have far-reaching consequences for mineral demand over the next 20 years. By 2040 total mineral demand from clean energy technologies double in the STEPS and quadruple in the SDS.

EVs and battery storage account for about half of the mineral demand growth from clean energy technologies over the next two decades, spurred by surging demand for battery materials. Mineral demand for use in EVs and battery storage grows nearly tenfold in the STEPS and around 30 times in the SDS over the period to 2040. By weight, mineral demand in 2040 is dominated by copper, graphite and nickel. Lithium sees the fastest growth rate, with demand growing by over 40 times in the SDS. The shift towards lower cobalt chemistries for batteries helps to limit growth in cobalt, displaced by growth in nickel.

Electricity networks are another major driving force. They account for 70% of today's mineral demand from the energy technologies considered in this study, although their share continues to fall as other technologies – most notably EVs and storage – register rapid growth.

Mineral demand from low-carbon power generation grows rapidly, doubling in the STEPS and nearly tripling in the SDS over the period to 2040. Wind power plays a leading role in driving demand growth due to a combination of large-scale capacity additions and higher

mineral intensity (especially with growing contributions from mineral-intensive offshore wind). Solar PV follows closely, with its unmatched scale of capacity additions among the low-carbon power generation technologies. Hydropower, biomass and nuclear make only minor contributions given their comparatively low mineral requirements and modest capacity additions.

The rapid growth of hydrogen use in the SDS underpins major growth in demand for nickel and zirconium for use in electrolyzers, and for copper and platinum-group metals for use in fuel cell electric vehicles (FCEVs). Despite the rapid rise in FCEVs and the decline in catalytic converters in gasoline and diesel cars, demand for platinum-group metals in internal combustion engine cars remains higher than in FCEVs in the SDS in 2040.

Demand for REEs – primarily for EV motors and wind turbines – grows threefold in the STEPS and around sevenfold in the SDS by 2040.

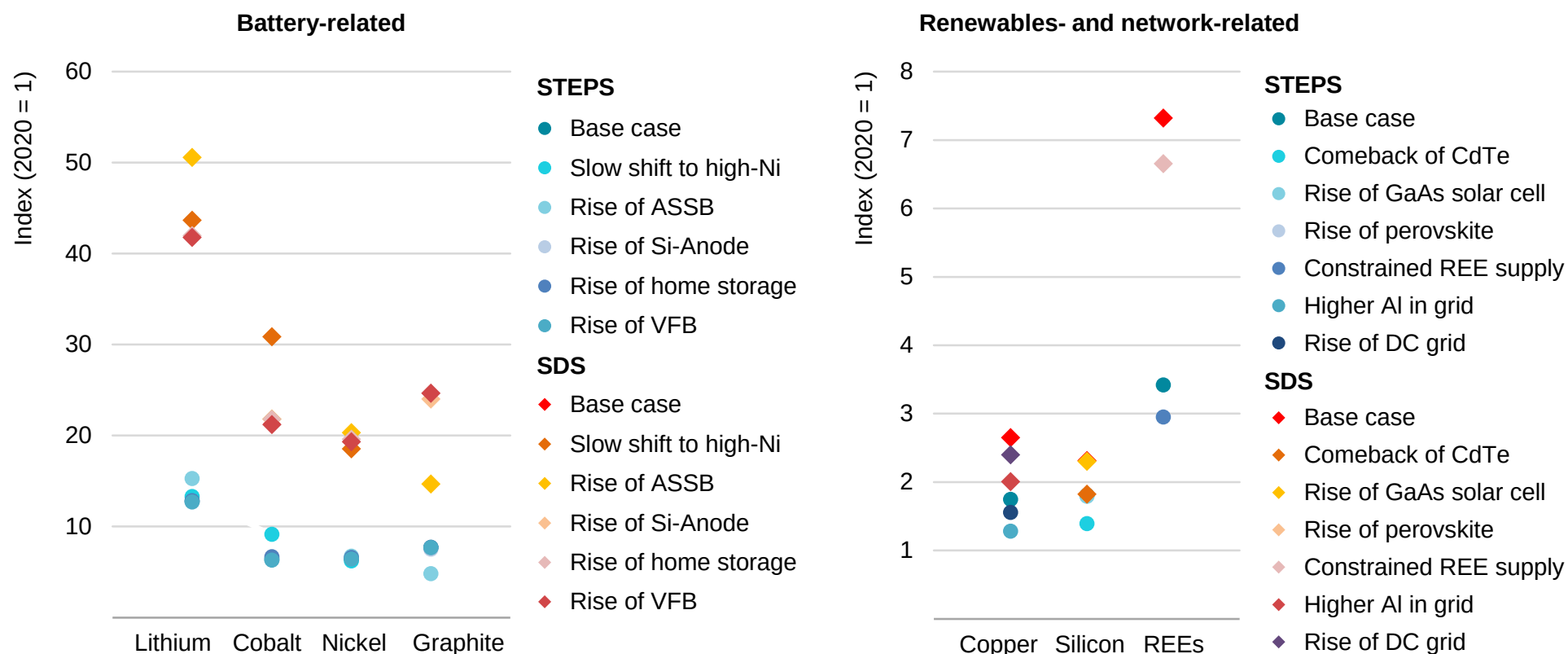
For most minerals, the share of clean energy technologies in total demand was minuscule until the mid-2010s, but the picture is rapidly changing. Energy transitions are already the major driving force for total demand growth for some minerals. Since 2015 EVs and battery storage have surpassed consumer electronics to become the largest

consumers of lithium, together accounting for 30% of total current demand. This trend is set to accelerate as countries step up their climate ambitions. Clean energy technologies become the fastest-growing segment of demand for most minerals, and their share of total demand edges up to over 40% for copper and REEs, 60-70% for nickel and cobalt and almost 90% for lithium by 2040 in the SDS.

Assessments based on total mineral weights often do not adequately account for the significance of certain minerals. It is also useful to consider the revenue generated from producing the minerals, as there is a wide range in monetary value between minerals. Coal is currently the largest source of revenue for mining companies by a wide margin. Revenues from coal production are about ten times larger than those from producing minerals used in clean energy technologies. However, accelerating clean energy transitions are set to change this picture radically. In the SDS, coal's stronghold on the energy system is increasingly challenged by phase-out policies in many countries and also by the rise of renewables. By contrast, many energy transition minerals are likely to face a tailwind from growing demand and upward pressure on prices. This underpins a sharp reversal of fortunes between coal and energy transition minerals. In the SDS, the combined revenue from energy transition minerals (including only the volume used in the clean energy sector) overtakes that of coal by 2040.

A wide range of futures are possible, mainly related to level of climate ambition and action, as well as technology uncertainties

Mineral demand from clean energy technologies in 2040 relative to 2020 under different scenarios and technology evolution trends



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Notes: Al = aluminium; ASSB = all-solid-state batteries; CdTe = cadmium telluride; DC = direct current; GaAs = gallium arsenide; Ni = nickel; Si = silicon; VFB = vanadium redox flow batteries.

Strong climate ambitions can reduce uncertainties around demand evolution, thereby stimulating investment and reducing security risks

Demand projections are subject to large variations, which lead to a wide range of possible futures. According to our analysis of the scenarios and alternative cases, lithium demand in 2040 may be 13 times higher (if vanadium redox flow batteries rapidly penetrate the market in the STEPS) or 51 times higher (if all-solid-state batteries commercialise faster than expected in the SDS) than today's levels. Likewise, cobalt and graphite may see 6- to 30-times higher demand than today depending on the scenario that unfolds. Among non-battery materials, demand for REEs grows by seven times in the SDS, but growth may be as low as three times today's levels should wind companies tilt more towards turbines that do not use permanent magnets in the STEPS context.

These large uncertainties around possible futures may act as a factor that hampers companies' investment decisions, which could in turn cause supply-demand imbalances in the years ahead. Despite the promise of massive demand growth, mining and processing companies may be reluctant to commit large-scale investment given the wide range of possible demand trajectories.

However, the biggest source of demand variance does not come from technology. It comes instead from the uncertainty surrounding

announced and expected climate ambitions – in other words, whether clean energy deployment and resulting mineral demand follows STEPS or SDS trajectories.

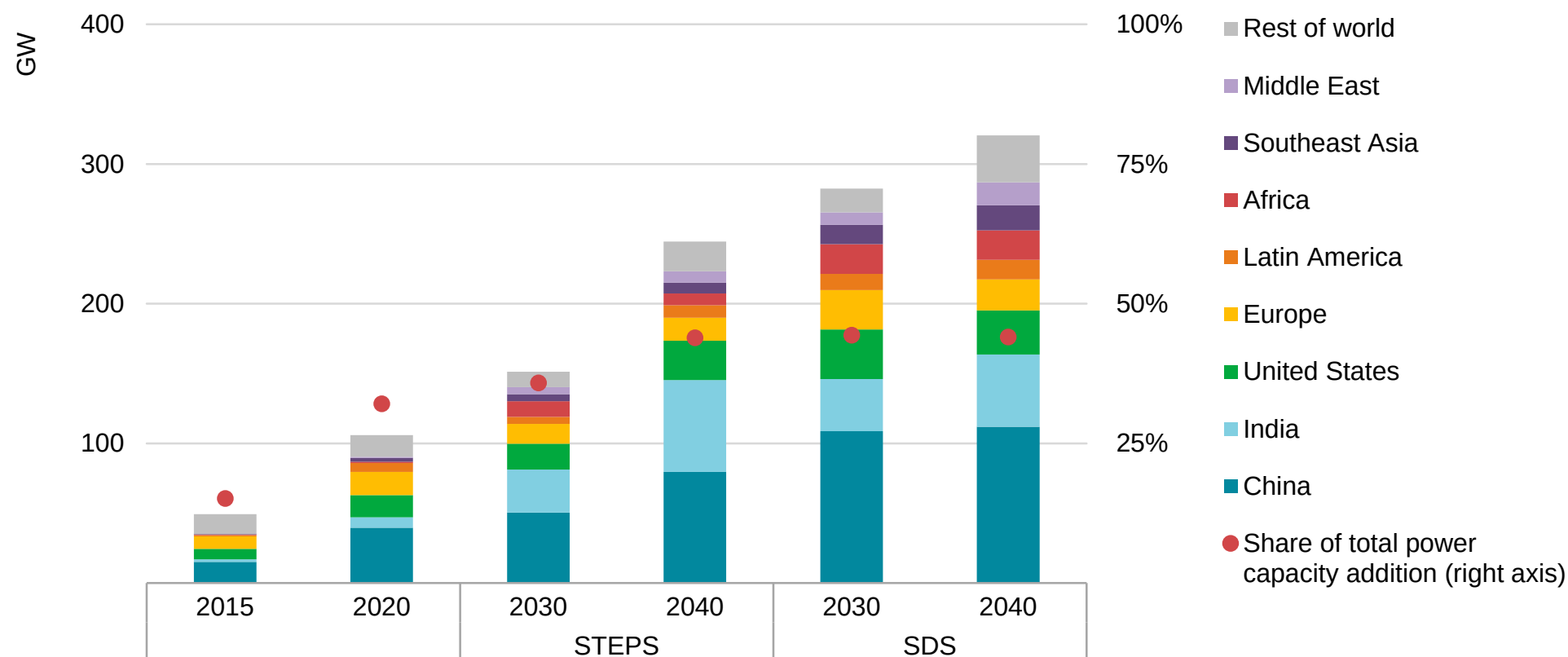
Here, governments have a key role to play in reducing uncertainty by sending strong and consistent signals about their climate ambitions and implementing specific policies to fulfil these long-term goals. The recent pickup in new project investments reflects the way that government climate commitments provide market signals for investments, which could help ensure reliable supply of minerals to support an orderly energy transition. The efforts also need to be accompanied by a range of measures to dampen the rapid growth in primary supply requirements such as promoting technology innovation for material efficiency or substitution, scaling up recycling and extending the lifetime of existing assets through better maintenance (see Chapter 3).

In the following sections we explore the mineral requirements for each clean energy technology under different scenarios and with varying trends in technology evolution.

Low-carbon power generation

Solar PV: Annual deployment of solar PV triples in the SDS by 2040, driven by huge growth in emerging economies

Annual solar PV capacity addition by region and scenario



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Note: GW = gigawatt. China = People's Republic of China.

Source: IEA (2020c).

Solar PV: Mineral use in solar PV varies widely by module type, currently dominated by crystalline silicon

Worldwide solar PV capacity has increased by almost 20 times over the past decade, spurred by declining costs and strong policy support in key regions (IEA, 2020c). With sharp cost reductions over the past decade, solar PV now offers some of the lowest levelised electricity costs in most countries, cheaper than new coal- or gas-fired power plants. In both the STEPS and SDS, solar sets new records for deployment each year after 2022, representing 45% of total power capacity additions by 2040. Innovation in solar PV technologies has also enabled remarkable advances in efficiency. For instance, the average module efficiency of commercial wafer-based silicon modules increased from about 12% to 17% in the past decade (Fraunhofer ISE, 2020), while cadmium telluride (CdTe) module efficiency doubled from 9% to 19%.

Solar PV plants are mainly composed of modules, inverters, trackers, mounting structures and general electrical components. For utility-scale solar PV plants, differences in mineral intensities come primarily from differences in module types. Crystalline silicon (c-Si) modules have become the dominant PV technology, followed by the “thin-film” alternatives: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si). By weight, c-Si PV panels typically contain about 5% silicon (solar cells), 1% copper (interconnectors), and less than 0.1% silver and other metals

(IRENA, 2016). Thin-film technologies require more glass but less minerals overall than c-Si. CdTe and CIGS panels use no silver or silicon, but instead require cadmium and tellurium (CdTe) or indium, gallium and selenium (CIGS). Distributed solar PV systems tend to have string inverters or microinverters, requiring about 40% more copper than utility-scale projects, which typically use central inverters. Other mineral intensities are similar between utility-scale and distributed applications.

Innovation in the manufacturing and design of c-Si panels over the past decade has contributed to large reductions in materials intensity. Since 2008 silicon intensity has more than halved as wafer thickness diminished substantially (Fraunhofer ISE, 2020), while silver intensity fell by 80% thanks to more efficient and less silver-intensive metallisation pastes (ITRPV, 2020).

Since silicon and silver are among the most expensive elements in solar PV cells, advances in material intensity are expected to continue, with further assumed reductions of around 25% and 30% in 2030 for silicon and silver respectively. The intensities of other minerals are also expected to decrease as overall efficiency improves, including through the use of new technologies such as bifacial, n-type or half-cut cells, multi busbars, dual-glass modules and string inverters.

Solar PV: Rapid deployment of solar PV in the SDS underpins more than doubling of mineral demand for solar PV by 2040 despite continued intensity reductions

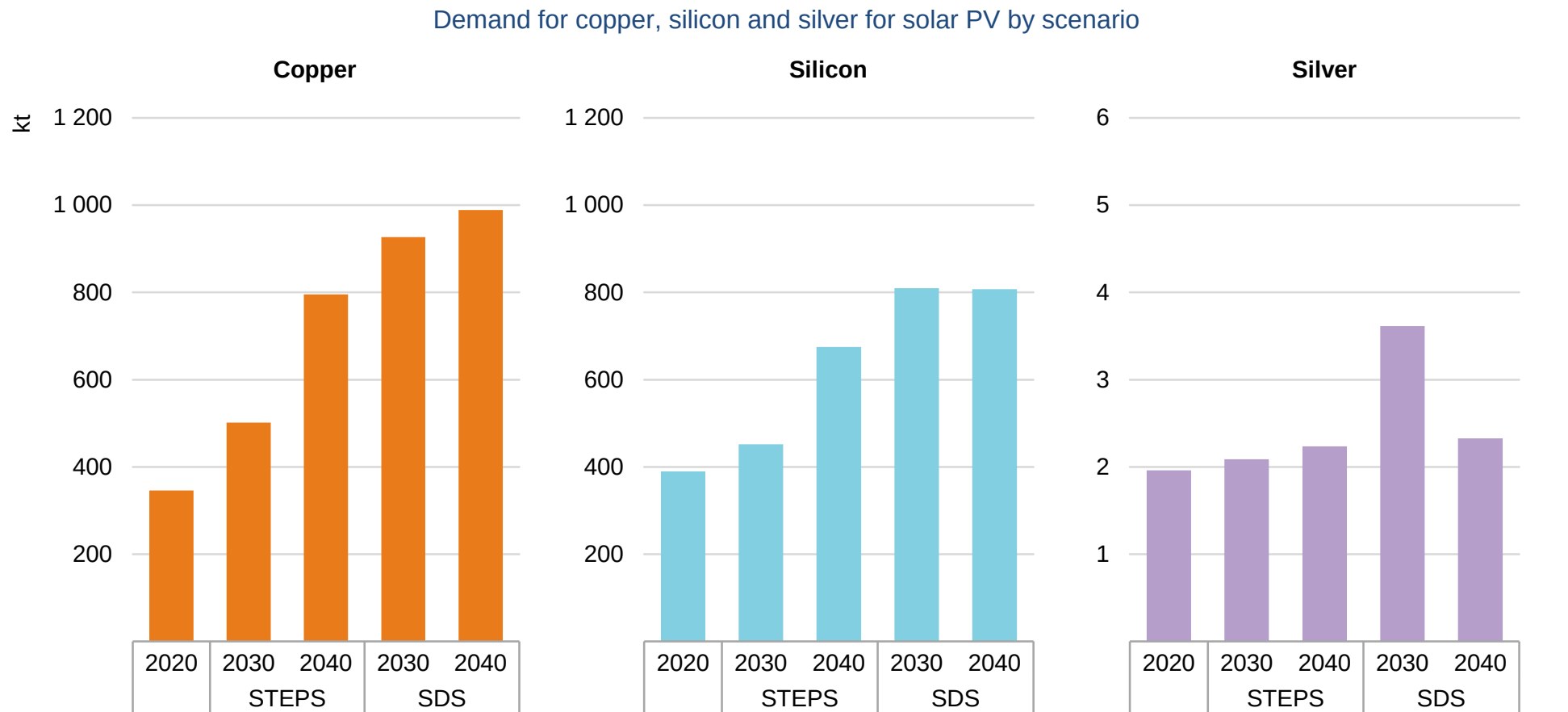
c-Si modules dominate the solar PV market, accounting for 95% of global solar PV capacity additions in 2020. They are expected to continue to dominate over the coming decades, as costs continue to decrease with further automation and larger, more durable cells. In addition, innovation is improving c-Si cell efficiency with the development of passivating contacts, the switch to n-type materials, and multi-junction/tandem solar cells, which helps cement c-Si's leading position. Silicon-based cells can also be combined with perovskite technologies with the aim of addressing their instability/lifetime issue and lowering the barriers to mass production of perovskite solar cells.

In our base case, thin film technologies remain niche over the coming decades, despite seeing further efficiency gains and cost reductions. Their use may be limited to applications where lower weight and/or greater flexibility is required, mostly in distributed and building applications.

In the SDS, capacity additions in 2040 are triple those of 2020, resulting in a near tripling of copper demand from solar PV. Material intensity reductions help to significantly dampen demand growth for silver and silicon. Despite higher annual capacity additions, demand for silver and silicon is lower in 2040 than in 2030, and only 18% and 45% higher than in 2020.

Capacity additions in 2040 in the STEPS are 25% lower than in the SDS. However, slower assumed improvements in material intensity for silver and silicon offset the lower capacity additions, resulting in similar demand for silver and silicon in the two scenarios.

Solar PV: Copper demand more than doubles by 2040, but continued innovation to reduce mineral intensity helps to offset demand growth for silicon and silver

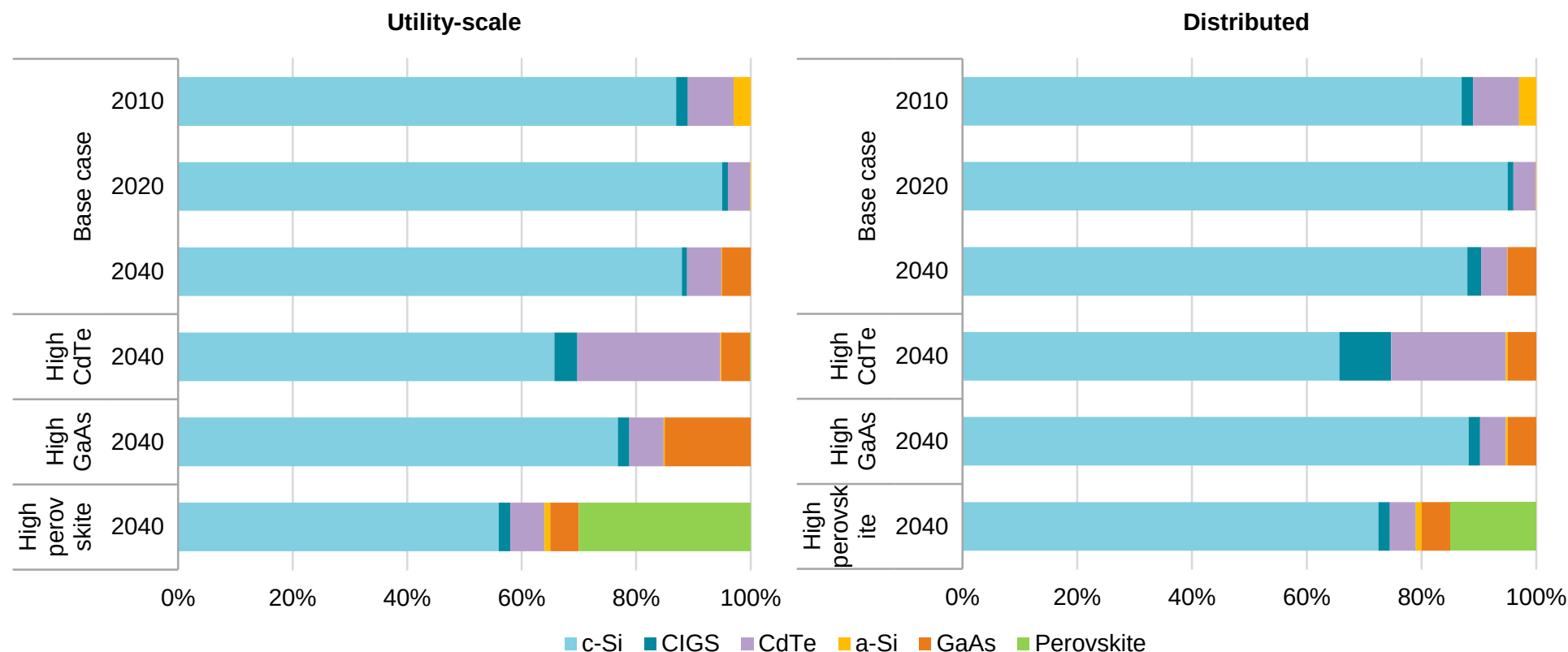


Note: kt = thousand tonnes.

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Solar PV: Crystalline silicon is expected to remain the dominant PV technology, but further progress on alternative technologies could see them taking significant market share by 2040

Share of annual capacity additions by PV technology under different technology evolution scenarios



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Notes: c-Si = crystalline silicon; CIGS = copper indium gallium diselenide; CdTe = cadmium telluride; a-Si = amorphous silicon; GaAs = gallium arsenide.

Solar PV: Demand for silicon falls in the alternative cases, but demand for other semiconductor materials rises

While c-Si modules are expected to continue to dominate the solar PV market, further progress on alternative technologies could see these technologies achieving growing market shares by 2040, which we explore in three alternative cases: high CdTe, high perovskite, and high GaAs.

High CdTe case

Further progress in CdTe technologies could lead to higher cell efficiency, longer lifetimes and reduced costs. The High CdTe scenario sees mass production of CdTe cells starting around 2030. The penetration of CdTe would be faster in distributed applications, where their lower weight and higher flexibility are an advantage.

In the High CdTe scenario, demand for cadmium and tellurium grows sevenfold by 2040 in the SDS to 1 300 tonnes and 1 400 tonnes respectively. This rapid growth would put pressure on supply capacities, which are currently around 23 000 tonnes for cadmium and 500 tonnes for tellurium (USGS, 2021).

High perovskite case

Perovskite solar cell technology has received a lot of research attention in the past decade as it holds the promise of much higher

efficiency levels, starting at around 9.7% in 2012 (Kim et al., 2012) and exceeding 25% today (NREL, 2019). However, in order to challenge the dominance of silicon in photovoltaics, perovskites will have to overcome significant technological hurdles. Most pure perovskite solar cells that have shown high efficiency are no larger than a fingernail and need to be scaled up enormously to match the output of commercial c-Si solar cells. The second major drawback for these cells is their stability. Perovskites are compounds that are highly soluble in water and even in the moisture in the air. This means that the perovskite layer thickness reduces rapidly within just an hour of exposure to ambient conditions even at a relatively low humidity of 40% (Shirayama et al., 2016). The final concern comes from the chemistry of the most frequently reported perovskite structure for solar cell applications (such as methylammonium lead triiodide or “MAPI”), which uses up to 10% lead by weight in pure perovskite solar cells (Saliba et al., 2018) and could hamper its adoption in certain jurisdictions. Alternative lead-free technologies are being studied, but are still far from reaching the record efficiencies synonymous with the lead-based counterparts (Zhao et al., 2017).

A pure perovskite solar cell does not contain silicon or most of the materials that are used in the fabrication of crystalline silicon solar cells. However, given the limitations of pure perovskite solar cells

described above, the easiest path to scale up and industrialise perovskite technology and circumvent many of its challenges is to combine it with the crystalline silicon technology (Nature Energy, 2020). This could be the fastest route to market for perovskites primarily because of the large market share held by silicon. Silicon solar cells have almost reached their physical efficiency limit in laboratory devices, but researchers at Oxford PV have demonstrated perovskite/silicon tandem solar cells that reach laboratory efficiencies of up to 28%, outperforming both perovskite and silicon single-junction devices (NREL, 2019).

In light of the constant development and strong research interest, this case assumes that perovskite/silicon tandem solar cell technology will capture 30% of the market for utility-scale PV and 15% for distributed PV by 2040. This would reduce silicon demand in 2040 by over 10%, while raising lead demand by around 45% compared to the base case in the SDS context.

High GaAs case

There are semiconducting materials whose physical and chemical characteristics make them much better candidates for solar cell technology than silicon. The III-V semiconductors such as GaAs, indium arsenide (InAs), gallium nitride (GaN) and indium phosphide, are a family of materials developed as binary compounds between elements from group 13 and group 15 of the periodic table. GaAs has the optimal bandgap energy for solar cell applications. It also has a

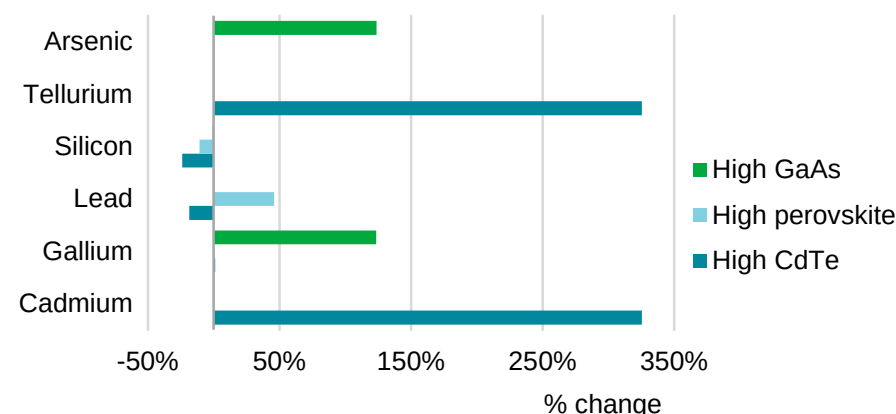
crystalline structure that makes it much more suitable for fabricating multi-junction solar cells by growing layers of different III-V crystalline materials on top of each other. The advantage of a multi-junction solar cell over a single-junction solar cell is that it allows the absorption of a wider range of the solar spectrum, thereby increasing the power conversion efficiency of the resulting solar cell. The research efficiency of GaAs-based multi-junction solar cells fabricated at the National Renewable Energy Laboratory (NREL) in the United States and Fraunhofer ISE in Germany is rapidly approaching 50%, making them the most efficient solar PV technology known to date (NREL, 2019). GaAs became the most commonly used material for photovoltaic arrays in satellites in the early 1990s and remains the preferred choice for aerospace applications. For terrestrial applications, GaAs-based multi-junction solar cells are most often employed in concentrator solar photovoltaic projects.

The main challenge to overcome for GaAs-based solar cells is the cost of raw materials and wafer manufacturing. It is reported that a wafer of GaAs is roughly 50 times more expensive than a wafer of c-Si of comparable size (Bleicher, 2010). This significant cost differential is what has prevented GaAs-based solar cells from entering the commercial solar PV market for terrestrial applications. However, latest developments indicate that this situation may not persist for long. In 2020 researchers at NREL reported a breakthrough in III-V cell technology that could significantly bring down costs (Willuhn, 2020). Recent studies (Horowitz et al., 2018)

suggest ample scope for major cost reductions via scaling up production volumes, reducing the cost of epitaxial crystal growth, lower substrate costs through recycling and lower metallisation costs. This could bring prices closer to c-Si within the next 10 to 15 years. Although direct competition with c-Si may not be possible, such cost reductions combined with advantages in weight, flexibility, energy density, temperature stability, radiation hardness etc. could make them attractive for use in very large terrestrial applications that cannot be served by silicon today.

Although GaAs represents a small share in the base case (5% in 2040), in the High GaAs case we assume a market share of 15% for utility-scale and 5% for distributed applications in 2040. Compared to the base case, this would add 8 kt of arsenic demand (25% of global production today), 3.5 kt of gallium (10 times more than high-purity refined gallium production today), and 0.1 kt of indium demand by 2040 in the SDS. This implies that scaling up the high GaAs technology needs to go hand in hand with efforts to recover more materials from a by-product stream of bauxite, zinc, copper and gold processing or via recycling.

Changes in mineral demand in alternative technology evolution cases in the SDS context

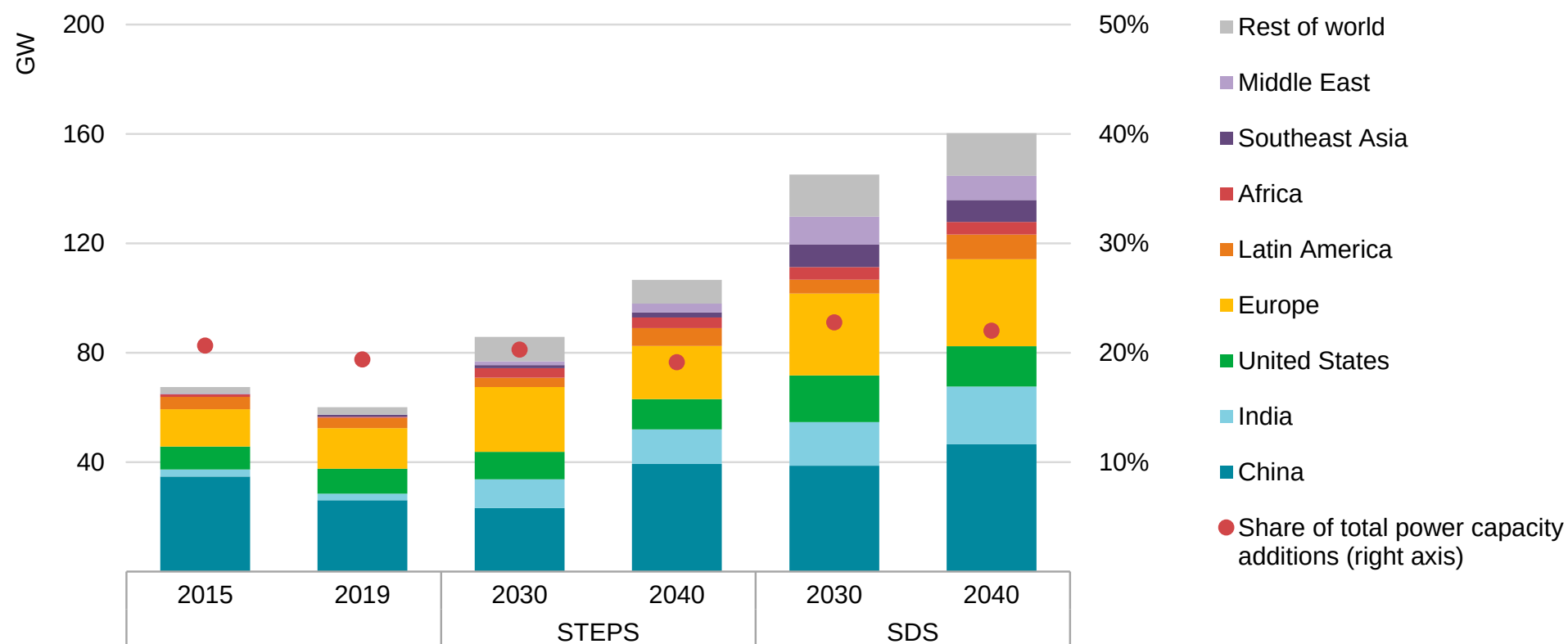


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Note: Relative change compared to the base technology evolution case in the SDS.

Wind: Wind deployment is expected to accelerate over the coming decades, thanks to falling costs, policy targets and increased investor confidence

Annual wind capacity addition by region and scenario



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Source: IEA (2020c).

Wind: Larger turbines – particularly offshore – help to accelerate annual capacity additions over the coming decades

Global installed capacity of wind power has nearly quadrupled over the past decade, spurred by falling costs, which have declined by about 40% on average globally, and policy support in more than 130 countries (IEA, 2020c). In both the STEPS and SDS, wind power is set for strong growth, with the offshore wind industry maturing and adding to developments in onshore wind on the back of technology improvements and low-cost financing. Annual capacity installations for wind in the SDS are expected to more than double by 2040 to 160 GW, representing more than a fifth of overall power capacity additions. Installations are currently concentrated in China, Europe and the United States, but the regional picture is set to become diverse with particularly strong growth in Southeast Asia, India, Latin America and the Middle East.

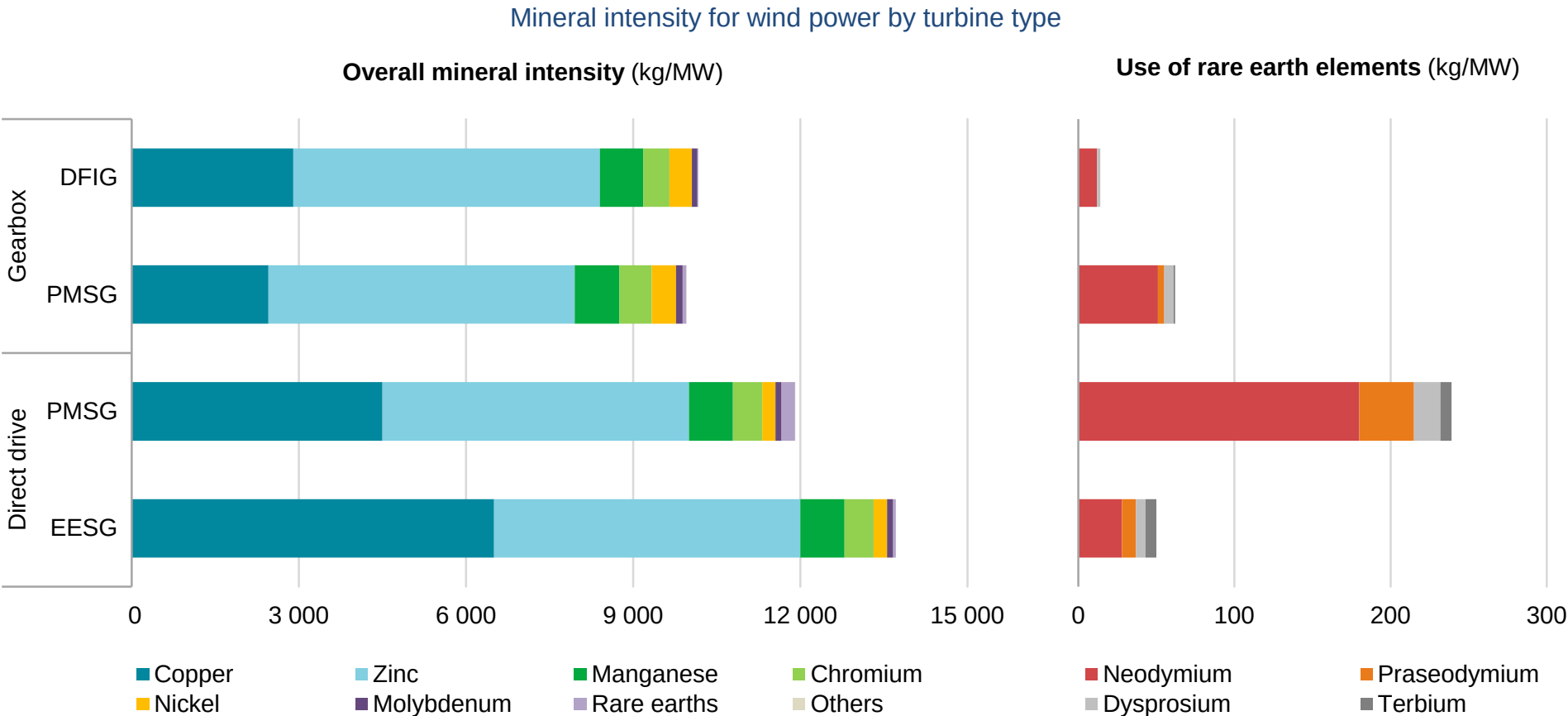
The share of offshore in total wind deployment is poised to grow considerably. Cost reductions and experience gained in Europe's North Sea are opening up huge opportunities in many parts of the world. Offshore wind offers higher capacity factors than onshore wind thanks to larger turbines that benefit from higher and more reliable wind speeds. There are further innovations on the horizon, such as floating turbines that can open up new resources and markets.

Turbine size has also grown considerably, from a global weighted average of 1.9 megawatts (MW) for onshore turbines installed in 2010 to 2.6 MW in 2018 (IRENA, 2019). Manufacturers are offering 5 MW onshore turbines in 2021. Turbine size has grown even more quickly in offshore wind, with an average rated capacity of 5.5 MW installed in 2018, compared with the newest turbine designs offering capacities of 10-14 MW. Even larger turbines are expected in the coming years, with promises of 20 MW turbines already on the horizon.

The growing size of turbines is an important contributor to the increase in capacity factor and the reduction in material use. Taller towers, larger rotors and lighter drivetrains have enabled higher capacity factors, which have risen from an average of 27% in 2010 for newly commissioned onshore projects to 34% in 2018.

These trends have also helped to reduce the material intensity for some materials in wind power. For example, on a kilogramme (kg) per MW basis, a 3.45 MW turbine contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine (Elia et al., 2020).

Wind: Mineral needs for wind power depend on the turbine type, with particularly high sensitivity for rare earth elements



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Notes: DFIG = double-fed induction generators; PMSG = permanent-magnet synchronous generator; EESG = electrically excited synchronous generator. The intensity numbers are based on the onshore installation environment. More copper is needed in offshore applications due to much longer cabling requirements. Sources: Carrara et al. (2020); Elia et al. (2020)

Wind: The growing market for turbines with permanent magnets – particularly for offshore projects – could dramatically increase rare earth demand over the coming decades

Wind turbines – which consist of a tower, a nacelle and rotors erected onto a foundation – require concrete, steel, iron, fibreglass, polymers, aluminium, copper, zinc and REEs.

Mineral intensities not only depend on the turbine size, but also on the turbine type. There are four main types of turbine: gearbox double-fed induction generator (GB-DFIG), gearbox permanent-magnet synchronous generator (GB-PMSG), direct-drive permanent-magnet synchronous generator (DD-PMSG) and direct-drive electrically excited synchronous generator (DD-EESG).

Turbines based on PMSGs require neodymium and dysprosium. DD-PMSGs generally contain larger amounts of REEs compared to GB-PMSGs for smaller overall size and lower weight and higher efficiency. Zinc is evenly used among turbine types as a protective coating against corrosion.

The onshore wind market is currently dominated by GB-DFIGs, accounting for more than 70% of the global market. DD-PMSGs have doubled their market share over the past 10 years from around 10% in 2010 to 20% in 2020. In the offshore sector, DD-PMSG turbines are the main choice, with around 60% of the market worldwide. Requiring taller and larger turbines, offshore wind sites generally opt for DD-PMSG configurations due to their lighter and more efficient

attributes as well as lower maintenance costs. In addition to REEs, copper intensity for offshore projects can be more than twice as high as onshore, with substantial copper usage in submarine collector and larger cables.

With increasing power per tower as turbines become taller and larger, lighter and more efficient configurations of PMSG technologies are becoming increasingly preferred. In the base case, PMSG technologies account for around 95% of the offshore market in 2040 and 40% of the onshore market.

In the SDS, demand for REEs in wind – neodymium and praseodymium in particular – is set to more than triple by 2040, driven by the doubling of annual capacity additions and a shift towards turbines with permanent magnets. Copper demand reaches 600 kt per year in 2040, propelled by offshore wind requiring greater cabling. Offshore wind accounts for nearly 40% of copper demand from wind despite accounting for only 20% of total wind capacity additions.

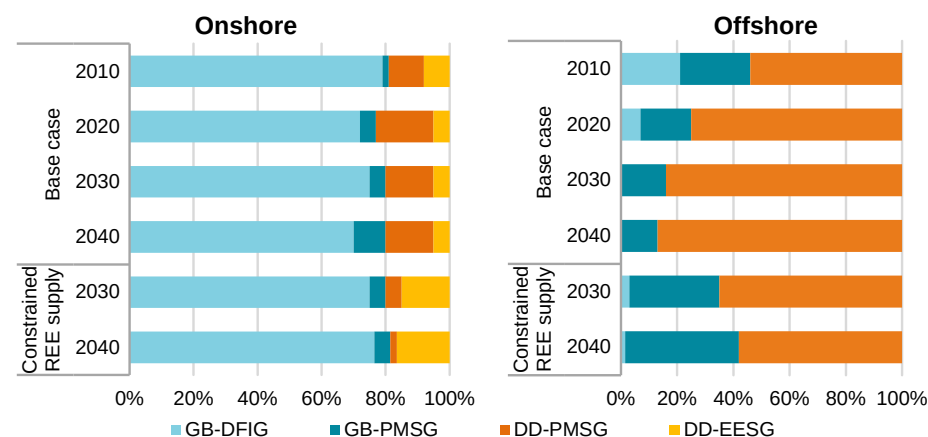
Constrained REE supply case

However, mounting demand for REEs from a variety of clean energy technologies such as wind and EVs, coupled with concerns around rising prices and geopolitical events, could lead to different technology choices. This is explored in the Constrained REE supply

case, which sees manufacturers gradually switching to non-magnet technologies and project developers adopting hybrid configurations with a gearbox and a smaller magnet. Onshore projects move towards DD-EESGs while, in offshore projects, DD-PMSGs cede some market share to technologies with lower REE use such as DD-EESGs. However, there would be no notable switch back to GB turbines given the technical fitness of DD turbines in the offshore environment and industry-wide efforts to reduce REE intensity in DD turbines.

In this case, neodymium demand in the SDS is contained to around 8 000 tonnes in 2030 and 40% lower in 2040 compared to the base case. Demand for praseodymium and dysprosium are 15% and 32% lower, respectively, compared to the base case in 2040.

Turbine shares for wind power capacity additions in the SDS

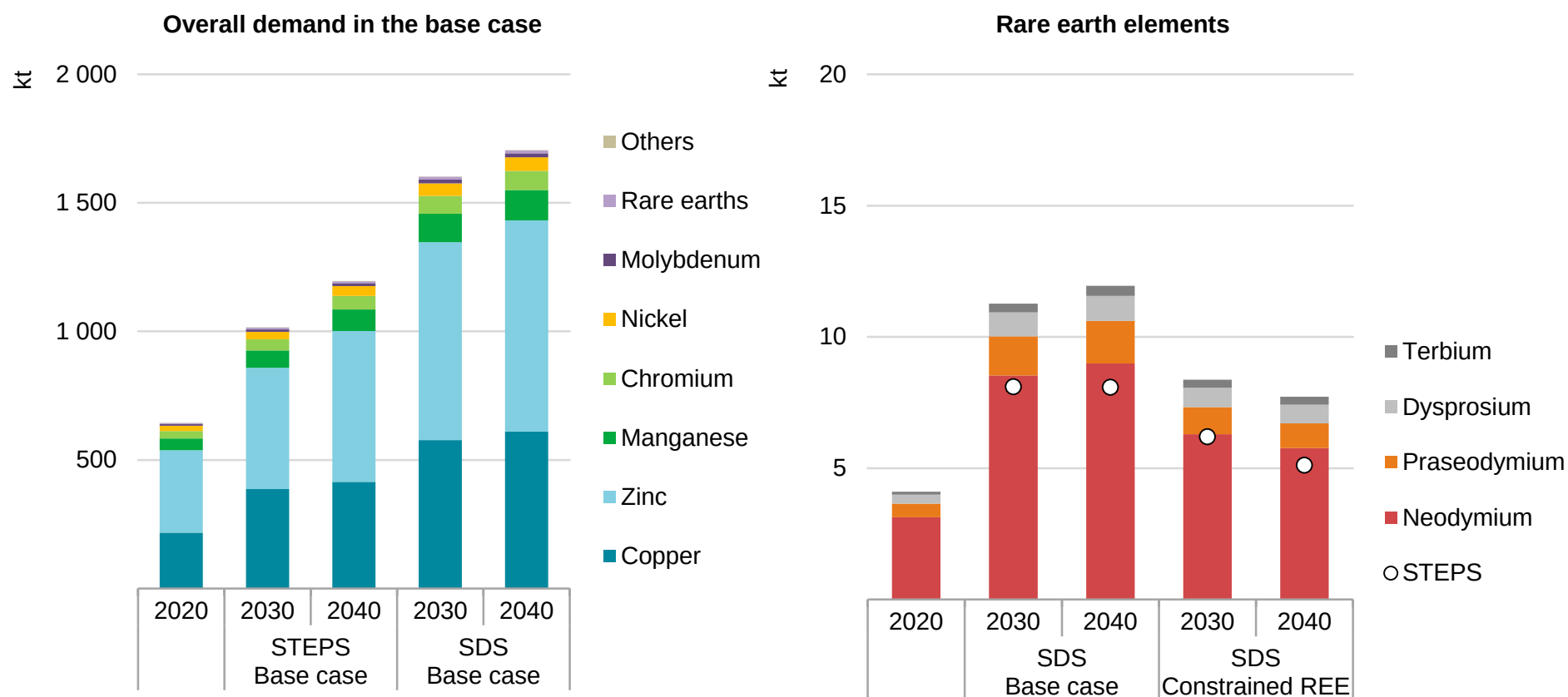


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Another option to reduce REE consumption in permanent magnets is to use a high-temperature superconductor (HTS). This offers potentially substantial reductions in mass and size, as they can achieve enormous current densities, but require extremely low temperatures and expensive cryostats. The technology is still at the R&D stage, with multiple designed prototypes and a sole 3 MW industrial-scale turbine developed so far. Despite promising results, HTS wind farms remain far from being competitive with existing wind technologies and we do not expect them to be a game changer in the next decade.

Wind: Demand for rare earths quadruples in the SDS by 2040, although the scale of growth may vary depending on the choice of turbine technologies

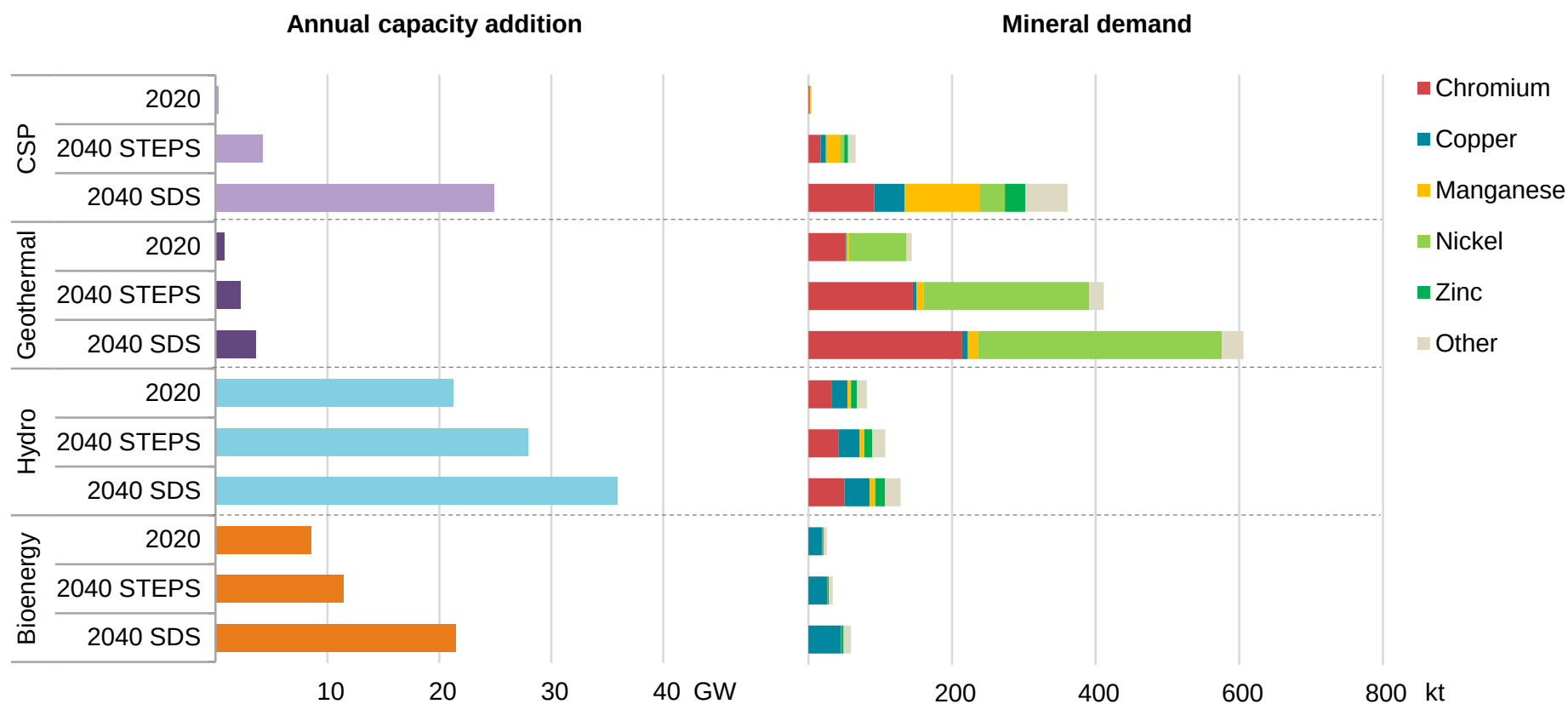
Mineral demand for wind by scenario



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Other renewables: Mineral demand from other renewables varies significantly depending on their mineral intensities

Annual capacity addition and mineral demand from other renewable technologies by scenario



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Note: CSP = concentrating solar power.

Concentrating solar power: Rapid growth in capacity additions comes with substantial demand for chromium, copper, manganese and nickel

Since 2010 policy and financing initiatives in Spain and the United States have helped to more than double the global installed capacity of CSP. However, overall installed capacity remains low at around 7 GW in 2020 owing to limited suitable geographies, high project costs and long distances to demand centres. In the SDS, installed capacity grows by nearly 40 times between 2020 and 2040 – albeit from a low base – driven by growth in the Middle East, Africa and Asia Pacific.

CSP systems use mirrors to direct solar radiance to a central receiver where energy is transmitted to a heat-exchange fluid used to generate electricity. Two main types of CSP technology – parabolic troughs and central towers – account for most of the installed, planned and projected additions. Parabolic trough systems direct solar radiance to a tube containing a heat-exchange fluid running along the length of a parabolic mirror. Central tower systems very closely track the movement of the sun reflecting and directing solar radiance to a centralised receiver tower containing a heat-exchange fluid.

Central tower systems generally require more materials than parabolic trough systems, including eight times more manganese, four times more nickel, and twice as much silver. However, parabolic trough systems require more than twice as much copper.

Parabolic troughs accounted for over 80% of CSP capacity additions in 2010, but their share has been steadily declining, ceding market share to central tower systems, which have higher efficiency and greater storage capacity (IEA, 2020c). Central towers accounted for around 60% of CSP capacity additions in 2020, and their share is expected to grow to 75% by 2040 in the SDS.

The expansion of CSP, driven by material-intensive central tower systems, comes with substantial demand growth for chromium, copper, manganese and nickel. Between 2020 and 2040 in the SDS, chromium demand from CSP grows by 75 times (to 91 kt), copper demand grows by 67 times (to 42 kt), manganese demand grows 92-fold (to 105 kt), and nickel demand grows 89-fold (to 35 kt).

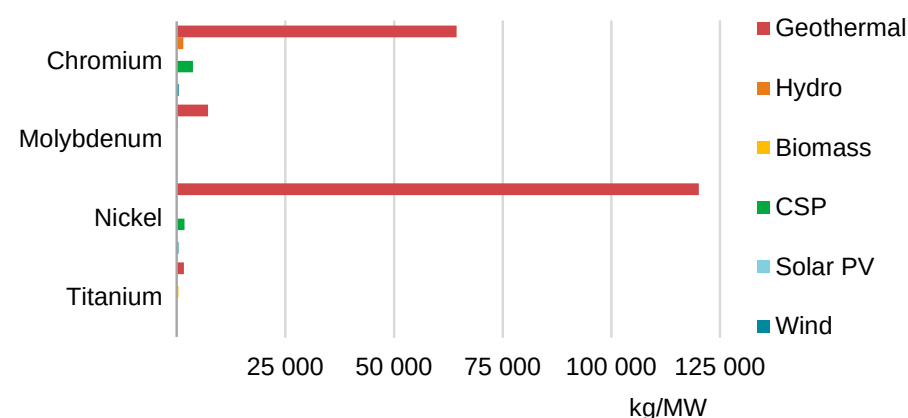
Geothermal: A key driver for growing nickel, chromium, molybdenum and titanium demand from low-carbon power technologies

Around 16 GW of geothermal capacity are currently installed, providing low-carbon baseload power in geo-hotspots such as Kenya, Iceland, Indonesia, the Philippines, Turkey and the United States. In the SDS, installed capacity grows fivefold to 82 GW by 2040.

Geothermal power plants generate electricity by powering turbines using underground hydrothermal resources (steam or hot water) piped to the surface. The very high temperatures and potentially corrosive nature of geothermal reservoirs require the use of specialised steel (high in chromium, molybdenum, nickel and titanium) in order to withstand the harsh operating environment.

In the SDS, mineral demand from geothermal more than quadruples between 2020 and 2040. Despite accounting for less than 1% of all low-carbon power capacity additions in 2040, geothermal power is a major source of demand for nickel, chromium, molybdenum and titanium from the power sector. Of the total mineral demand from all low-carbon power sources in 2040, geothermal accounts for three-quarters of nickel demand, nearly half of the total chromium and molybdenum demand, and 40% of titanium demand.

Mineral intensity of key minerals in geothermal in 2019



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Notes: CSP mineral intensity is for central tower systems; solar PV mineral intensity is for utility-scale cSi; wind mineral intensity is for onshore GB-DFIG.

In addition to power, geothermal resources can provide heating and cooling services. However, ground-source heat pumps require relatively minimal steel and instead rely on plastic piping, with some systems relying high-conduction copper for heat exchange.

Hydropower and bioenergy: Limited impacts on mineral demand due to low material intensity

Hydropower is the largest renewable source of electricity, accounting for 17% of global electricity generation in 2020. While it plays an important role in providing flexibility to the power system, its share of total power capacity additions continues to decline in the SDS through to 2040, as high capital costs and geographic constraints limit further growth.

In the SDS, hydropower capacity additions in 2040 are only 70% higher than in 2020, representing the lowest relative growth among all renewable sources. Between 2020 and 2040, nearly 60% of cumulative capacity additions occur in Asia Pacific, with China alone accounting for a quarter of the global total.

While hydropower uses substantially more cement and concrete than any other generation technology, it has a relatively low mineral intensity compared to other sources of low-carbon power. Hydropower does not use REEs, and its current use of copper (1 050 kg/MW), manganese (200 kg/MW) and nickel (30 kg/MW) are among the lowest of all low-carbon sources (Ashby, 2013). Hydropower accounts for 2% and 11% of the total demand for copper and chromium respectively from all low-carbon power capacity additions in 2040 in the SDS.

Bioenergy is a major source of renewable power today, generating as much electricity as solar PV in 2019. In the SDS, annual

generation triples by 2040 to 2 150 terawatt hours (TWh), with total installed capacity rising to 420 GW. China, the United States, Russia and India account for over half of the cumulative capacity additions to 2040.

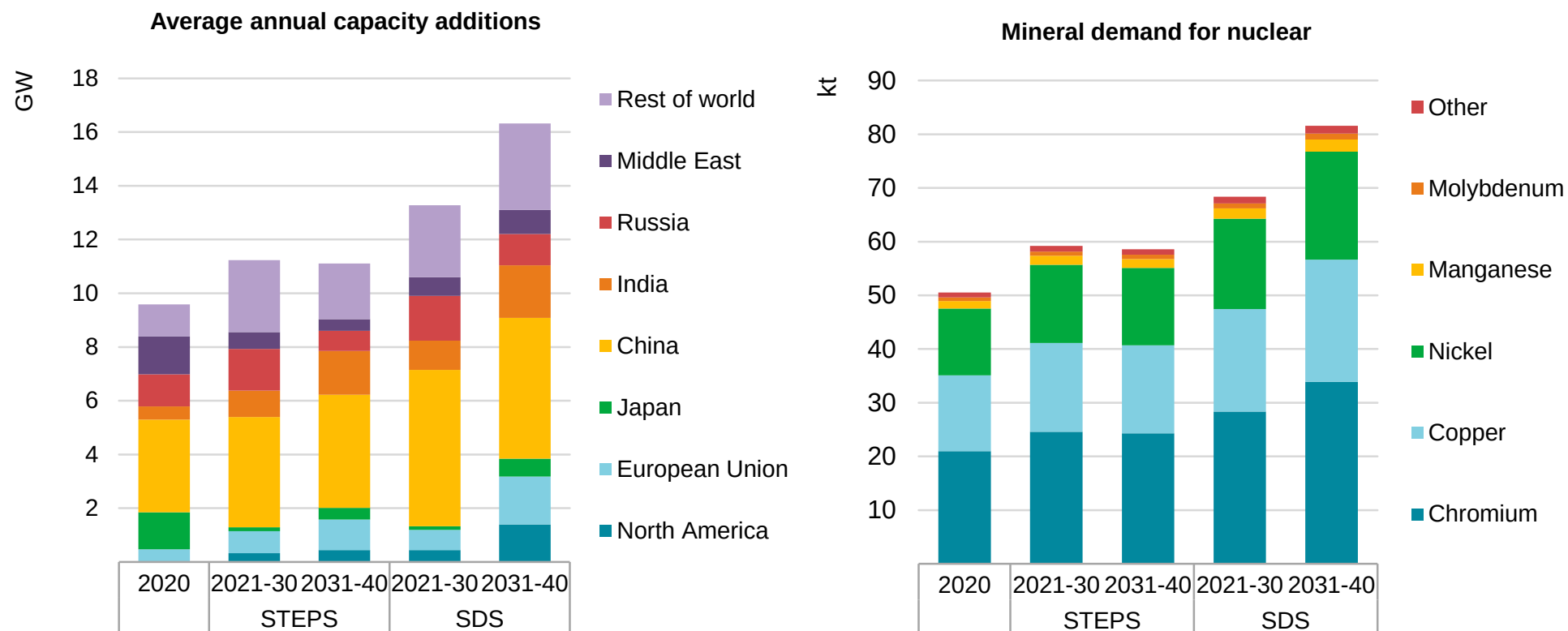
Mineral demand from bioenergy comes mostly from copper (2 270 kg/MW in 2019), which is similar to that of most other renewable generation technologies (Ashby, 2013). While the exact design of bioenergy boilers is different, overall mineral requirements are similar to those of coal and gas-fired power generation. However, bioenergy demands significant levels of titanium (400 kg/MW), which is higher than all other generation technologies except geothermal.

In the SDS, overall mineral demand from bioenergy more than doubles by 2040 compared to 2020, with copper accounting for more than three-quarters of the total. However, copper demand from bioenergy only accounts for 2.5% of the total copper demand from all low-carbon power sources in 2040. Conversely, titanium demand from bioenergy accounts for nearly 60% of all titanium demand from low-carbon power in 2040.

Overall, combined with their modest capacity growth, hydropower and bioenergy are unlikely to face any significant supply constraints for minerals.

Nuclear: Modest growth in mineral demand from nuclear power

Average annual capacity additions and mineral demand from nuclear power



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Note: Russia = Russian Federation.

Nuclear: Limited implications for minerals due to low material intensity

Nuclear power is the second-largest source of low-carbon power behind hydropower, accounting for about 10% of global electricity generation in 2020. Global installed capacity of nuclear power grows modestly to 2040 (by 15% in the STEPS and 45% in the SDS compared to 2020), as capacity declines in North America and Europe are offset by growth in emerging economies.

China is on track to become the leader in nuclear power around 2030, overtaking the United States and the European Union, more than doubling its current capacity to around 110 GW in the SDS. Significant programmes underway in India and the Middle East also contribute to the expansion of nuclear power. Capacity additions in 2020 were around 10 GW, and increase to an average of 11 GW in the STEPS and 16 GW in the SDS between 2031 and 2040.

Along with hydropower, nuclear is one of the low-carbon technologies with the lowest mineral intensity. Key mineral needs include chromium (2 190 kg/MW in 2019), copper (1 470 kg/MW), nickel (1 300 kg/MW), hafnium (0.5 kg/MW) and yttrium (0.5 kg/MW) (EC JRC, 2011). Uranium is not within the scope of our analysis, as this report focuses on mineral requirements for production of equipment, and not for operations. Around 16% of the worldwide supply of hafnium is currently used for nuclear reactor applications (EC JRC, 2011). However, the mineral intensity of chromium and nickel are

highly sensitive to the use of high-alloy steel in nuclear power plants. Quantities of high-alloyed, low-alloyed and unalloyed steel used in a nuclear power plant are seldom reported.

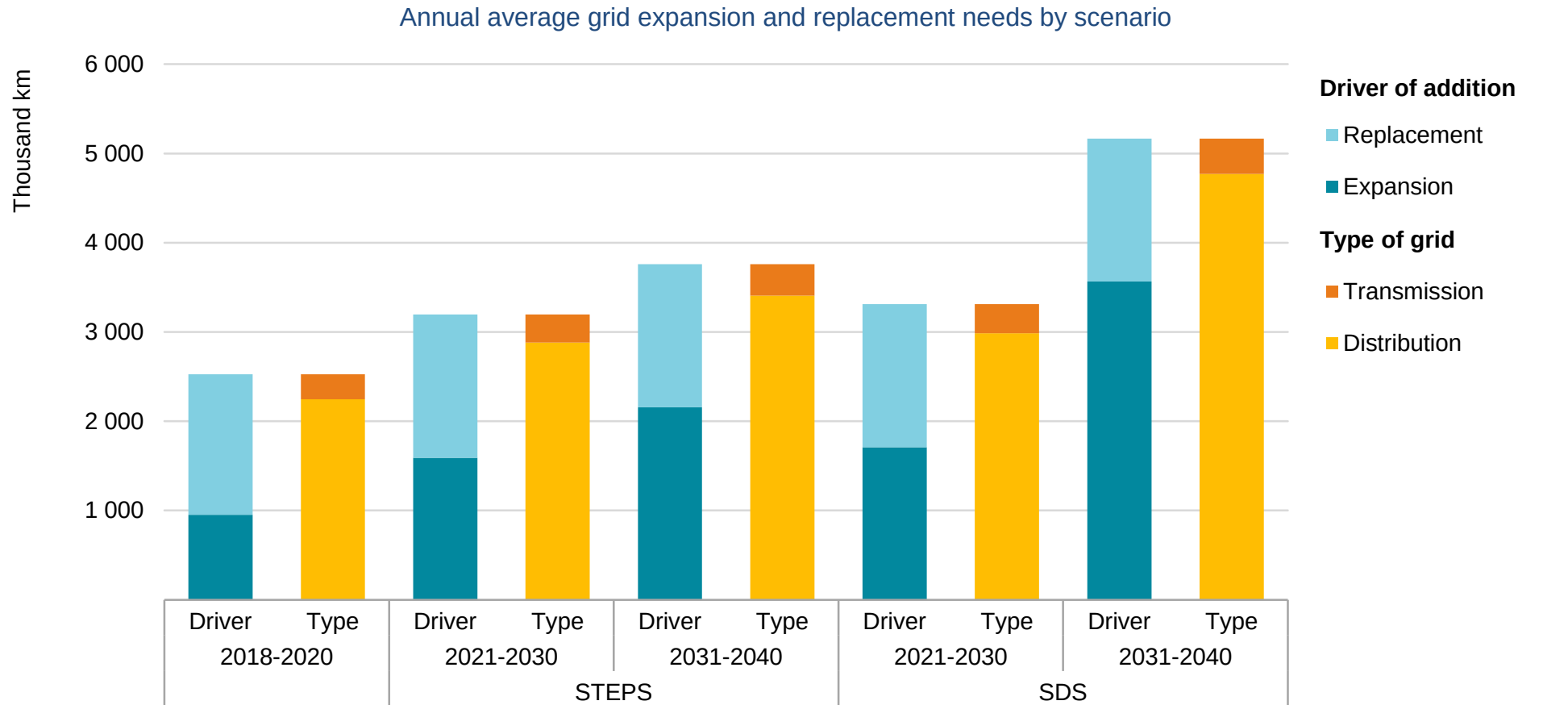
Considering the maturity of the technology, there are unlikely to be drastic reductions in mineral intensity over the coming decades. As a result, mineral intensity is assumed to be similar in the STEPS, and decline slightly in the SDS.

In the SDS, average annual mineral demand from nuclear power between 2031 and 2040 grows by around 60% compared to 2020 levels, reaching 82 kt. It is dominated by chromium (42%), copper (28%) and nickel (25%). Yttrium demand in 2040 is around 7.7 tonnes, or around 0.0015% of current global reserves.

We conducted our assessment based on mineral requirements for light-water reactor technology, which dominates the world's nuclear fleet (accounting for over 80% of all reactors in operation). Both pressurised-water reactors – the dominant choice for future expansion – and boiling-water reactors have similar mineral intensity. However, mineral intensities can be different for small modular reactors or more advanced nuclear technologies, but data for these technologies remains scarce.

Electricity networks

Rising electricity demand, alongside much higher shares of wind and solar PV, requires a significant expansion of electricity networks



Source: IEA (2020c).

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Electricity networks are the backbone of secure and reliable power systems, and have a vital role in integrating clean energy technologies

With over 70 million km of transmission and distribution lines worldwide, electricity networks are the backbone of today's power systems. Distribution systems currently account for over 90% of total line length, and play an increasing role in supporting the integration of residential solar PV and onshore wind capacity, in addition to their traditional role of delivering electricity to regional end users. Likewise, transmission systems, which are instrumental in connecting large hydro, thermal and nuclear power fleets with load centres, have new tasks to fulfil. For example, they now integrate large amounts of solar PV and wind capacity (in particular offshore wind), strengthen interconnection between countries and increase the resiliency of power systems. These new tasks are supported by the rise of high-voltage direct current (HVDC) technologies. HVDC systems have been used since the 1950s, but over two-third of total installed HVDC transmission capacity has been added in the past 10 years. Today, HVDC systems represent around 7% of newly installed transmission systems and their share is expected to rise further given the considerable technological progress made over the past decade.

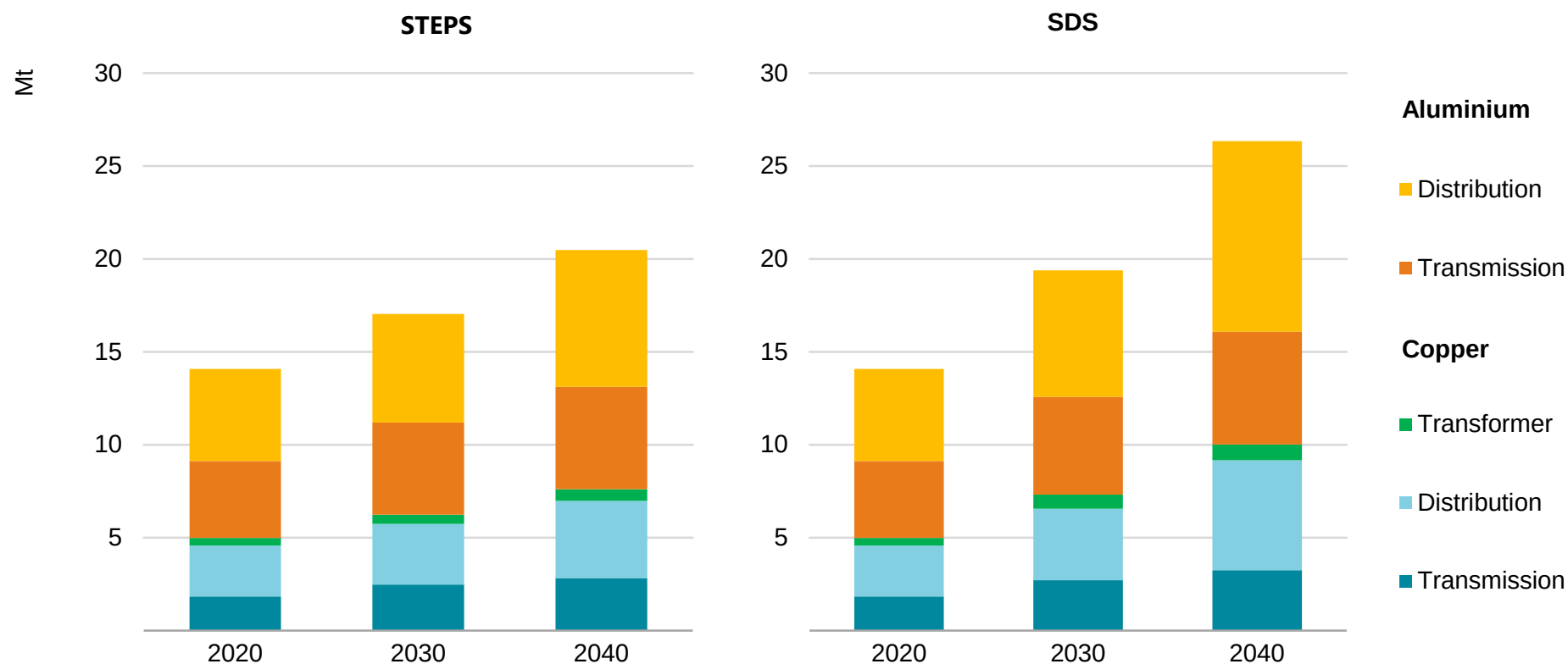
Many of the features that characterise a clean energy system – the growing role of electricity in final consumption, rising contributions from renewables in electricity supply and the greater need for

flexibility – all necessitate significant expansion of electricity grids. The projected requirement for new transmission and distribution lines worldwide in the STEPS is 80% greater over the next decade than the expansion seen in the last ten years. The importance of electricity grids is even greater in the case of faster energy transitions. In the SDS, the annual pace of grid expansion needs to more than double in the period to 2040. Around 50% of the increase in transmission lines and 35% of the increase in distribution network lines are attributable to the increase in renewables.

In addition to additional lines, there is scope to refurbish grids to strengthen the resiliency of electricity systems to climate change and extreme weather events. Refurbishment of electricity grids is also strongly linked to digitalisation, given the rising need for smart and flexible grids. Investment in digitalisation and grid flexibility helps increase reliability and can reduce the cost of generating, transmitting and distributing electricity. In the SDS, some 55% of the expansion to 2030 in advanced economies such as the European Union and the United States are attributable to refurbishment and digitalisation.

Growing need for grid expansion underpins a doubling of annual demand for copper and aluminium by 2040 in the SDS

Demand for copper and aluminium for electricity grids by scenario



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Note: Includes demand for grid expansion and replacement.

The choice of material in electricity networks is mainly driven by the type of power line, but is also influenced by cost and technical considerations

The huge expansion of electricity grids requires a large amount of minerals and metals. Copper and aluminium are the two main materials in wires and cables, with some also being used in transformers. It is estimated that some 150 Mt of copper and 210 Mt of aluminium are “locked in” the electricity grids operating today.

Copper has long been the preferred choice for electricity grids due to its inherent performance advantages. Its electrical conductivity is the second best among various metals after silver and 60% higher than aluminium. Its thermal conductivity, an often-overlooked attribute when designing and operating a grid, is also some 60% higher than aluminium. However, it also has drawbacks. Copper is over three times heavier by weight than aluminium and is more costly – average prices for copper over the past 10 years were USD 7 100 per tonne (in 2019 dollars) whereas those for aluminium averaged at around USD 2 000 per tonne.

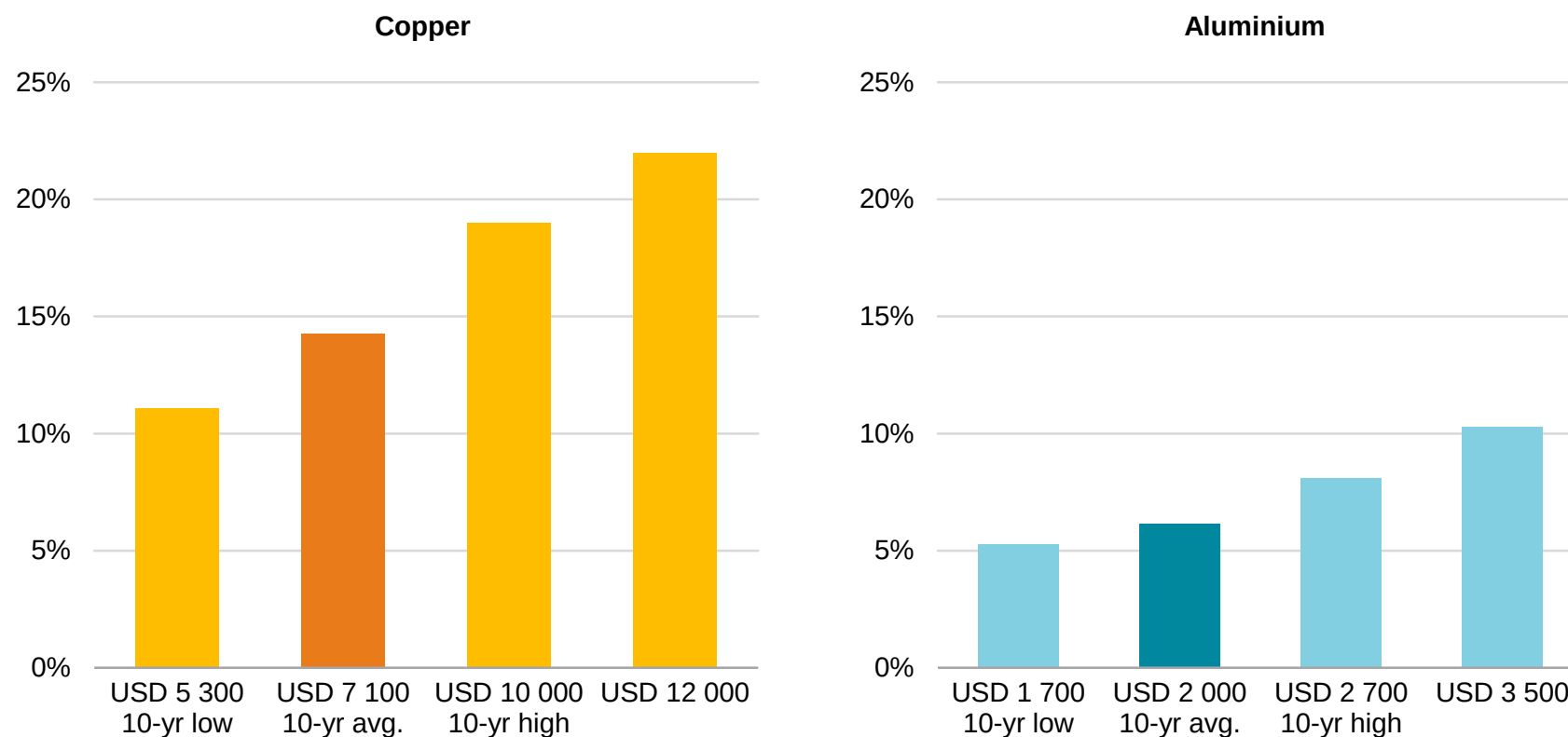
This underpins different material choices according to the type of power line. Copper is widely used for underground and subsea cables where weight is not a major concern and superior technical properties (e.g. corrosion resistance, tensile strength) are required.

By contrast, aluminium is commonly used for overhead lines given its weight advantage. In some instances, aluminium is also used for underground and subsea cables.

We estimate that some 5 Mt of copper and 9 Mt of aluminium were used in 2020 to build electricity grids, of which over 55% is attributable to distribution grids. We conducted bottom-up assessments of projected line additions and replacements by type (overhead, underground and subsea), voltage level and respective material choice. These show annual copper demand for electricity grids growing from 5 Mt in 2020 to 7.5 Mt by 2040 in the STEPS, and more than double that to almost 10 Mt in the SDS. Aluminium demand increases at a similar annual pace, from 9 Mt in 2020 to 13 Mt in the STEPS and 16 Mt in the SDS by 2040. Overhead lines account for a larger share of future expansion by line length, but underground and subsea cables require higher mineral content per unit length. The scope for significant demand growth, coupled with a higher share of raw materials in total cost, raises questions over how companies can reduce material intensity in their grids in order to lower material cost.

Costs for copper and aluminium currently represent around 20% of total grid investment; higher prices could have a major impact on the adequacy of grid investment

Share of copper and aluminium costs in new grid investment under different price assumptions

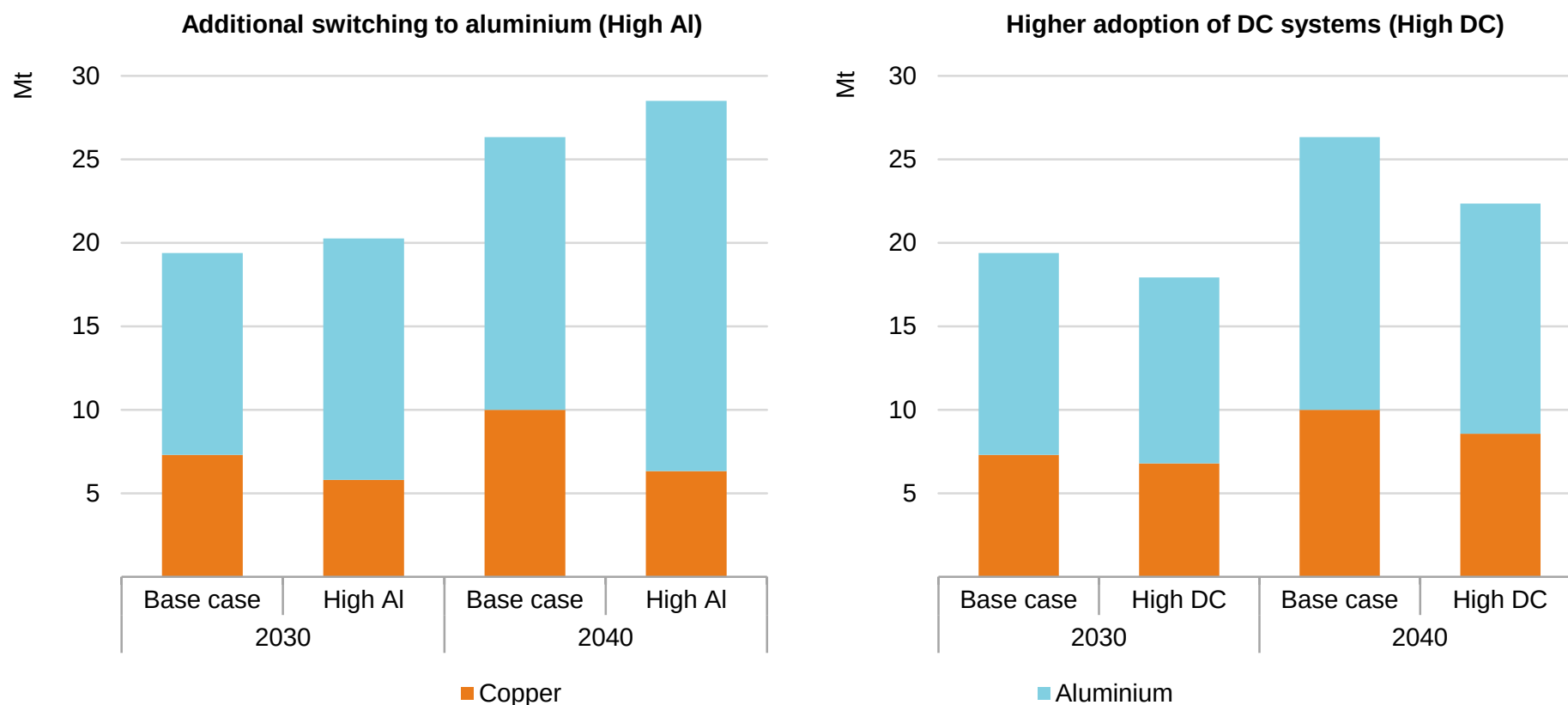


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Notes: The shares have been calculated according to total electricity grid investment in 2019, with raw material prices adjusted. Darker bars indicate average costs between 2010 and 2019; costs are in USD per tonne.

Additional switching to aluminium for underground cables and the wider uptake of DC systems can alter the material requirements considerably

Copper and aluminium demand for electricity networks in the SDS under alternative cases



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Increased use of aluminium could reduce copper demand by one-third, while wider adoption of DC systems could reduce aluminium and copper demand by 15%

As grids are modernised, expanded and digitalised, projected investment in electricity grids reaches USD 460 billion in 2030 in the STEPS and USD 620 billion in the SDS. However, shortfalls in grid revenues can put the adequacy of grid investment at risk.

Prices for minerals may add to this pressure given their considerable share in total investment costs. Using average prices over the past 10 years, copper and aluminium costs are estimated to represent around 14% and 6% of total grid investment respectively. At the highest prices observed over the past decade, these increase to almost 20% and 8% respectively, highlighting the major impacts that mineral prices can have on the ability of grid operators to undertake investment.

Increased use of aluminium in underground cables

Grid operators have long been working to reduce raw material costs. One option is to switch from copper to more affordable aluminium. When comparing the costs of the two materials, this seems to be an obvious option to improve the economics of grid investment. This is possible in cases where technical or regulatory boundaries allow, and has happened in recent years. Some drawbacks such as the lower electrical conductivity of aluminium can be compensated by the use

of larger conductors, although technical or environmental requirements often do not allow such shifts.

If aluminium takes a higher share in underground and subsea cables than our base case assumptions – accounting for 50% for distribution lines and 30% for transmission lines by 2040 – this reduces copper demand in 2040 by 3.7 Mt (down by a third) while raising aluminium demand by 5.8 Mt (up by over a third).

Wider adoption of DC systems

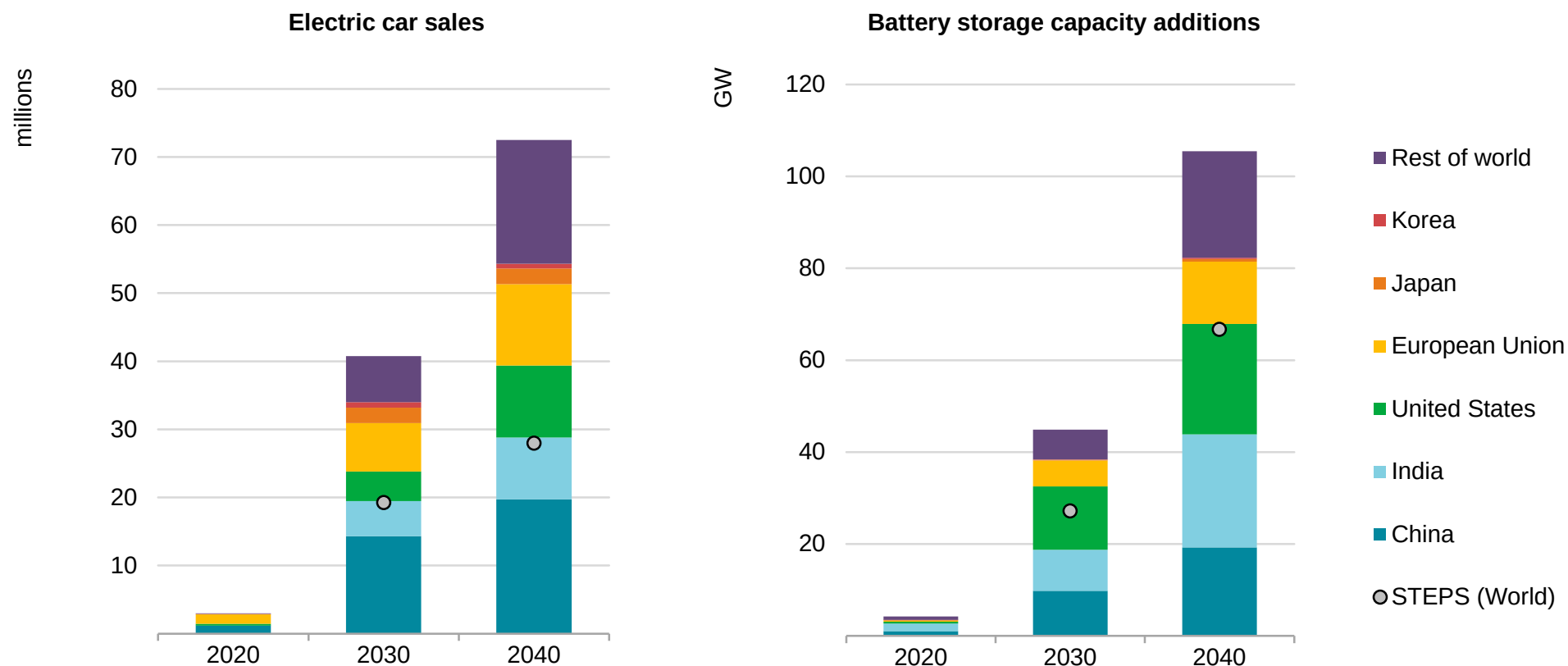
Another option is to adopt HVDC systems more widely. At present electricity networks are largely operated via alternating current (AC) systems, which require a minimum of three wires to transmit electricity. However, HVDC systems use only two wires, which implies a direct saving on metal consumption of one-third compared to AC systems. HVDC systems are also capable of transporting more electricity (theoretically up to 3.5 times more) compared to AC systems, which could reduce copper and aluminium demand and also the need for grid expansion (which results in further savings).

In the case of a wider uptake of HVDC systems – accounting for 50% of new transmission lines and 30% of distribution lines by 2040 – would reduce combined demand for copper and aluminium in 2040 by 4 Mt (or 15%) in the SDS.

Electric vehicles and battery storage

The adoption of EVs and battery storage is set to accelerate rapidly over the coming decades

Annual electric car sales and battery storage capacity additions in the SDS



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Notes: Electric cars include battery electric and plug-in hybrid electric passenger light-duty vehicles, but exclude 2/3-wheelers.

Source: IEA (2020c).

Policy support will continue to play a key role in accelerating the growth in EVs and battery storage, alongside a wider range of model offerings from automakers

EVs

Electric car sales worldwide climbed 40% in 2020 to around 3 million, reaching a market share of over 4% (IEA, 2021). As a result, more than 10 million electric cars are now on the road globally. However, to achieve global climate goals, their share of sales needs to climb rapidly to around 40% by 2030, alongside the rapid electrification of light commercial vehicles, buses and freight trucks.

Policy support has been a major driver of initial EV deployment, and will continue to play a critical role in accelerating the growth of the EV fleet over the coming decades. As of April 2021, over 20 countries and 70 subnational and city governments have announced 100% zero-emission vehicle targets or the phase-out of internal combustion engine (ICE) vehicles before 2050 (Cui et al., 2020; Hall et al., 2020; IEA, 2021; Wappelhorst & Cui, 2020).

Most major car markets currently offer some form of subsidy or tax reduction for the purchase of electric cars as well as support schemes for deploying charging infrastructure (IEA, 2020b, 2021). Provisions in building codes to encourage charging facilities and the “EV-readiness” of buildings are becoming increasingly common. So too are mandates to build fast charging infrastructure along highways.

Policy developments over the past year have been positive for EVs, and are discussed in further detail in *Global EV Outlook 2021* (IEA, 2021). In the European Union, increased stringency of the CO₂ emissions regulation for cars and vans in 2021 and beyond should contribute to maintaining the momentum for EV deployment. The European Commission is also in the process of revising the 2025-2030 targets for CO₂ emissions regulation for cars and vans, the Alternative Fuels Infrastructure Directive, the Batteries Directive and the EURO pollutant emissions standard.

Sales are likely to grow in Japan and Korea over the near term, with these governments significantly increasing EV subsidies. China has set a target of 20% of vehicle sales to be ZEVs by 2025, and announced plans to phase out conventional gasoline-powered vehicles by 2035 (General Office of the State Council of the People’s Republic of China, 2020; Nishiyama, 2020). In India, national, state and city governments have announced efforts to accelerate the adoption of EVs. For example, New Delhi recently announced major EV subsidies and awareness programmes to achieve its target for battery EVs to account for 25% of all new vehicles sales by 2024 (Times of India, 2021).

In the United States stimulus measures and longer-term goals adopted by the new administration will be critical to further

accelerating EV deployment. In particular, the new administration appears likely to prioritise fuel economy standards, promote charging station deployment, provide tax credits and help factories making internal combustion engine cars retool to make EVs.

Several major automakers have announced plans to invest aggressively in EVs and to rapidly scale up model availability. There were around 370 EV models available in 2020, a 40% increase from 2019 (IEA, 2021). Automakers have announced plans to have an additional 450 models available by 2022 (McKinsey, 2020). General Motors recently announced plans to phase out conventional gasoline and diesel vehicles by 2035, while Volvo's CEO indicated that the company would only sell EVs by 2030 (Campbell, 2021).

Emerging technologies and business models such as shared and/or autonomous vehicles – expected to have much more intensive use patterns than privately owned vehicles – could alter demand projections for new vehicles and minerals over the longer term. However, given the uncertainty of their uptake, we do not consider these trends within the scope and timeline of this analysis.

Battery storage

As of the end of 2020, around 15.5 GW of battery storage capacity were connected to electricity networks. After annual installations of battery storage technologies fell for the first time in nearly a decade in 2019, they rebounded by over 60% in 2020 (BloombergNEF, 2021; IEA, 2020a).

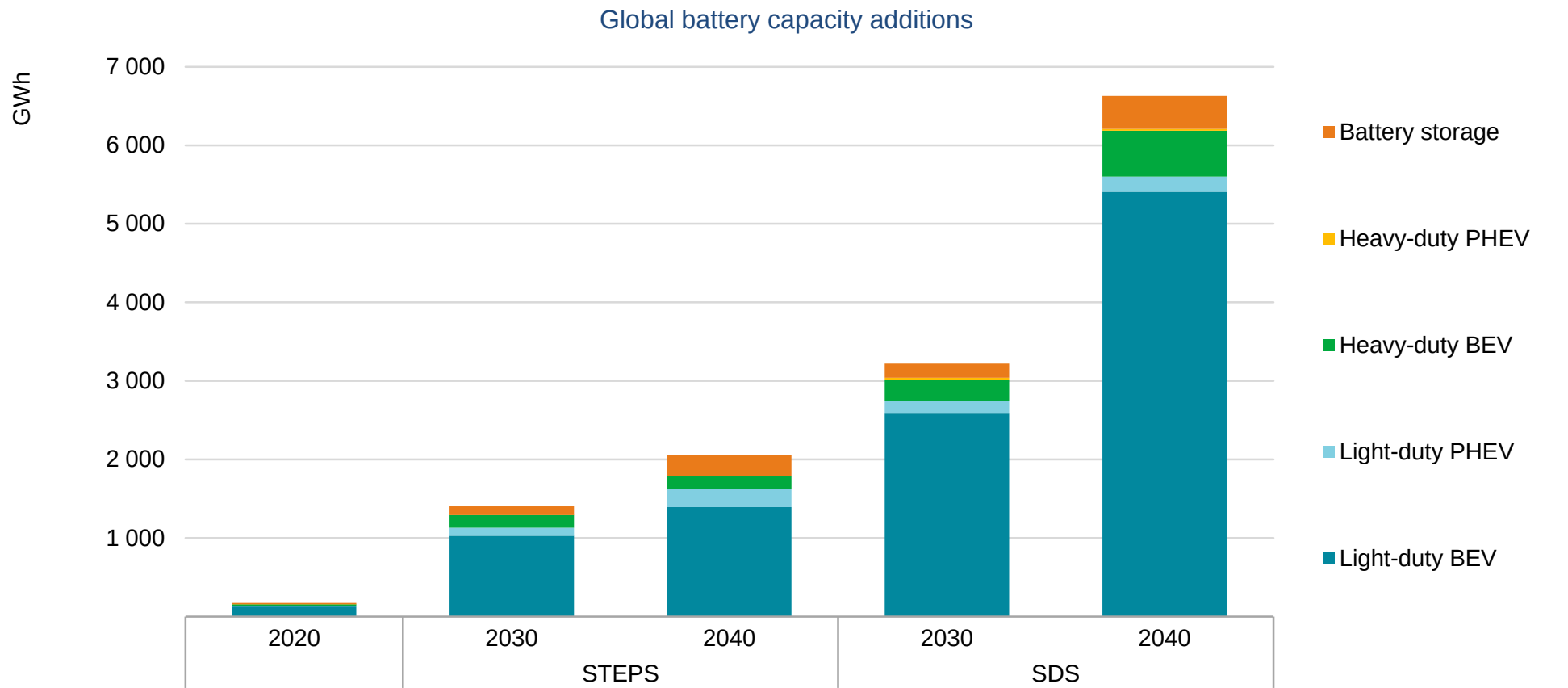
Prospects for battery storage systems look set to improve as advances in technological innovation and new business models emerge. Battery storage systems are well suited to short-duration storage that involves charging and discharging over a span of hours or days. This makes them a good partner for short-run fluctuations in the output from variable renewables, and there is a growing trend for battery storage paired with solar PV and wind.

In the SDS, global installation of utility-scale battery storage is set for a 25-fold increase between 2020 and 2040, with annual deployment reaching 105 GW by 2040 (IEA, 2020c). The largest markets for battery deployment in 2040 are India, the United States and China.

The growth of battery storage remains strongly dependent on effective regulation that reflects the value of the flexibility services it provides and enables fair access to markets. The need to properly value the high performance of battery storage systems, including their accurate and fast frequency response, is one aspect of a broader need for wholesale electricity market reform in the face of rapidly evolving power systems.

A number of regulatory barriers specific to batteries are starting to be addressed, including the rates applied to behind-the-meter batteries and the issue of double-charging, where energy storage systems are charged twice for using the grid – once when charging and again when discharging.

EV and battery storage deployment grows rapidly over the next two decades, with light-duty EVs accounting for around 80% of the total



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Notes: Light-duty includes passenger light-duty vehicles, light commercial vehicles, and two- and three-wheelers. Heavy-duty vehicles include medium-sized freight trucks, heavy freight trucks and buses. BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; GWh = gigawatt hour.
Source: IEA (2020c).

A range of minerals are needed in EV motors and batteries

Most of the critical minerals in EVs are in two components: electric motors and batteries.

EV motors

The two most common electric motor technologies for plug-in EVs are permanent-magnet synchronous motors and asynchronous induction motors (Ballinger et al., 2019).

Permanent-magnet motors have the highest efficiency and power density, but their use of REEs make them expensive compared to other technologies. In addition to neodymium (0.25–0.50 kg/vehicle) and other REEs (0.06–0.35 kg/vehicle), permanent-magnet motors also require copper (3–6 kg/vehicle), iron (0.9–2 kg/vehicle) and boron (0.01–0.03 kg/vehicle) (Ballinger et al., 2019; Fishman et al., 2018; Nordelöf et al., 2019; Sprecher et al., 2014).

Induction motors have the advantage of lower costs, but only have moderate efficiencies due to electrical losses in copper windings. While induction motors do not require REEs, they require a substantial amount of copper (11–24 kg/vehicle) for the rotor cage and copper stator (Ballinger et al., 2019).

We assume that permanent-magnet motors remain the dominant EV motor. We discuss alternative motors and the implications of high REE prices at the end of the EV section.

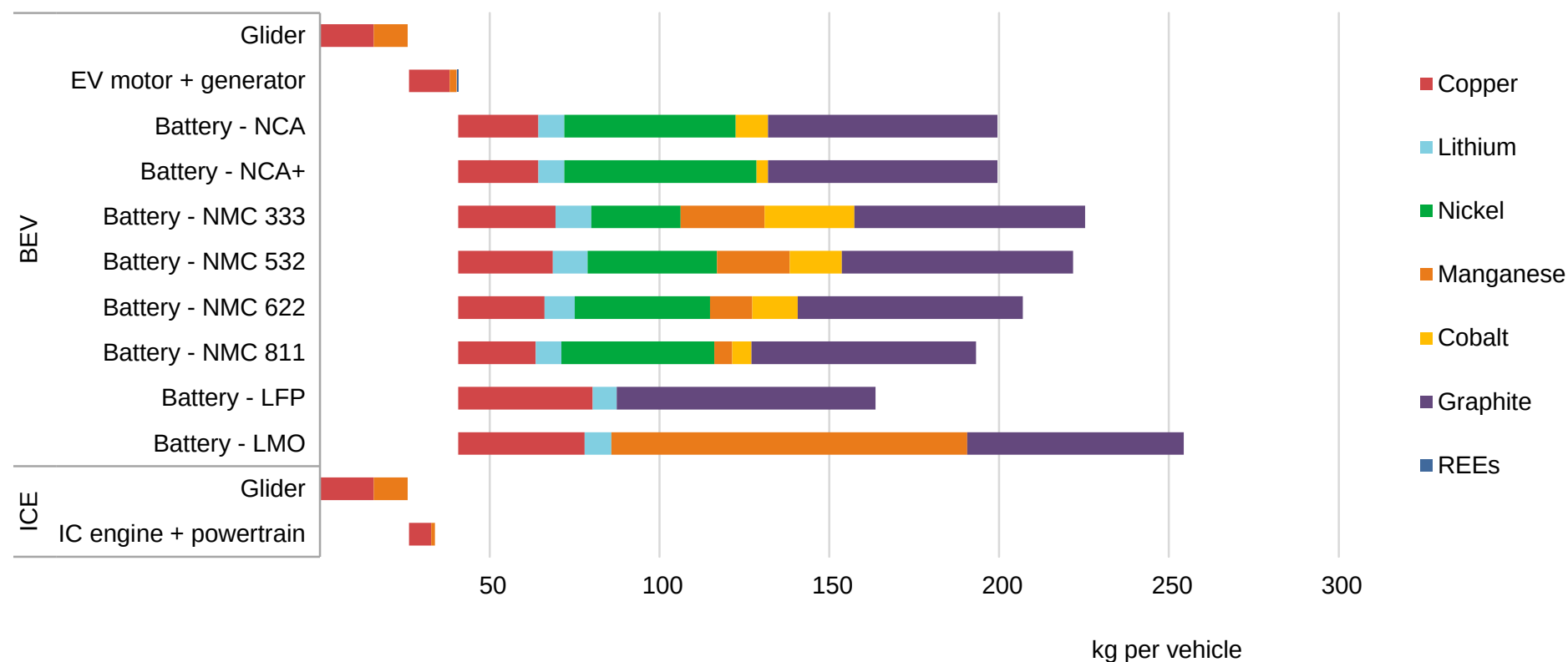
Batteries

Lithium-ion batteries used in EVs and energy storage are composed of battery cells contained in battery modules within a battery pack. Cells typically account for 70% to 85% of the total battery weight, and contain a number of minerals in the active cathode material (e.g. lithium, nickel, cobalt and manganese), anode (e.g. graphite), and current collector (e.g. copper) (Argonne National Laboratory, 2020a). The remaining modules and pack components consist mostly of aluminium, steel, coolants and electronic parts.

The need for each mineral varies considerably depending on the cathode and anode chemistries. For example, nickel manganese cobalt oxide (NMC) 111 batteries typically require almost eight times more cobalt than nickel cobalt aluminium oxide (NCA+) batteries, but half as much nickel. Lithium iron phosphate (LFP) batteries do not require nickel, cobalt or manganese, but need about 50% more copper than NMC batteries.

EVs use around six times more minerals than conventional vehicles

Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle



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Notes: For this figure, the EV motor is a permanent-magnet synchronous motor (neodymium iron boron [NdFeB]); the battery is 75 kilowatt hours (kWh) with graphite anodes.

Sources: Argonne National Laboratory (2020b, 2020a); Ballinger et al. (2019); Fishman et al. (2018b); Nordelöf et al. (2019); Watari et al. (2019).

The evolution of cathode and anode chemistries could drive mineral use for batteries in varying directions

From the perspective of global energy transitions, the last ten years have proved to be the decade of the lithium-ion battery. The 2019 Nobel Prize-winning innovation not only transformed the world of electronics and realised the dream of electric mobility more rapidly than any of its predecessors, but it is also widely considered to be a vital missing piece of the puzzle integrating greater shares of variable renewables into our conventional electricity networks.

The fundamental advantage of lithium-ion batteries over alternatives like lead acid or nickel cadmium batteries is their much higher energy density. While lead acid batteries have specific energies in the range of 35 to 40 watt-hours per kilogramme (Wh/kg), lithium-ion batteries have a range of around 90–260 Wh/kg. This allows them to be stacked into far lighter and more compact battery packs than those made of other materials. The four main components of a lithium-ion cell are the cathode, anode, liquid electrolyte and separator. The lithium-ion donor from the cathode that travels through the liquid electrolyte is the primary determinant of cell properties and gives the technology its name.

Cathode chemistries

Lithium-ion batteries are often categorised by the chemistry of their cathodes. The most commonly used varieties are lithium cobalt oxide

(LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). The different combination of minerals gives rise to significantly different battery characteristics.

Among the variants, LCO has the greatest energy density. Its high specific energy (150–190 Wh/kg) and technological maturity makes it a popular choice for portable electronics. The main drawback of the LCO battery is its thermal instability and its relatively short cycle life (500–1 000 full cycles). Coupled with safety concerns, LCO batteries are not favoured for application in EVs.

The LMO battery has a high specific power, a longer cycle life (1 000–1 500 cycles) and much better thermal stability than LCO. Being cobalt-free is often considered as a key advantage of this chemistry. However, it has a notably lower energy density, in the range of 100–140 Wh/kg. Presently, it finds use in the production of electric bikes and some commercial vehicles.

The LFP battery offers thermal stability even at high temperatures, low cost and high durability (up to 2 000 full cycles while maintaining its performance). However, its relatively low specific energy (90–140 Wh/kg) is a limitation for use in long-range EVs compared with other chemistries. Nevertheless, LFP batteries could be particularly

favoured in stationary energy storage applications and heavy-duty vehicles like trucks where the size and weight of a battery are secondary considerations. Automakers in China are showing renewed interest in using LFP technology for manufacturing electric cars as they are cheaper, safer, simpler to package and do not require the use of cobalt or nickel. Volkswagen recently announced plans to use LFP batteries in its entry-level models (S&P Global Platts, 2021).

The NCA battery has the highest specific energy range (200–250 Wh/kg) in the current class of technologies as well as high specific power, combined with a lifetime of 1 000 to 1 500 full cycles. NCA is the technology preferred by manufacturers like Tesla, and has immense potential for use in power systems in backup and load shifting applications. However, they are more expensive than other chemistries.

NMC batteries have longer cycle life (1 000–2 000 cycles) compared to NCA, but a lower energy density (140–200 Wh/kg). It has dominated the BEV and PHEV markets since its commercialisation in the early 2000s. While NCA batteries have higher specific energy to their name, NMC batteries possess longer lifetimes, which makes them the favoured choice for PHEVs. Manufacturers producing both BEVs and PHEVs, such as General Motors, are known to use NMC variants of lithium-ion batteries.

Tug of war between nickel and cobalt

Advancement in lithium-ion battery technology involves more than just the challenge of improving energy density, durability, safety and cost. It also includes the effort to do so while minimising the environmental, social and political costs of acquiring their constituent materials.

Owing to price spikes and concerns over ethical mining practices in the 2010s, EV producers have been working to reduce the amount of cobalt in batteries over the past several years — this implies, in many cases, an increase in the quantity of nickel. NCA batteries transitioned to NCA+, a nickel-rich variant of NCA, and NMC 111 batteries have moved increasingly towards NMC 532, NMC 622 and NMC 811, and could move to even more nickel-rich chemistries (e.g. NMC 9.5.5). This trend of moving away from cobalt could therefore have major implications for the requirement for nickel.

Recent efforts to reduce the use of nickel capitalise on the potential of manganese, which is in relatively ample supply. SVOLT Energy Technology introduced battery cells that have a lower share of nickel and no cobalt by raising the use of manganese (Kane, 2021). A manganese-rich cathode is less expensive and safer than nickel-rich chemistries, but decreases the cathode's stability, which can have impacts on performance over the longer term (Nunez, 2020).

Anodes must complement the cathode chemistries

Anode materials are selected for their charge collection capability. Graphite is currently the dominant choice for the anode in most lithium-ion batteries, although certain manufacturers also use lithium titanate instead of graphite. Efforts to replace some or most atoms of carbon in the graphite anode with silicon atoms are underway (e.g. Tesla, Porsche) and are expected to drastically improve the energy density of the cells. However, silicon anodes swell during charging, causing its surface to crack and performance to drop.

Another alternative to the graphite anode is pure lithium metal, which also has far greater charge collection capability than graphite. But this anode cannot be used with liquid electrolyte batteries due to undesirable chemical interactions between the electrolyte and the metal anode, which drastically reduces the lifetime of the cell. The use of a lithium metal anode may increase significantly with the advent of all-solid state batteries (ASSBs). Lithium-metal anodes do not have the expansion problem of silicon anodes, but they are expensive and present other technical problems.

Further technology innovation is needed to continue cost reductions

The average cost of lithium-ion batteries has declined by almost 90% over the past decade, falling to USD 137/kWh in 2020 (BNEF, 2020).

These rapid cost reductions were made possible thanks to the remarkable growth in EV sales over the past decade and the continued penetration of high-energy density cathodes.

New pack designs and falling manufacturing costs can lead to further cost reductions in the near term. Costs are expected to fall below USD 100/kWh by the mid-2020s, a milestone often considered as one that will bring price parity between EVs and internal combustion engine vehicles (BNEF, 2020).

The path to lower battery costs could follow many routes, depending on a few major factors. First, as demand growth accelerates, maintaining a steady supply to meet that demand and preserve the drop in costs is likely to be increasingly challenging. Next, as we analyse in the next chapter, the sources and supply chains of the various critical minerals that are needed to bring these energy density improvements are often geographically concentrated in certain regions, and an uninterrupted supply cannot be taken for granted. Finally, as we reach the physical limits of improvement with current technology and materials, notable cost reductions can only be achieved by the disruption of the current technology – for example in the form of ASSB with lithium anodes or increased use of silicon in graphite anodes for existing chemistries. Therefore, the continued cost decline at a pace observed during the past decade cannot be taken for granted without a further acceleration in technology innovation.

Innovation on the horizon: The advent of all-solid state batteries

As current technology and materials bring us ever closer to the theoretical limits of improving energy density, and battery prices start to plateau by the middle of this decade, the world needs to look beyond the liquid electrolyte-based lithium-ion batteries. A significant improvement in the energy density of EV batteries and a steep decline in battery prices would require the disruption of the present technology. Such a breakthrough is expected from the advent of lithium metal anode all solid-state batteries (ASSBs).

Most state-of-the-art commercial batteries with NCA, NMC or LFP cathodes require a liquid electrolyte for ion transfer and a graphite-based anode. These two components fundamentally limit the functionality and energy density of lithium-ion batteries today. The flammability of the solvent in the electrolyte raises many safety concerns (Hess et al., 2015), and undesirable reactions between the solvent and the conductive lithium salt lead to capacity fading and ageing (Hendricks et al., 2015). Moreover, the electrolyte filling process makes the production line more cumbersome and expensive (Wood et al., 2015). A compact solid electrolyte not only circumvents these issues but also enables³ the use of lithium metal as the anode (Varzi et al., 2016).

ASSBs equipped with lithium metal anodes could achieve a volumetric energy density up to 70% greater than today's lithium-ion batteries that have conventional graphite anodes (Janek & Zeier, 2016), making them the ideal batteries for EVs of the future. As an added advantage, ASSB do not require expensive cooling systems due to the absence of a flammable electrolyte. They have in fact displayed better functionality at higher temperatures due to increased conductivity.

While experts predict that current lithium-ion batteries could reach a maximum energy density of 300 Wh/kg after 2025, lithium metal solid-state batteries with densities of 320 Wh/kg have already been fabricated (Placke et al., 2017) and their maximum potential could be as high as 480 Wh/kg. This improvement in energy density would mean that batteries of the same size could contain much more energy in the future, thereby resulting in an effective reduction in the weight and cost of the new battery packs. The greatest challenge facing this new technology is scaling up the production to make it commercially viable, since a direct transfer of laboratory preparation methods to industrial-scale fabrication is not always successful.

³ Solid electrolytes act as a physical barrier to the formation of lithium dendrites that could form from the lithium anode and short-circuit the cell by connecting the anode and the cathode.

Solid-state lithium metal anode batteries are reported to mostly be designed with NMC cathodes; however, they could also be combined with new cathode chemistries. The use of sulphur in lithium-based cathodes (Li-S) is being viewed as a promising technological avenue because of its very high theoretical energy density. Current prototypes developed by start-ups (Oxis-energy) already reach cell-level energy densities of over 500 Wh/kg; however, they are limited to aerospace applications due to their low cycle life. Another study published by Samsung reported an anode made of carbon black, and silver nanoparticles (Ag-C) coated on stainless steel as the anode (Lee et al., 2020). This allows even better energy density than a lithium metal anode. Nevertheless, for this analysis the ASSB scope is limited to lithium-metal anodes combined with traditional NMC cathodes, due to greater availability of data and information on the prototypes of this technology.

After a robust and cost-effective scale-up process is found, the design of electric cars equipped with ASSB would take between three to five years; this explains why several manufacturers have already begun investing in R&D for this new battery technology. For example, Colorado-based start-up Solid Power already has partnerships with Ford Motor Company and BMW Group, and they believe the roadmap for commercial use of their ASSB in the automotive industry is well-defined. The company estimates a 10–15% reduction in the total cost of a battery pack compared to their liquid electrolyte counterparts, with most of the savings coming from enhanced packing density. If researchers and manufacturers find the solution to

mass producing these new batteries within the next five years, ASSB would be competing with the incumbent lithium-ion batteries for space on the roads by the early 2030s and, thus, launch the next phase of electric mobility.

Synergies between EVs and battery storage

Historically, trends from the automotive industry have often transferred to the power sector. Progress on improvement in EV batteries could benefit stationary storage system technologies, while the converse may not necessarily be true. Batteries for EVs must be energy dense, small, safe and light, and have high cycle life. Energy storage systems, by contrast, do not have such strict requirements for size and weight, but instead prioritise cost, durability and safety.

Although NCA and NMC batteries might be considered too expensive for most large-scale energy storage systems, they are ideal for wall-mounted residential batteries used in combination with solar panels, and their price could also be justified in certain large-scale storage applications in cities with high population densities, where space is limited and energy density becomes crucial. A fair compromise between the two applications is the LFP battery, with lower energy density than NMC and NCA, but still small enough for buses and trucks, inherently safer chemical composition, non-reliance on cobalt and nickel, and lower prices more suitable for stationary applications.

Besides lithium-ion batteries, flow batteries could emerge as a breakthrough technology for stationary storage as they do not show

performance degradation for 25–30 years and are capable of being sized according to energy storage needs with limited investment. One of the most modern commercial Vanadium redox flow batteries, with a lifetime of 12 000 cycles at full power, went online in eastern Spain to operate with the Vega wind farms in December 2019 (Bellini,

2020). However, flow batteries employ a completely different technology, wherein their specific energy depends on the volume of the electrolyte and specific power depends on the surface area of the electrodes, and they are therefore much too large for EV applications.

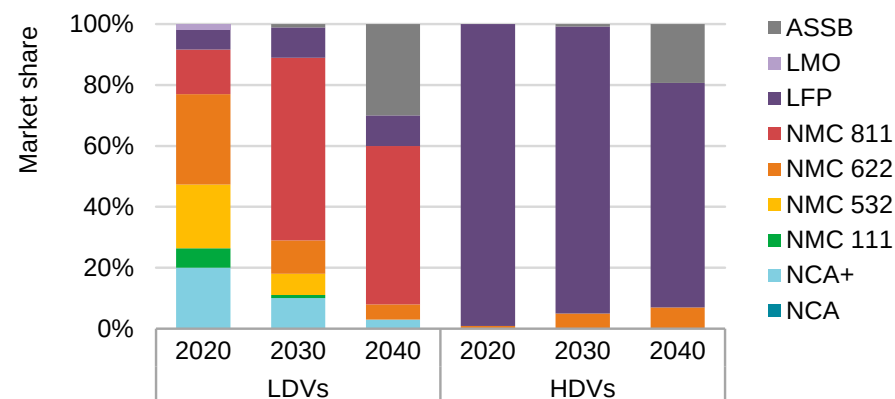
Passenger EVs shift from cobalt towards nickel-rich cathodes, with a slow uptake of solid state batteries

As it has become evident that reducing cobalt content in the cathode and striving for higher energy density are key concerns for most manufacturers and countries, the base case scenario sees a shift away from cobalt-rich chemistries. This is achieved in both NCA batteries and NMC variants, where the ratio of nickel and manganese are increased in the transition from NMC 111 to NMC 532, NMC 622 and ultimately NMC 811.

While most heavy trucks are reliant on LFP batteries in the medium term, our base case also sees modest growth in the market share of LFP for cars due to its increasing use in China and entry-level models from VW.

The base case sees ASSB becoming commercially available by around 2030 and requiring another 5 years for manufacturing capacity to build up. Even in 2040, ASSB remain more expensive than lithium-ion batteries and are therefore limited to premium vehicles and developed countries. In the longer term, heavy trucks operating long haul are likely to use ASSB as soon as they become available because of the great benefits of energy density improvement in these applications. They would enable increased payload, greater operating range and shorter charging times.

EV cathode chemistries in the base case



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Notes: LDVs = light-duty vehicles (passenger cars and vans, light commercial vehicles, and 2- and 3-wheelers); HDVs = heavy-duty vehicles (trucks and buses).

Sources: IEA analysis complemented by Adamas Intelligence (2021a) and EV-Volumes (2021).

For the anode, natural graphite is expected to continue to account for the majority of market share. Even as artificial graphite starts to replace natural graphite for reasons of improved purity and hence energy density, a small number of manufacturers choose lithium titanate (LTO) instead of graphite for heavier vehicles due to its fast-charging advantages. The dominance of graphite declines very slightly over the years to make way for nanocomposite graphite

doped with silicon and for lithium metal that emerges with the advent of ASSBs.

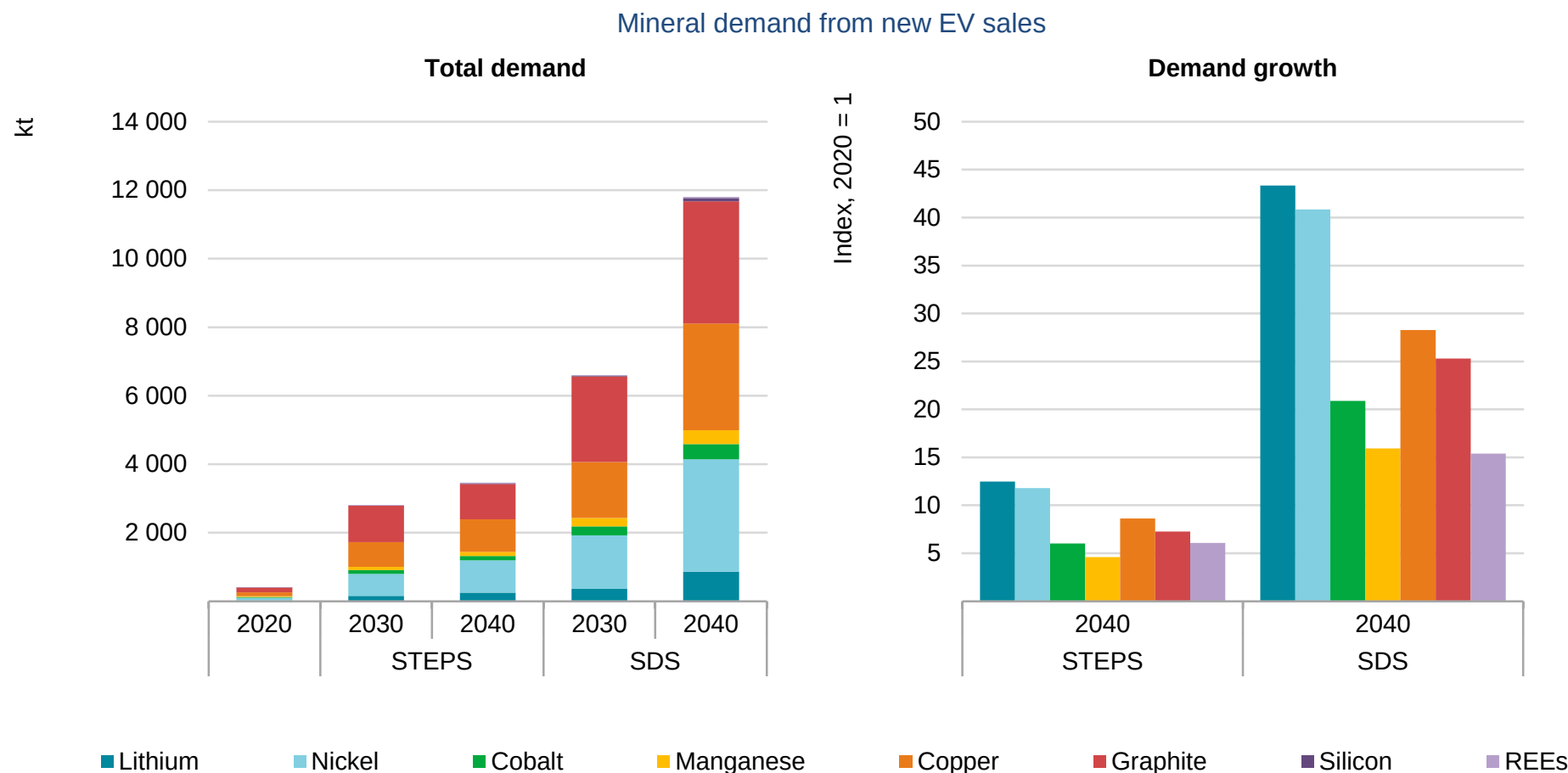
Results

In the SDS, battery demand from EVs grows by nearly 40 times between 2020 (160 GWh) and 2040 (6 200 GWh). Overall demand for minerals under the base case assumptions grows by 30 times between 2020 and 2040, from 400 kt to 11 800 kt. In the STEPS, battery demand from EVs grows just 11 times to nearly 1 800 GWh in 2040, with demand for minerals growing ninefold to around 3 500 kt in 2040.

In the SDS, nickel demand grows by 41 times to 3 300 kt, while cobalt increases by only 21 times, as cathode chemistries shift away from NMC 111 towards lower-cobalt chemistries (NMC 622 and NMC 811). Lithium demand grows by 43 times, while copper grows 28 times.

Graphite demand grows 25 times from 140 kt in 2020 to over 3 500 kt in 2040. Silicon registers the largest relative growth, up over 460 times, as graphite anodes doped with silicon grow from a 1% share in 2020 to 15% in 2040. Demand for REEs grows 15 times to 35 kt in 2040.

Mineral demand for EVs in the SDS grows by nearly 30 times between 2020 and 2040, with demand for lithium and nickel growing by around 40 times



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Note: Silicon is excluded from the demand growth graph due to its very high growth (over 500-fold increase), starting from a low base.

Alternative cases for EVs

The base case projections are founded on a set of assumptions, which, when altered due to reasons of technology advancements, could result in scenarios that produce very different results. We therefore built three alternative scenarios and assessed how the demand outlook for various minerals could change under varying technology evolution trends.

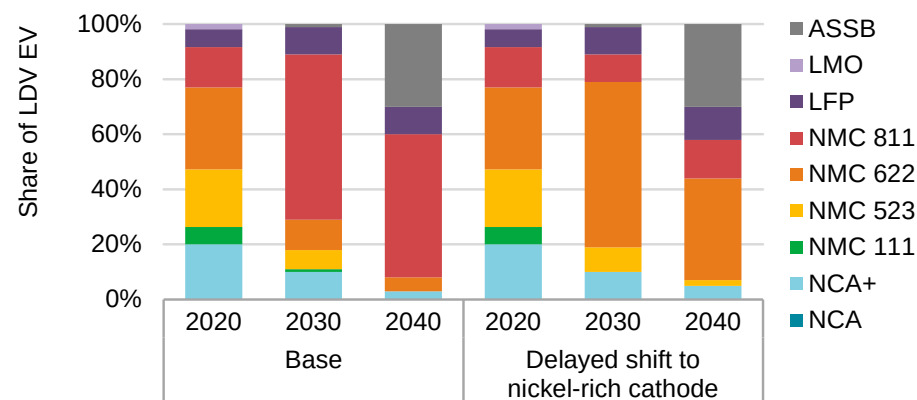
Delayed shift to nickel-rich cathode

On the cathode side, price spikes and social concerns surrounding cobalt mining a few years ago triggered efforts to reduce cobalt content in lithium-ion batteries. But cobalt currently appears to be well supplied, at least in the short term. Instead, a rapid move towards nickel-rich chemistries may be causing signs of tightness in the nickel supply chain. The near-term supply prospects for Class I nickel depend on whether planned projects in Indonesia can be carried out smoothly (see Chapter 3).

The first alternative case therefore explores the outcome of the growing concerns about nickel supply and potential price increases in the medium term. Should there be delays and cost overruns at planned projects, it is not inconceivable for battery-grade nickel prices to rise, in conjunction with relatively stable cobalt prices, to slow shift towards the nickel-rich chemistries.

In this case, we study the impact of a delayed shift to nickel-rich chemistries for NCA and NMC batteries due to supply uncertainties for nickel, while LFP, the emergence of ASSB and anode materials remain as they are in the base case.

Cathode chemistries for light-duty EVs in the delayed shift to nickel-rich cathode case



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A delayed shift to nickel-rich chemistries (and away from cobalt-rich chemistries) results in nearly 50% higher demand for cobalt and manganese in 2040 compared to the base case. Nickel demand is 5% lower in 2040 compared to the base case.

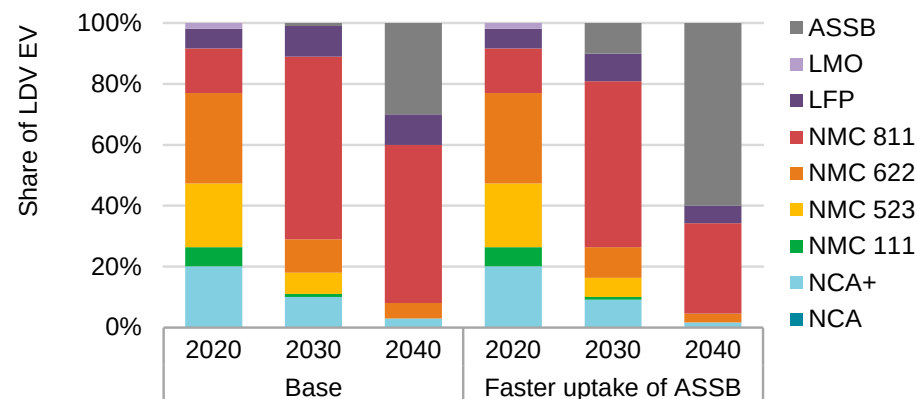
Faster uptake of lithium metal anode all-solid state batteries

While we assumed ASSB to take off meaningfully in the 2030s given the challenges around scale-up, much earlier commercialisation and faster penetration of ASSB in the EV market could alter the outlook for minerals considerably. This would reflect major breakthroughs in ASSB that have been made in recent years. ASSBs are safer as they do not contain a flammable liquid electrolyte and could be cheaper as their cell structure is simpler and does not need cooling mechanisms for safety. They represent disruption of current technology, rather than incremental improvements in existing lithium-ion technologies.

We explore a much faster uptake of ASSB in the EV market, starting with a small market share as early as the late 2020s. Its presence in the market then grows significantly in the 2030s, even taking up more than half the market by 2040 and ultimately capturing around three-quarters of the electric car market by 2050. This case would imply higher consumption of lithium, as ASSBs considered in this report use pure lithium metal anodes instead of graphite. (Lithium metal can only be used as the anode in ASSBs; undesirable interactions with the liquid electrolyte in lithium-ion batteries rapidly reduces the lifetime of the battery.)

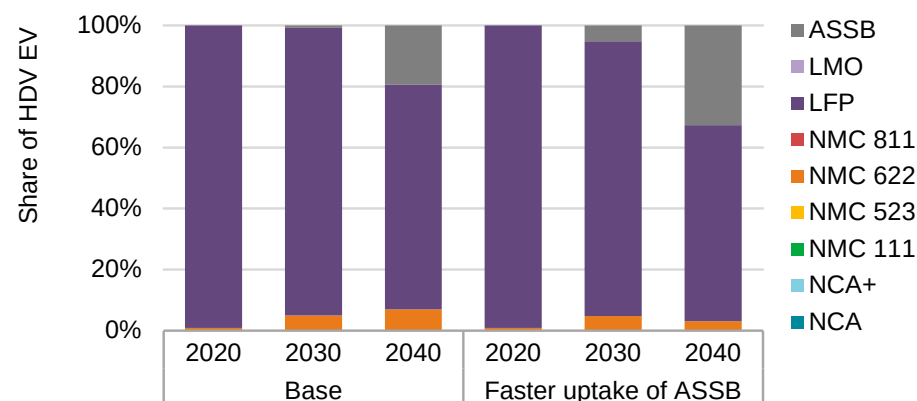
The faster uptake of lithium metal anodes and ASSB results in 22% higher lithium demand in 2040 compared to the base case, but also much lower demand for graphite (down 44%) and silicon (down 33%).

Cathode chemistries for light-duty EVs in the faster uptake of ASSB case



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Cathode chemistries for heavy-duty EVs in the faster uptake of ASSB case



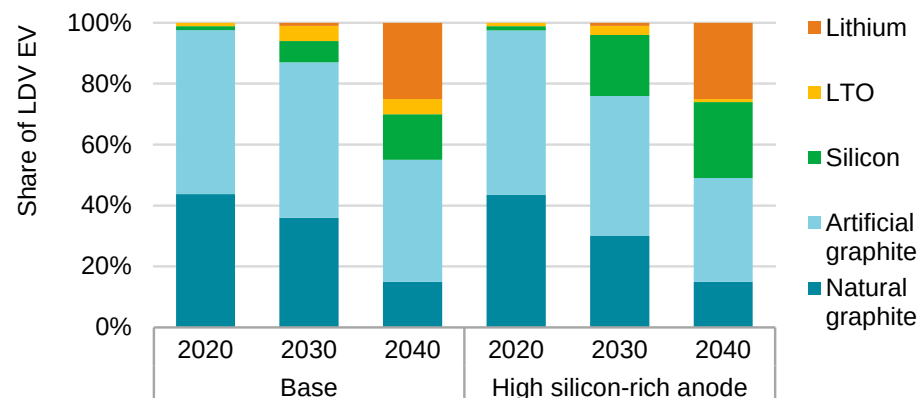
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Moving more rapidly towards a silicon-rich anode

For the anode, silicon (and lithium) have roughly 10 times as much capacity to hold electrons as graphite and, thus, can improve the energy density of a battery by 20–50%. Many major manufacturers of lithium-ion batteries are increasingly venturing into higher silicon quantities in the anode in order to improve energy density. In this alternative case, we consider the result of achieving higher-level (around 20%) silicon doping for graphite anodes compared to the base case by 2030, and further improvement in the technology leading to even higher doping levels by 2050.

Moving rapidly towards a silicon-rich anode results in nearly three times as much silicon demand in 2030 compared to the base case, and a slight decrease in graphite demand (down 6%). By 2040 silicon demand is only 70% higher, owing to a higher adoption of silicon-rich anodes even in the base case.

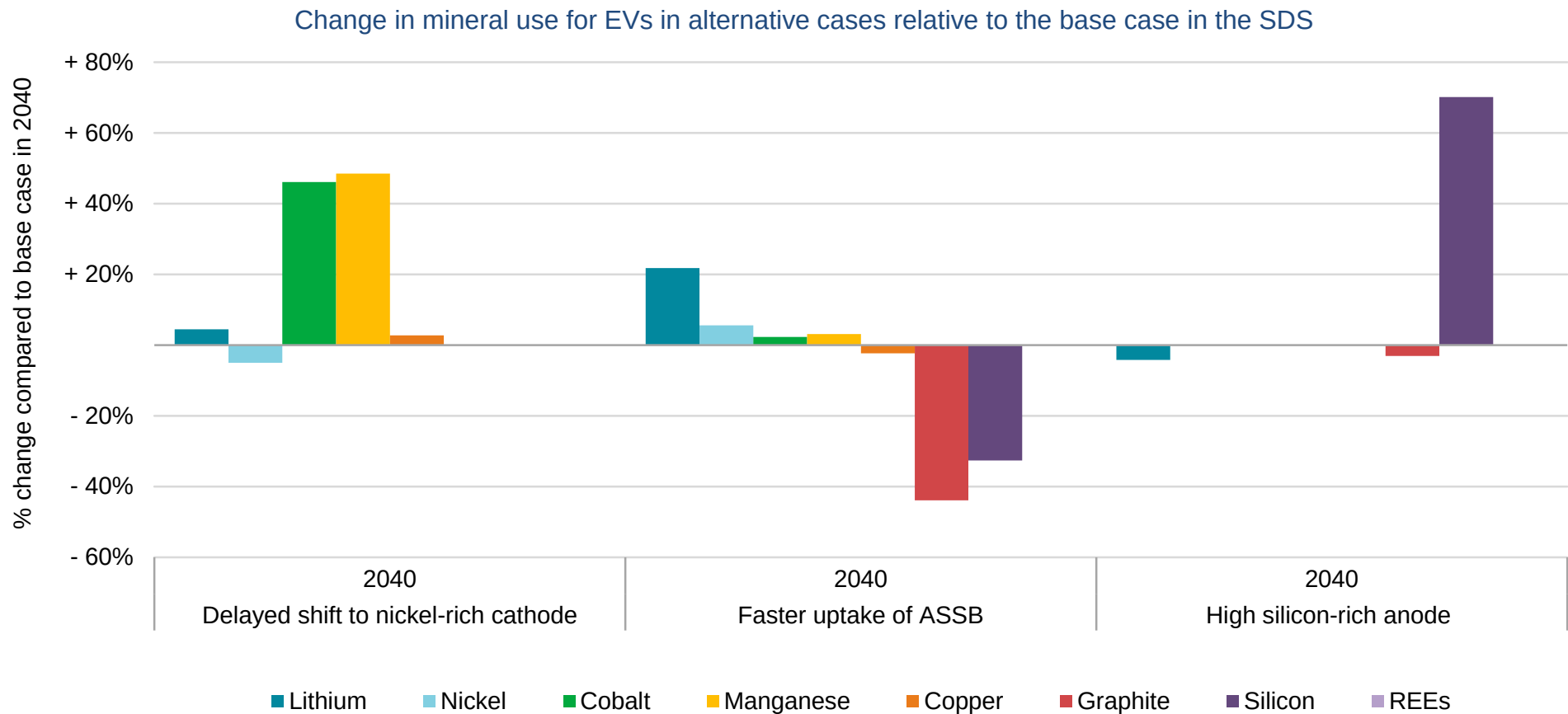
Anode shares for light-duty EVs in the high silicon-rich anode case



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Note: LTO = lithium titanate oxide.

The alternative cases demonstrate the considerable sensitivity and uncertainty of mineral demand to the future mix of EV battery chemistries



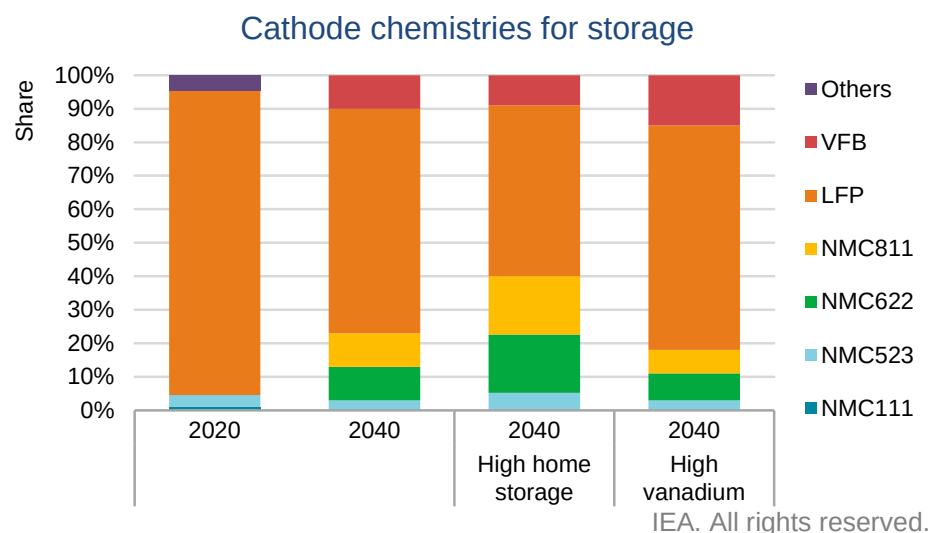
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Utility-scale storage is expected to dominate the battery storage market

Safe and cheap LFP batteries for utility-scale storage are expected to dominate the overall battery storage market. The remaining demand is covered by the more expensive, but energy-dense, NMC 111 and NMC 532 used predominantly for home energy storage. The NMC variants transition towards NMC 622 and NMC 811 in a similar way to the market for EV batteries, albeit with a delay owing to the time needed for transfer of technology and sufficient reduction in prices. Vanadium flow batteries (VFBs) first become commercially suitable in 2030 with a small share, growing modestly to capture a wider market for storage applications in large renewables projects.

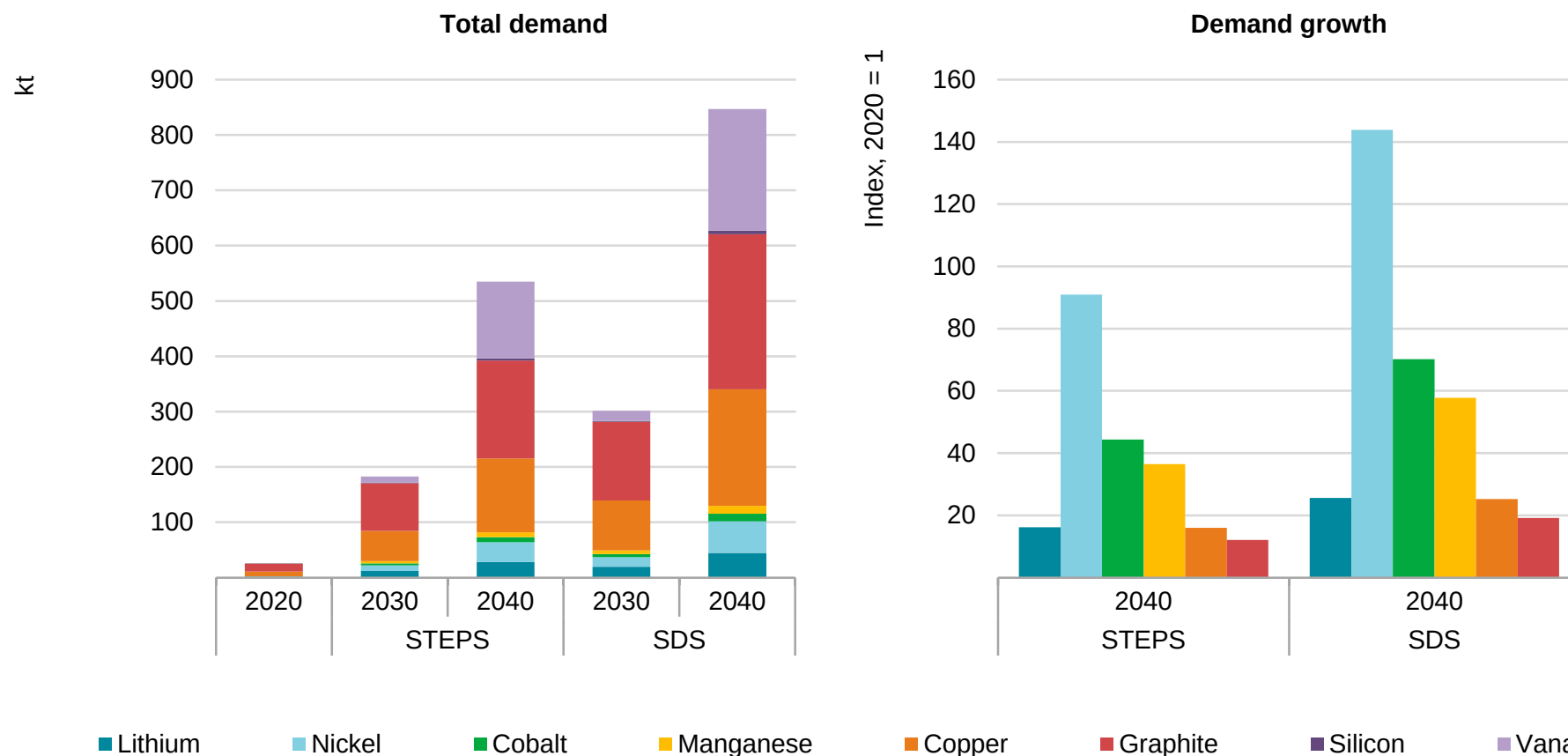
In the SDS, battery storage grows by 11 times between 2020 (37 GWh) and 2040 (420 GWh). Overall demand for minerals in the base case grows by 33 times between 2020 and 2040, from 26 kt to nearly 850 kt. Overall mineral demand outpaces battery demand growth, as the market share for LFP batteries is displaced by more mineral-intensive NMC chemistries.

The largest relative growth is seen in nickel, which grows more than 140 times from 0.4 kt in 2020 to 57 kt in 2040. Cobalt demand increases by 70 times while manganese demand increases by 58 times.



Mineral demand for storage in the SDS grows by over 30 times between 2020 and 2040, with demand for nickel and cobalt growing by 140 times and 70 times respectively

Mineral demand from battery storage additions in the SDS



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Note: Silicon and vanadium are excluded from the demand growth graph.

Alternative cases for energy storage

The base case for energy storage systems is built on the assumption that utility-scale storage forms a major proportion of the demand, wherein cost (and not space) is the primary concern for the technology selection. However, several alternative scenarios could alter the base case projections. For instance, more rapid adoption of wall-mounted home energy storage would make size and thus energy density a prime concern, thereby pushing up the market share of NMC batteries such as those already used by the Tesla Powerwall. Conversely, if the technology for flow batteries, which have the advantage of virtually unlimited energy capacity and very long lifetimes, reaches a stage of widespread commercialisation earlier than expected, then utility-scale storage technology could shift away from LFP batteries towards VFBs.

Rapid adoption of home energy storage

In this alternative case, we investigate the outcome of a scenario where demand for storage beyond utilities grows rapidly. Here, the NMC battery share grows faster, achieving around a quarter of the market share by 2030 and almost half by 2050. They are used in applications such as home energy storage (e.g. storing solar electricity for self-consumption, time-of-use load shifting, backup power and increased off-grid applications). In many of these applications, space is one of the most important concerns, making

the more energy-dense NMC more favourable than their LFP counterparts. The split between NMC 532, NMC 622 and NMC 811 evolves more or less as for the EV batteries base case. The trajectory for VFBs remains as for the base case.

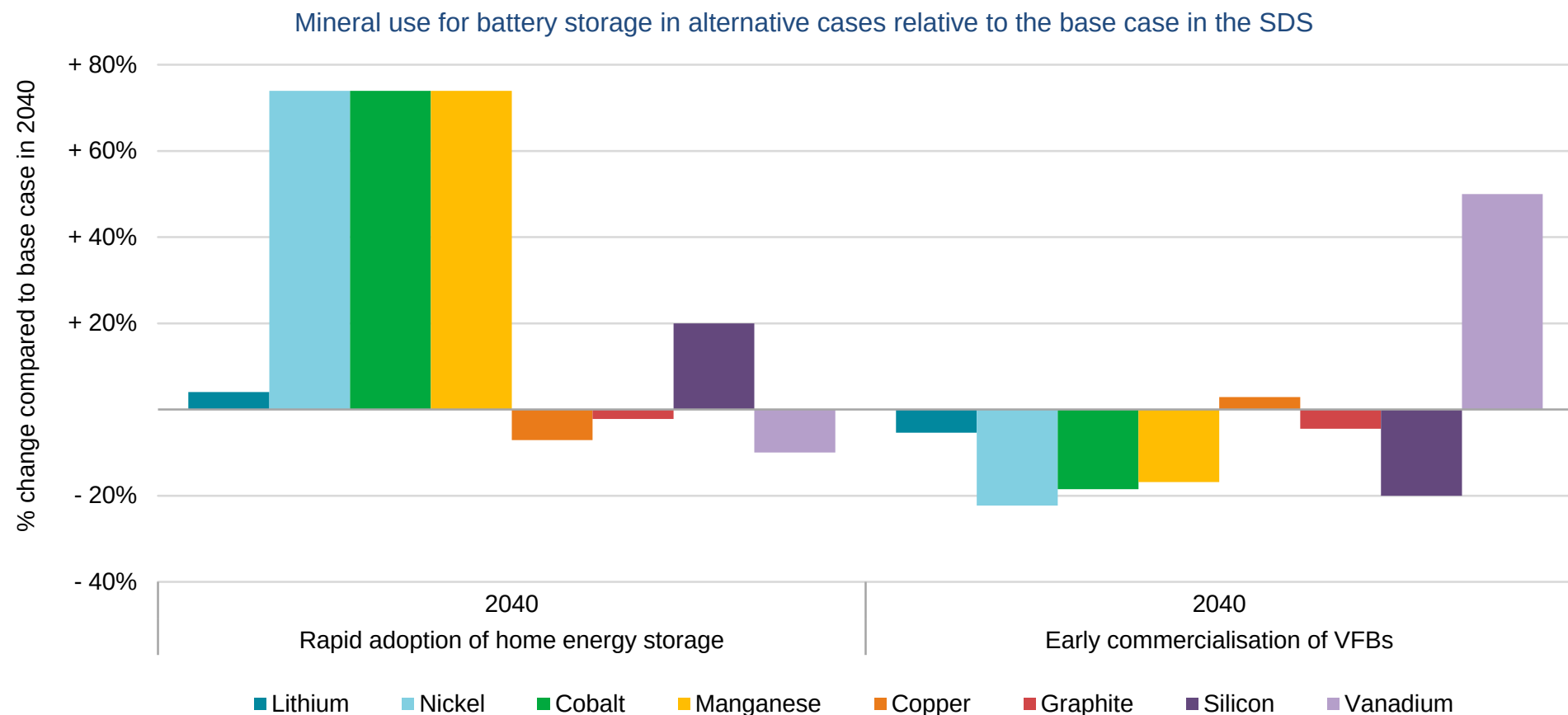
The rapid adoption of home energy storage with NMC chemistries results in 75% higher demand for nickel, manganese and cobalt in 2040 compared to the base case. A faster uptake of silicon-rich anodes also results in 20% greater demand for silicon compared to the base case in 2040.

Early commercialisation of Vanadium flow-batteries

In this case, the technology for VFBs reaches the level of maturity required to be deployed in large-scale projects earlier than in the base case. They increase their market share from 2030 onwards and capture almost a third of the energy storage market by 2050, with maximum applications in large wind and solar farms.

The early commercialisation of VFBs results in 2.5 times more demand for vanadium compared to the base case in 2030 and 50% more demand in 2040. As a result of lower market shares for NMC chemistries, demand for nickel, cobalt and manganese are about 20% lower in 2040 compared to the base case.

More rapid adoption of home energy storage could increase demand for nickel, cobalt and manganese – but these increases are dwarfed by demand from EVs



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Could mineral prices be an obstacle for further battery cost declines?

The average cost of lithium-ion batteries has fallen dramatically over the past decade, reaching USD 137/kWh in 2020 (BloombergNEF, 2020). Further cost reductions are necessary for EVs to achieve the adoption rates observed in the SDS. In the near term, the US Department of Energy has set a target of reaching USD 125/kWh by 2022 for BEVs to attain cost parity with internal combustion engine vehicles. Tesla expects to slash costs by half between 2020 and 2023 to achieve pack costs of around USD 60/kWh (Irvine & Rinaldo, 2020). The SDS requires battery prices to reach USD 100/kWh by 2030.

Several automakers are scaling up battery production to drive further cost reductions. For example, Tesla's first Gigafactory in Nevada began mass production of cells in January 2017, helping to reduce battery production cost by 30%. In addition to scaling up production volume, further cost reductions can be achieved by optimising cell fabrication to increase energy density, reducing manufacturing costs and enhancing pack assembly efficiency (Ding et al., 2019).

However, with major technological improvements achieved over the past decade, raw materials now account for the majority of total battery costs (50–70%), up from around 40-50% only five years ago (Argonne National Laboratory, 2020a; Pillot, 2017, 2019). Cathode (25–30%) and anode materials (8–12%) account for the largest shares. Labour costs account for around 2–4%.

Models used to project future battery costs typically rely on production volume assumptions and technology learning rates. However, the growing share of raw materials in total battery costs implies that this approach based on economies of scale and efficiency improvement might not provide a good guide to future cost developments, as raw material costs may well develop in a different direction from other cost components.

Given the importance of material costs in total battery costs, higher mineral prices could have a significant effect on achieving industry cost targets. For example, a doubling of lithium or nickel prices would induce a 6% increase in battery costs. If these events happen at the same time, the cost increase would eat up the anticipated learning effects associated with a doubling of capacity.

It is therefore of paramount importance for governments and industry to work to ensure adequate supply of battery metals to mitigate any price increases, and the resulting challenges for clean electrification.

High prices for rare earth elements could see a shift away from permanent-magnet motors towards induction motors, increasing demand for copper or aluminium

Over 90% of the EVs marketed today use permanent-magnet synchronous motors due to their high efficiency, compact size and high power density (Adamas Intelligence, 2021b; Pavel et al., 2017). However, their use of REEs such as neodymium, praseodymium, dysprosium and terbium – upwards of 1 kg per motor – raises concerns given the geographical concentration of raw material and processing in China, the lack of recycling pathways and high price fluctuations. For example, the price of neodymium has surged over the past six months from around USD 60/kg in June 2020 to over USD 120/kg in February 2021.

There are several pathways to reducing REE use in EV motors: (i) improving material efficiency in magnet production to obtain NdFeB magnets with less REE content but with similar performance; (ii) reducing the amount of NdFeB magnets in permanent-magnet synchronous motors; (iii) substituting permanent-magnet motors with REE-free motors.

Improved material efficiency in magnet production can reduce REE content in permanent magnets but with similar performance characteristics. For example, material efficiency for neodymium and praseodymium may improve by up to 30% between 2015 to 2030 in a permanent magnet of equal magnetic strength and cost (Pavel et al., 2017).

The use of permanent-magnet motors with less (or no) rare-earth magnets could also reduce REE use. For example, the BMW i3 uses a “hybrid” motor that uses around half the REE. Induction motors use no REEs, but require a substantial amount of copper (11–24 kg/motor) and are less efficient than those with permanent magnets. They are already used in several BEV models, including the Tesla Model S. There are options to also reduce copper use in induction motors: for example, the Audi e-tron uses an aluminium-rotor induction motor. Switched reluctance motors are also REE-free, but are still in the early stages of development.

Summary of motor types

	Mineral use	Current status and examples
Permanent-magnet synchronous	Neodymium, dysprosium, dysprosium, terbium	Used in all HEV and most PHEV and BEV
Induction	No rare earths; but significant copper or aluminium use	Some BEVs (e.g. Tesla S, Mercedes B)
Permanent-magnet without REE	No rare earths; potentially some nickel and cobalt use	Prototypes using ferrite or AlNiCo magnets
Switched reluctance	No rare earths or copper	First prototypes

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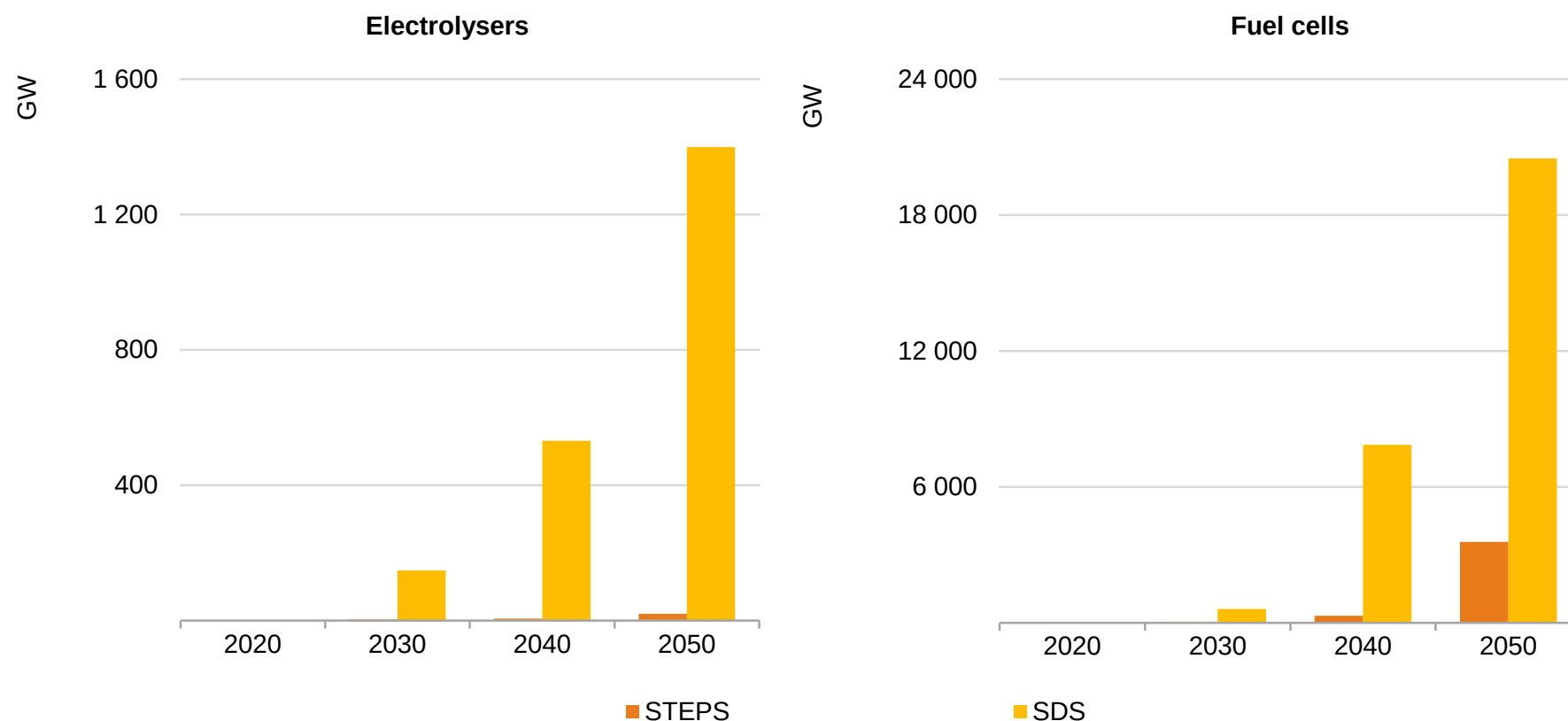
Note: HEV = hybrid electric vehicle.

Sources: Agamloh et al. (2020); Pavel et al. (2017); Widmer et al. (2015).

Hydrogen

Electrolysers that supply hydrogen and fuel cells that use it in vehicles are both major growth areas in the SDS, and present different mineral requirements

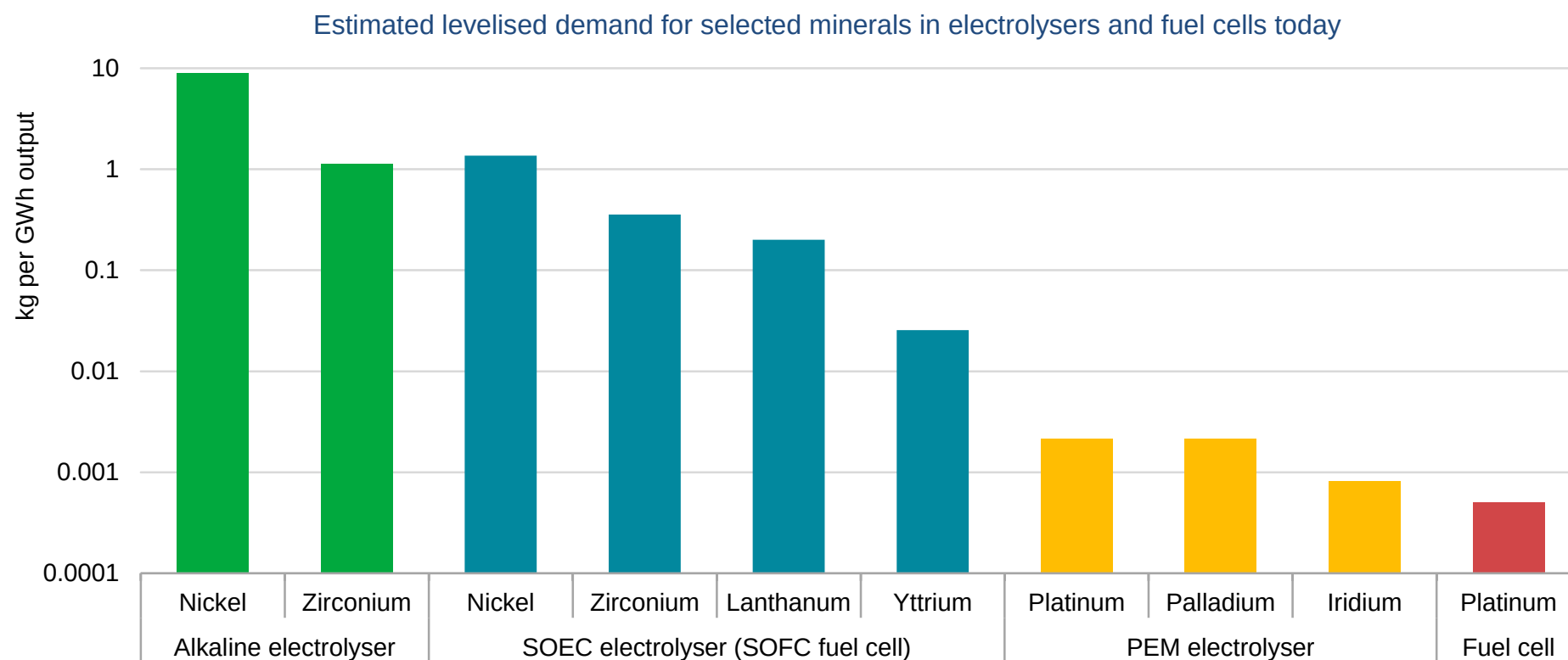
Global installed capacity of electrolysers and fuel cells in the SDS



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Source: IEA (2020c).

Hydrogen electrolysis and fuel cells could drive up demand for nickel, platinum and other minerals, but the market effects will depend on the shares of the different electrolyser types



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Notes: PEM = proton exchange membrane; SOEC = solid oxide electrolysis cells; SOFC = solid oxide fuel cell. Normalisation by output accounts for varying efficiencies of different electrolysis technologies. Full load hours of electrolysis assumed to be 5 000 hours per year.

Sources: Bareiß et al. (2019); Fuel Cells and Hydrogen Joint Undertaking (2018); James et al. (2018); Kiemel et al. (2021); Koj et al. (2017); Lundberg (2019); NEDO (2008); Smolinka et al. (2018); US Department of Energy (2014; 2015).

Alkaline and PEM, the two dominant types of electrolyzers, have very different mineral requirements; solid oxide electrolyzers present fewer mineral concerns, but are less developed

Hydrogen is a versatile energy carrier that can be produced from fossil fuels, biomass or electricity via electrolysis of water. Electrolyzers are a promising means of expanding the uses of renewable and nuclear electricity to include applications that benefit from storing or using a gaseous source. However, there is uncertainty about which of the three main types of electrolyser might dominate the market.

Alkaline electrolyzers

Alkaline electrolysis is a mature and commercial technology that has been used since the 1920s in both small and large plants. However, very large plants have not been built in recent decades because they were uncompetitive against hydrogen production from natural gas. The largest plants being built today are around 10 MW, with a single-stack demonstration project of this size entering operation in Japan in 2020. Compared with other electrolysis technologies, manufacturing capacity for alkaline electrolyzers is much larger, with an estimated 2 GW per year available today. European manufacturers have published plans to expand existing plants to achieve a capacity of over 6 GW per year. In China, where the manufacturing base is being developed rapidly, the cheaper and more familiar alkaline technology is also dominant.

Alkaline electrolyzers have low capital costs, partly because of their avoidance of precious metals. However, current designs do require nickel in quantities of more than one tonne per MW, or 1 000 tonnes for a 1 GW electrolyser plant, similar to some of the largest sizes currently proposed. Reductions in nickel demand for alkaline electrolyzers are expected, but nickel is not expected to be eliminated from future designs. However, if today's state-of-the-art design that use around 800 kg per MW were representative of future requirements, and even if alkaline electrolyzers dominate the market, then nickel demand for electrolyzers would remain much lower than that for batteries in the SDS. Nonetheless, in such a case, if nickel prices rise strongly due to challenges in the battery supply chain, electrolyser costs would be affected. In addition to nickel, 1 MW of alkaline electrolyser could today require around 100 kg of zirconium, half a tonne of aluminium and more than 10 tonnes of steel, along with smaller amounts of cobalt and copper catalysts.

Proton exchange membrane (PEM) electrolyzers

PEM electrolyzers have the advantages of smaller size, more flexible operation and higher-pressure output than alkaline, but are less mature, more costly and currently have shorter lifetimes. However, PEM represents the majority of current hydrogen demonstration

projects outside China, partly because there are incentives for electrolyser users to test the options and determine whether the operational benefits of PEM are worth the additional costs compared with alkaline electrolyzers.

The largest PEM facility – 20 MW – began operation in Canada in 2021, and others near this scale are in development in Europe. Globally, PEM manufacturing capacity stands at less than 500 MW per year, but two sites in Europe are under development to raise this to more than 1 GW per year by 2023. As more experience is gained and manufacturing scales up, capital costs are expected to decline significantly.

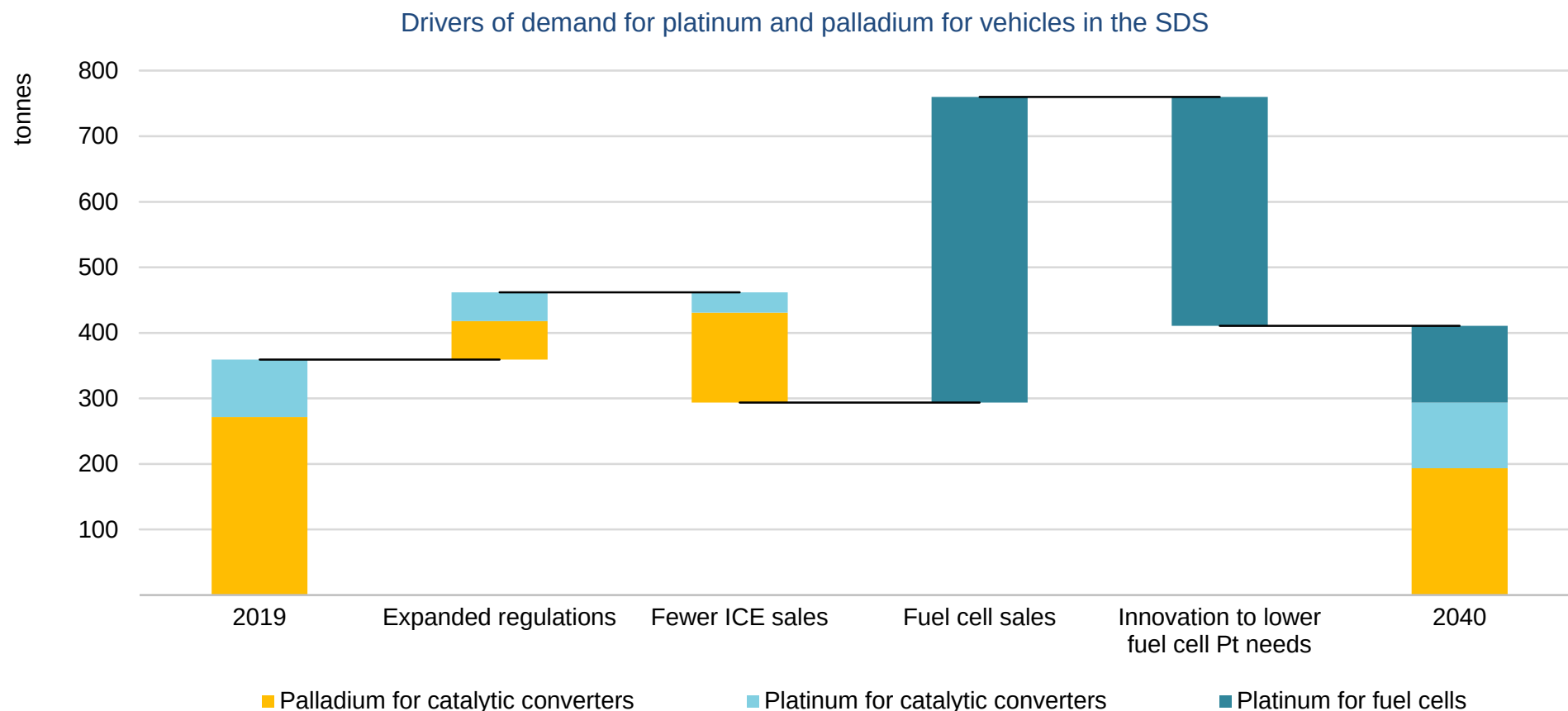
If PEM were to dominate the hydrogen market, it would increase energy-sector demand for platinum and iridium. PEM catalysts currently use around 0.3 kg of platinum and 0.7 kg of iridium per MW. Experts believe reductions to one-tenth of these amounts are possible in the next decade in order to minimise costs (Kiemel et al., 2021). A separate approach in development, using anion exchange membranes, could avoid the use of these metals altogether.

Solid oxide electrolysis cells (SOECs)

SOECs are currently being tested at smaller scales and have higher efficiencies and low material costs. It is not expected that they will come to dominate the market, but they have significant promise, especially because they can operate in reverse as fuel cells and can be integrated into other high-temperature processes or synthetic fuel

production. The primary mineral demands of SOECs are nickel (150-200 kg per MW), zirconium (around 40 kg per MW), lanthanum (around 20 kg per MW) and yttrium (less than 5 kg per MW). It is expected that each of these quantities could be halved through better design in the next decade, with technical potential to drop nickel content to below 10 kg per MW. To enable comparison with other electrolyzers, these quantities need to be adjusted downwards in line with the higher efficiencies of SOECs.

In the SDS, platinum demand for vehicles in 2040 remains dominated by catalytic converters and not fuel cells



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Note: Pt = platinum.

Major improvements that reduce the platinum intensity of fuel cells have been made in the past decade, with the amount of platinum in fuel cell cars halving

In clean energy transitions, internal combustion engine vehicles might be largely replaced by EVs, including fuel cell electric vehicles (FCEVs), with other important roles for non-vehicular transport and biofuels. While the automotive sector is set to become a dominant source of global demand for lithium, nickel and cobalt for EV batteries, it already leads demand for platinum and palladium for use in catalytic converters. For these so-called platinum group metals, a key issue is whether new demand from fuel cells will offset declining demand from internal combustion engine vehicles.

Fuel cells

While fuel cells for converting hydrogen to electricity have been in production for many years, the introduction of commercial passenger FCEVs has spurred innovation to reduce the use of platinum to limit costs. In 2014 Toyota's first-generation Mirai car used around 40g of platinum, around three-quarters less platinum per kW of output than the 2008 prototype (James et al., 2018). The second-generation Mirai, released in 2020, reduced this by roughly a further third per kW and increased the maximum power output from 114 kW to 158 kW. Plans are in place in Japan to reach 5g per car in 2040. Similar targets for reduced platinum loading per kW have also been set by US DOE, including targets for trucks, which require three times more power than cars. If these targets are met, demand for FCEVs in the SDS would grow platinum demand to just over 100 tonnes by 2040.

Catalytic converters

Catalytic converters represent around 40% of global platinum demand today, and are also the major source of demand for two other platinum group metals: rhodium and palladium. Despite all early catalytic converters using mostly platinum, gasoline-based systems now have a palladium to platinum ratio of 5:1 or higher, partly because palladium has been cheaper historically. Catalytic converters for diesel engines use a more equal share of platinum and palladium, while all systems use smaller quantities of rhodium for controlling nitrogen oxides.

The higher prevalence of catalytic converters in gasoline vehicles means that palladium demand now outstrips platinum demand in the automotive sector by between 200% and 300%. Tightening regulations and responses to car emissions scandals have pushed up palladium prices to double those of platinum per tonne. While substitution between the metals is possible, it requires a redesign of the catalyst system and therefore needs more certainty about future relative prices than exists today. In the SDS, an increase in the coverage of emissions regulation to include all new cars by 2030, coupled with continued sales of internal combustion engine, especially hybrids, keeps demand for platinum group metals for use in catalytic converters above that for fuel cells by 2040.

Reliable supply of minerals

Introduction

In Chapter 2 we explored how the material-intensive nature of a clean energy system is set to drive a huge rise in demand for critical minerals. This naturally raises questions about whether this growth – in most cases well above the historical pace – can be supplied in a reliable manner, and whether the environmental and social consequences associated with mineral production can be managed properly.

For some minerals, demand and supply were delicately balanced before the pandemic, and there were expectations that supply imbalances might emerge in the coming years. While Covid-induced demand reductions alleviated some of these pressures, concerns about the adequacy and affordability of future supply are ever-present as the world emerges from the crisis and many countries put renewables and batteries at the heart of their economic stimulus packages. The price rallies in the latter part of 2020 and early 2021 may have provided a preview of what could happen when the world accelerates onto a decarbonisation pathway, although these price increases were not always linked to physical market balances.

If history is any guide, the market responds to strains on supply by reducing demand, substitution or increasing supply. But this is typically accompanied by price volatility, considerable time lags or

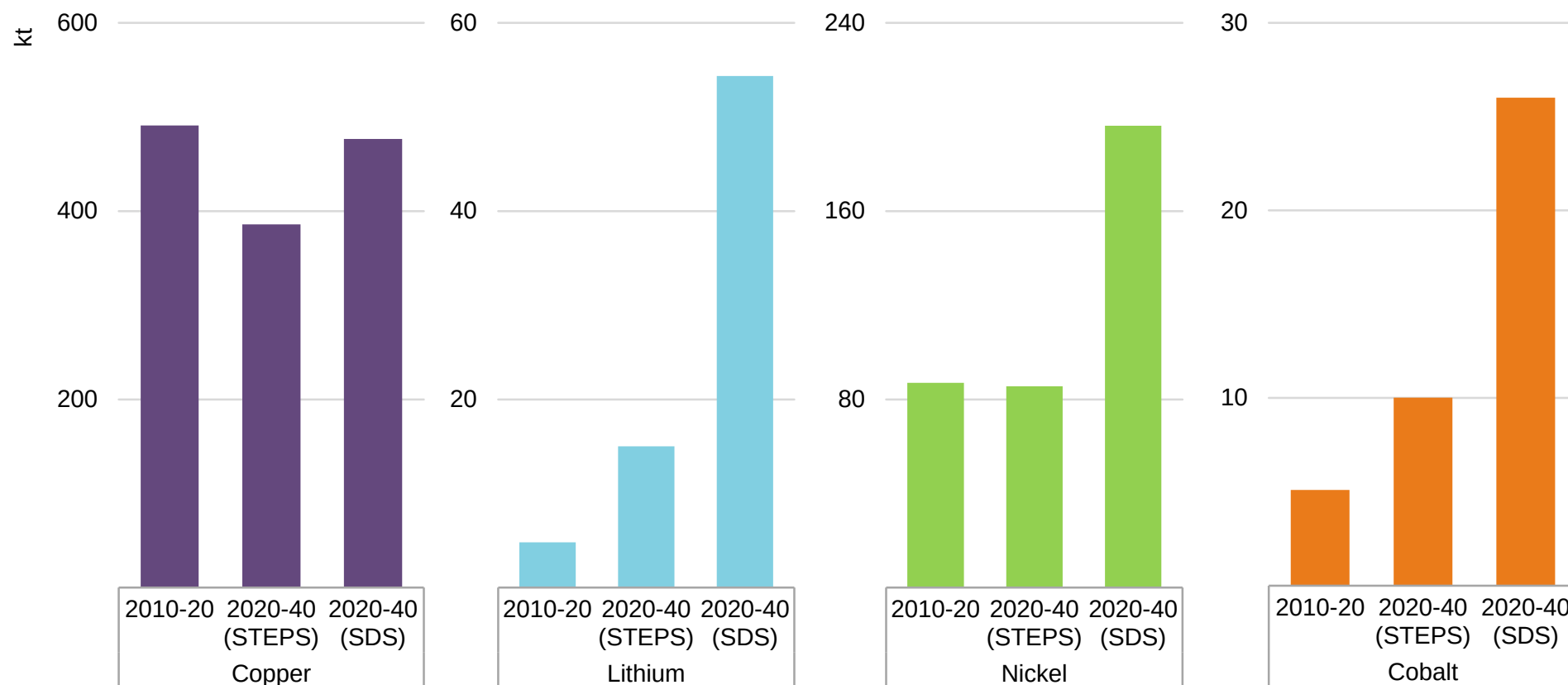
some loss of performance or efficiency. In the context of clean energy transitions, inadequate mineral supply could result in more expensive, delayed or less efficient transitions. Given the urgency of reducing emissions, this is a possibility that the world can ill afford.

In this chapter we examine some of the major vulnerabilities that may hinder adequate supply and lead to greater price volatility, focusing on the five focus minerals (copper, lithium, nickel, cobalt and rare earth elements [REEs]) that play a particularly important role in many clean energy technologies. We also consider the specific challenges that each mineral faces. We then discuss policy approaches to ensure reliable supply of minerals, drawing lessons from historical episodes of disruption as well as the IEA's long-standing experience in safeguarding oil market security. Finally, the chapter assesses the potential contributions from secondary supply, via recycling, and discusses what can be done to scale up recycling to reduce primary supply requirements and in turn security risks.

How policy makers and companies handle the challenges around reliable and sustainable supply will determine whether critical minerals are a vital enabler of clean energy transitions or a bottleneck in the process.

In the SDS, the required level of supply growth for most minerals is well above the levels seen in the past decade

Annual average total demand growth for selected minerals by scenario

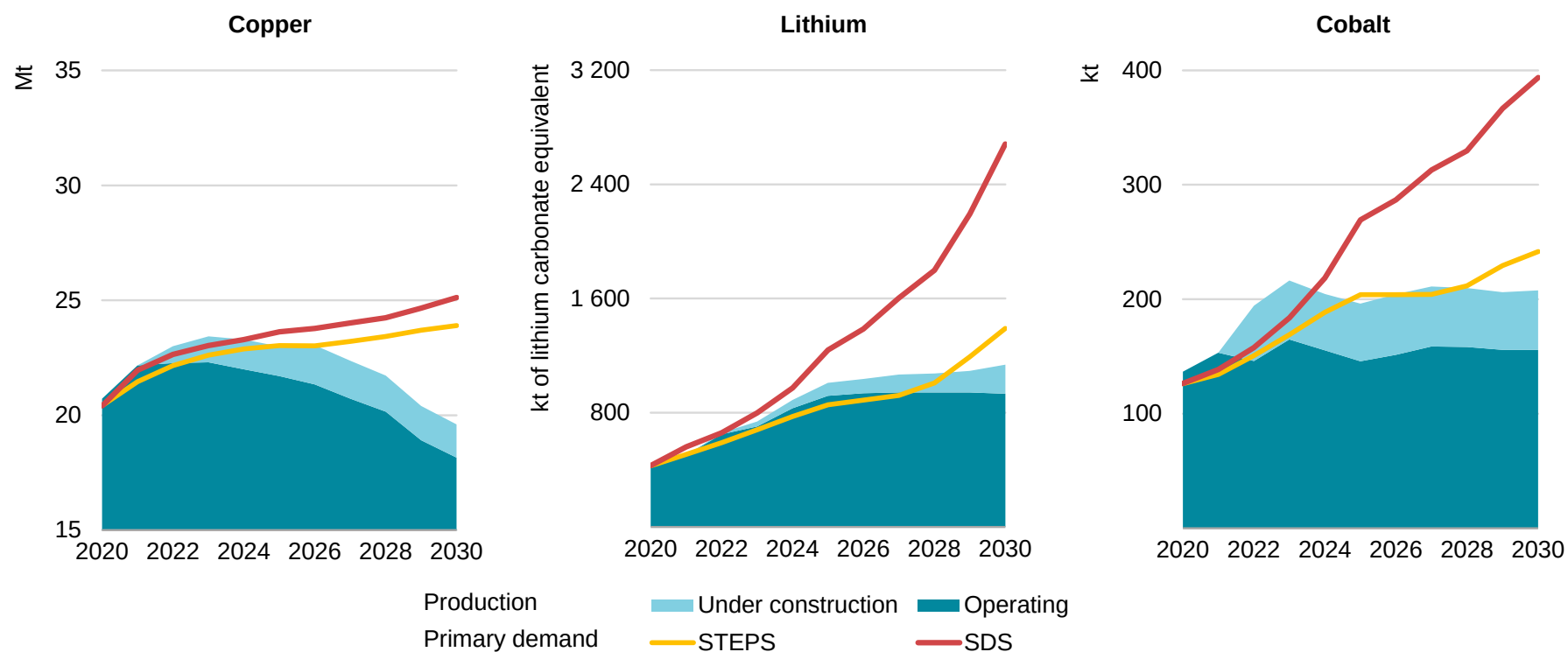


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Notes: Total demand includes both demand from clean energy technologies and other consuming sectors. kt = thousand tonnes; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

Meeting primary demand in the SDS requires strong growth in investment to bring forward new supply sources over the next decade

Committed mine production and primary demand for selected minerals



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Notes: Primary demand is total demand net of recycled volume (also called primary supply requirements). Projected production profiles are sourced from the S&P Global Market Intelligence database with adjustments to unspecified volumes. Operating projects include the expansion of existing mines. Under-construction projects include those for which the development stage is indicated as commissioning, construction planned, construction started or preproduction. Mt = million tonnes.

Source: IEA analysis based on S&P Global (2021).

Current supply and investment plans are not yet ready for accelerated energy transitions

In today's markets, most minerals that are vital to clean energy technologies are relatively well supplied. Prices for certain minerals have risen strongly since the second half of 2020, with some reaching multi-year highs. This was due to expectations of strong future growth, as well as demand recovery in the People's Republic of China ("China"). While it is too early to brace for the next price cycle, if we slightly extend the time horizon, we see ample reasons to be vigilant about the ability of supply to meet demand – especially as many governments redouble efforts to accelerate energy transitions.

In the SDS, the scale of demand growth is well above the levels seen in recent decades. For example, in the period to 2040 annual average demand growth for nickel and cobalt is two and five times higher respectively than the levels seen in the 2010s. In the case of copper, the SDS sees a continuation of strong demand growth in the 2010s through the coming decades.

The picture for near-term supply is mixed. Some minerals such as lithium raw material and cobalt are expected to be in surplus in the near term, while lithium hydroxide, battery-grade nickel and certain REEs (e.g. neodymium and dysprosium) might face tight supply in

the years ahead as demand rises. However, after the medium term, projected demand surpasses the expected supply from existing mines and projects under construction for most minerals, meaning that significant additional investment will be needed to support demand growth.

This is especially the case to meet requirements in the SDS. Current supply and investment plans are geared to a world of gradual, insufficient action on climate change (the STEPS trajectory), but not sufficient to support accelerated energy transitions. While there are a host of projects in the pipeline at varying stages of development, several risk factors may, if unchecked, increase the possibility of market tightness and new price cycles, slowing energy transitions. These include (i) higher geographical concentration of production, (ii) a mismatch between the pace of change in demand and the typical project development timeline, (iii) the effects of declining resource quality, (iv) growing scrutiny of environmental and social performance of production, and (v) higher exposure to climate risk such as water stress, among others (which are explored in more detail in the following pages).

Major producing countries of selected minerals, 2019 and 2025

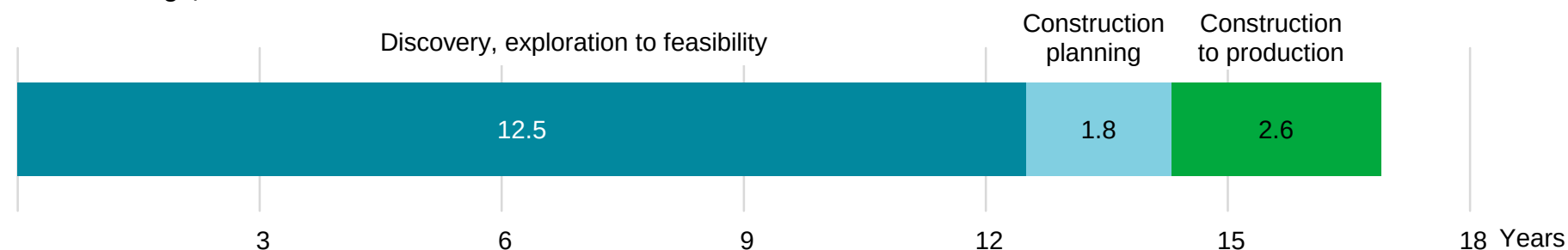


Source: IEA analysis based on the project pipeline in S&P Global (2021) complemented by World Bureau of Metal Statistics (2020) and Adamas Intelligence (2020) (for REEs).

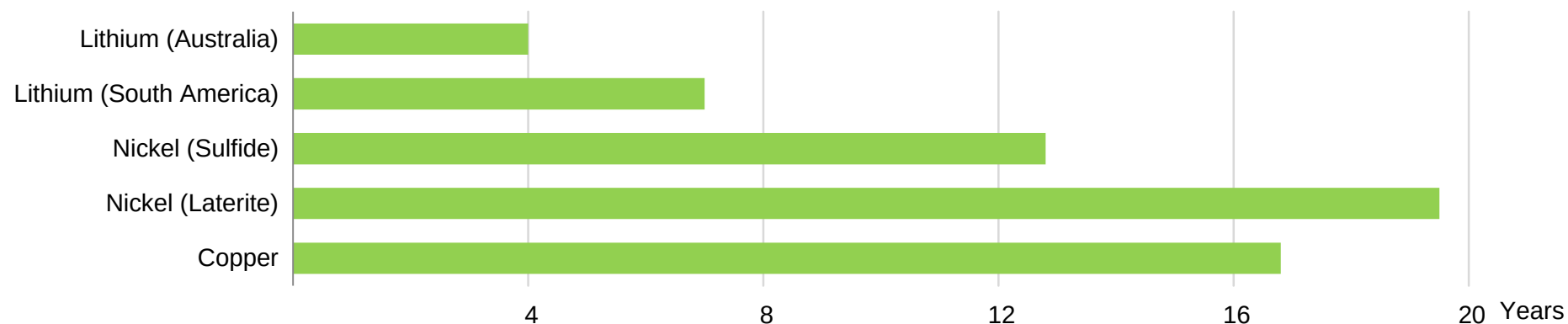
Project development lead times: Market tightness can appear much more quickly than new projects

Global average lead times from discovery to production, 2010-2019

Global average, 2010-2019



Average observed lead time for selected minerals (from discovery to production)

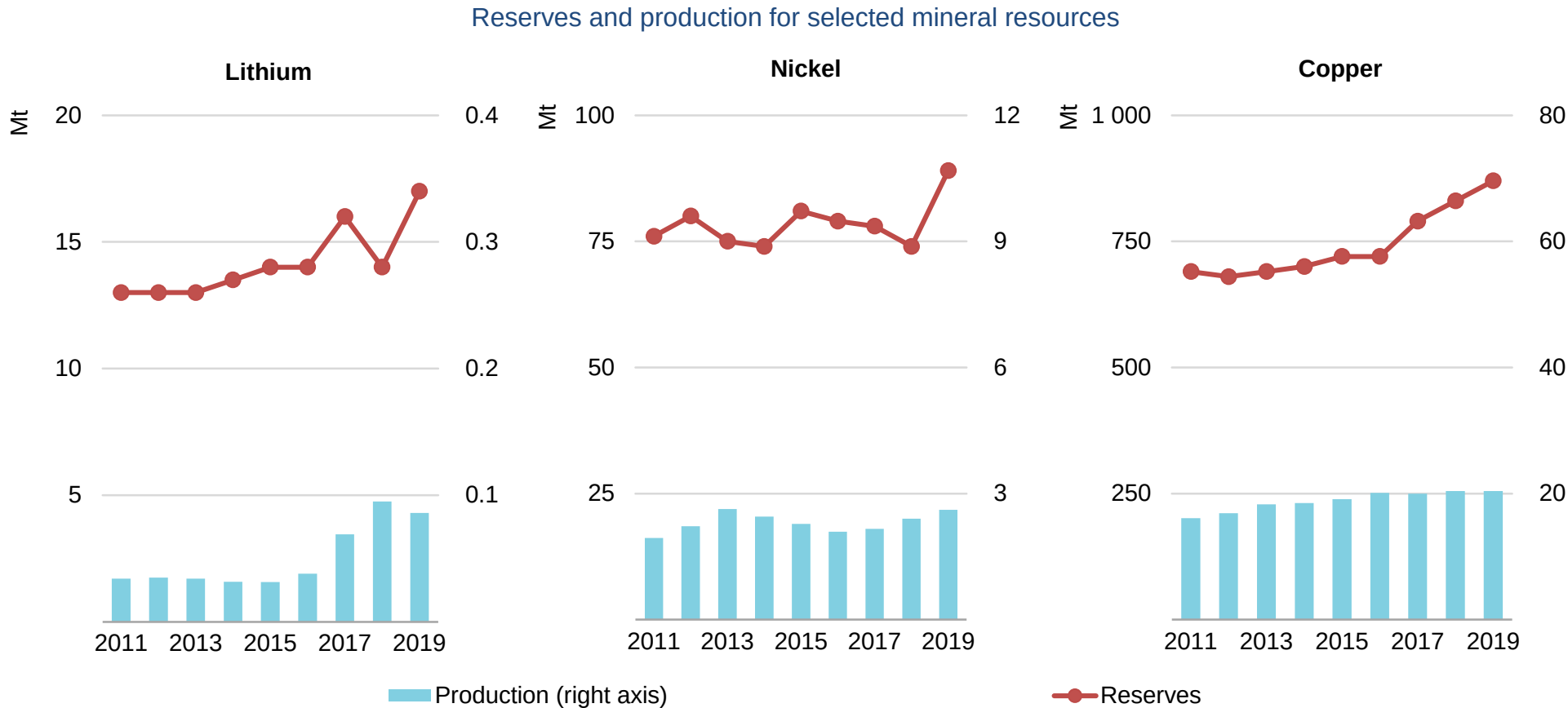


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Note: Global average values are based on the top 35 mining projects that came online between 2010 and 2019.

Source: IEA analysis based on S&P Global (2020), S&P Global (2019a) and Schodde (2017).

Resources: There is no shortage of resources. Economically viable reserves have been growing despite continued production growth

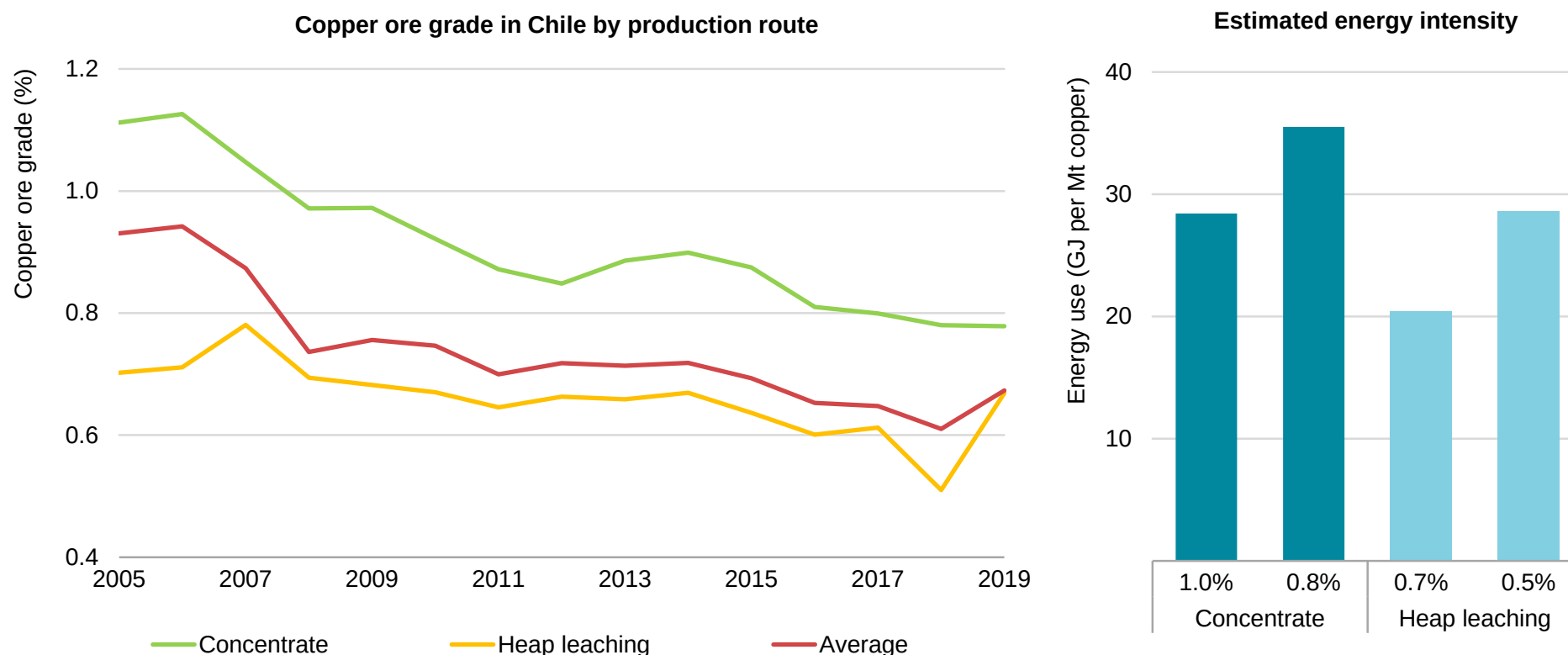


Sources: USGS (2021); USGS (2020).

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Resources: However, declining ore quality poses multiple challenges for extraction and processing costs, emissions and waste volumes

Average ore grade in Chile and estimated energy intensity by quality



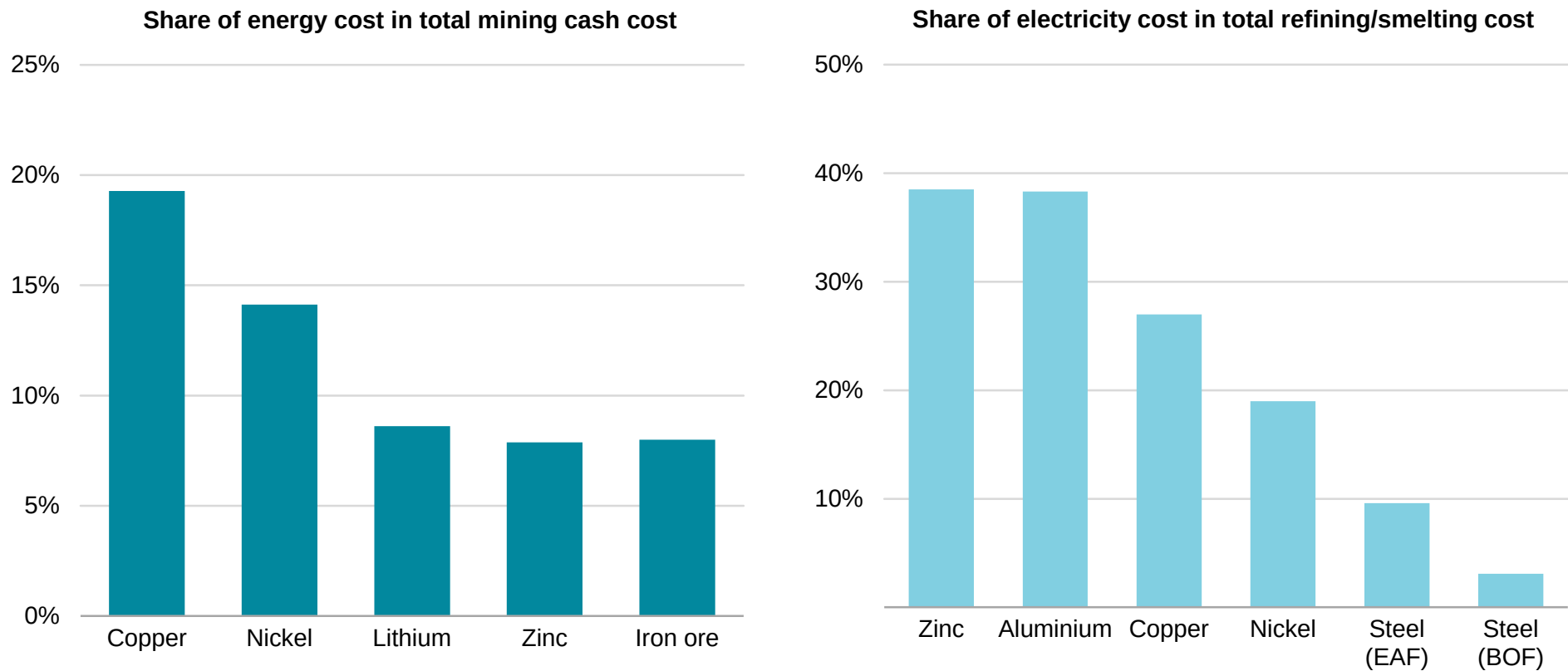
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Notes: Energy use for concentrate covers mine, concentrating plant, smelter, refinery and services. For heap leaching, energy use covers mine, leaching, solvent extraction, electro-winning processes and services. GJ = gigajoule.

Source: IEA analysis based on COCHILCO (2019) and Rötzer and Schmidt (2020).

Scrutiny of ESG issues: Growing imperative to improve environmental performance could also put upward pressure on production costs of energy-intensive mining and processing activities

Share of energy cost in total mining cash cost and electricity intensity for selected materials



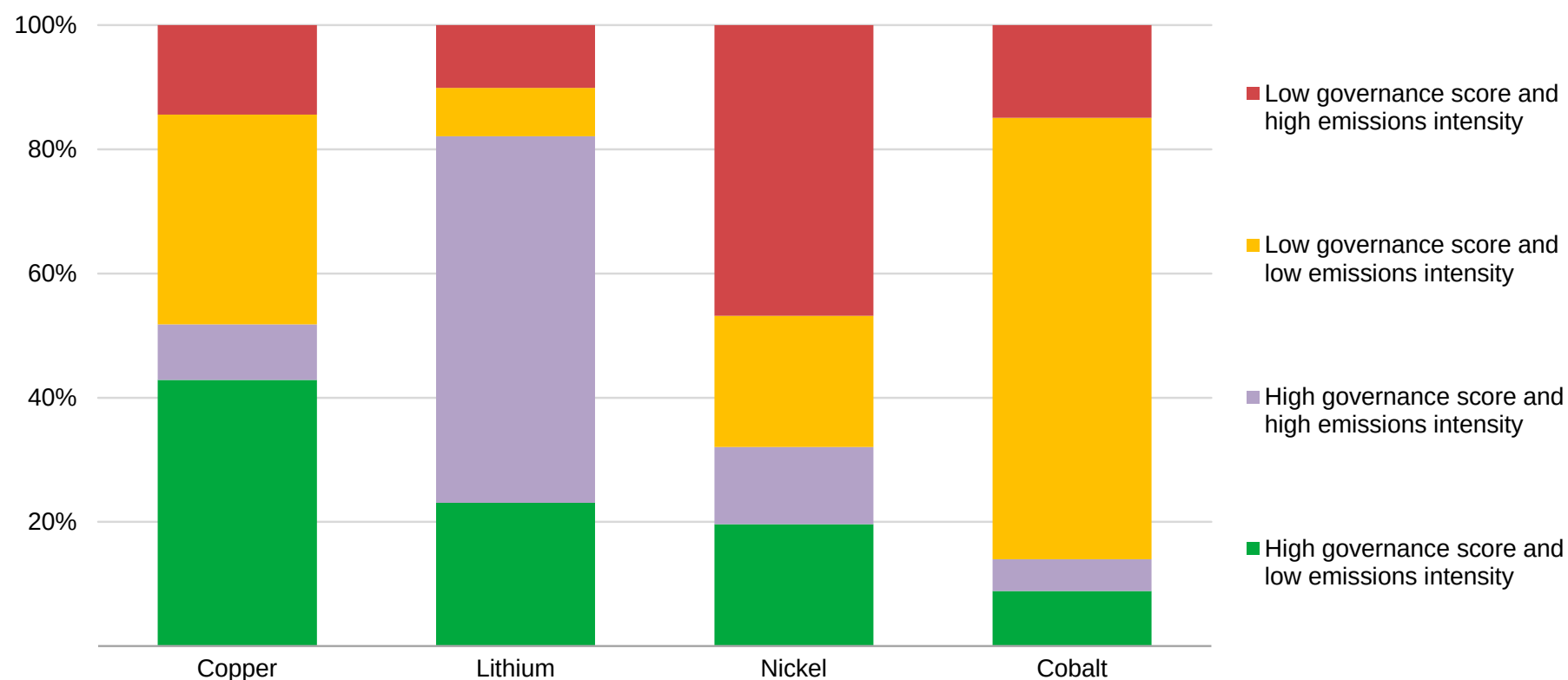
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Notes: ESG = environmental, social and governance; EAF = electric arc furnace; BOF = basic oxygen furnace. Energy and electricity costs show global average values, and can vary by region and operational practice.

Source: IEA analysis based on S&P Global (2021) for mining, BHP (2011) for iron ore and Eurometaux (2020) for refining/smelting.

Scrutiny of ESG issues: The majority of current production volumes come from regions with low governance scores or high emissions intensity

Distribution of production of selected minerals by governance and emissions performance, 2019



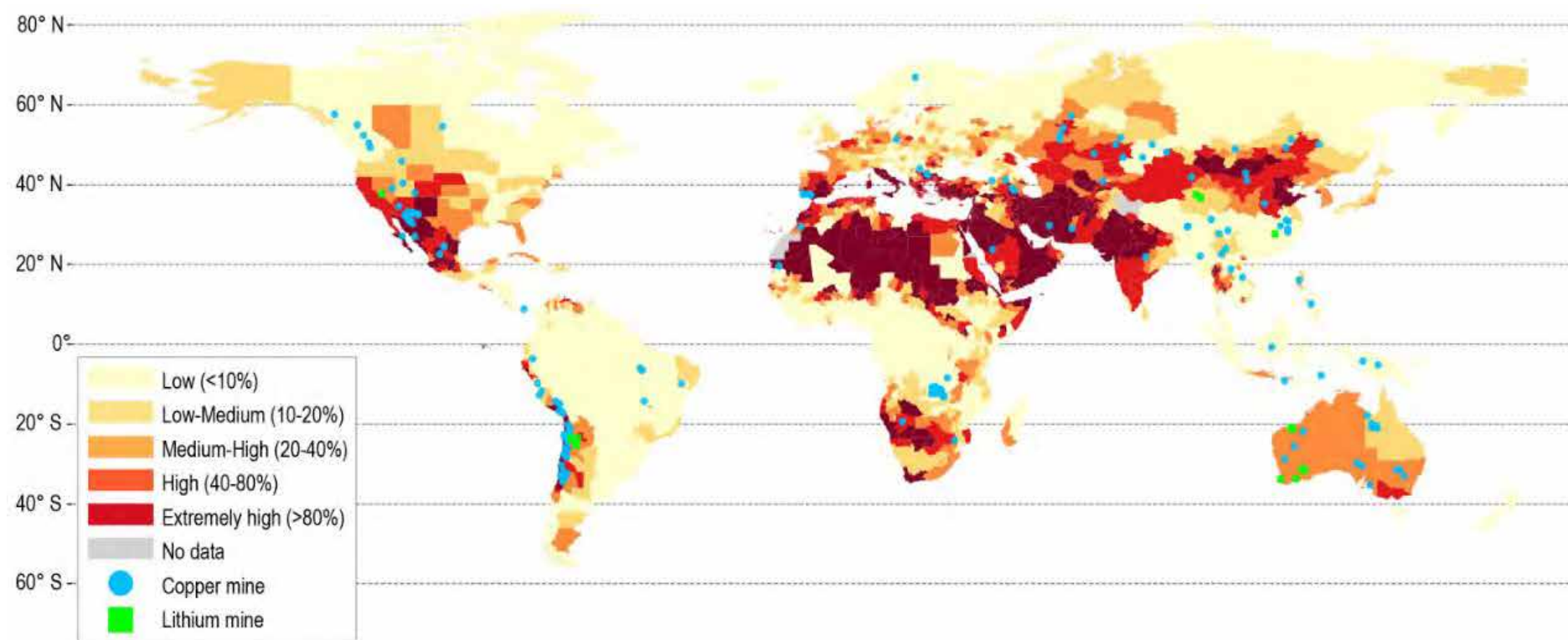
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Notes: Analysis using the World Bank Worldwide Governance Indicator (as a proxy for governance) and electricity CO₂ intensity (as a proxy for emissions performance). Composite governance rank scores below 50 were classified as low governance; electricity CO₂ emissions intensity above 463 g CO₂/kWh (global average value in 2019) was classified as high emissions intensity.

Source: World Bank (2020), IEA (2020).

Climate risk: Mining assets are exposed to growing climate risks and water stress

Location of copper and lithium mines and water stress levels, 2020



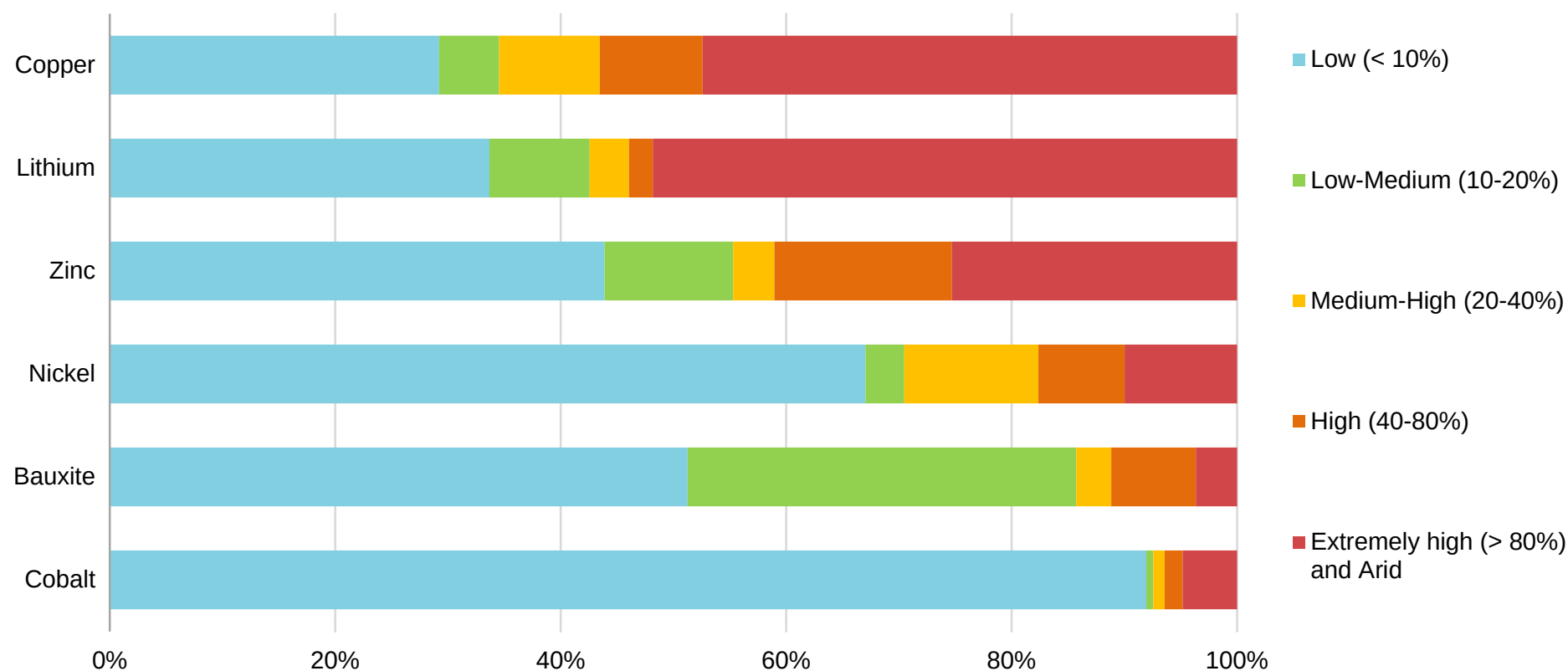
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Note: The exact water stress levels vary by location. While we assessed the share of mines located in water stress areas according to granular regional representations (shown on the following page), we aggregated them at the sub-national level on the map for the sake of simplification. Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.

Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Climate risk: Around half of global lithium and copper production is concentrated in areas of high water stress

Share of production volume by water stress level for selected minerals, 2020



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Note: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.

Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Several vulnerabilities may hinder adequate mineral supply and lead to greater price volatility

As countries step up their climate ambitions, securing reliable supplies of critical minerals may have major impacts on the affordability of clean energy technologies and the prospects for countries to nurture a clean technology manufacturing industry. Several risk factors are in play.

Geographical concentration: Today's production and processing operations for many energy transition minerals are highly concentrated in a small number of countries, making the system vulnerable to political instability, geopolitical risks and possible export restrictions (see Chapter 1).

Our analysis of today's project pipeline indicates that this picture is unlikely to change in the near term. With the exception of copper, where planned production growth in the United States, DRC and Indonesia helps diversify the pool of supply, most of the output growth for lithium, nickel and cobalt are expected to come from today's major producers, implying a higher degree of concentration in the years ahead. Under these circumstances, physical disruptions (e.g. earthquakes, tsunamis and flooding) or regulatory and geopolitical events in major producing countries can have large impacts on the availability of minerals, and in turn on prices. Recent events, such as Indonesia's ban on nickel ore export and China's export ban on REEs, serve to highlight these concerns. More recently, the military coup in Myanmar has raised concerns over

supply disruption of heavy REEs, fuelling a surge in prices (Reuters, 2021a). Natural disasters have also become one of the most frequent causes of mineral supply disruption, third only to accidents and labour strikes (Hatayama and Tahara, 2018).

Project development lead times: The recent pick-up in investment in many minerals offers some support for near-term supply, but additional investment will be required to satisfy rising demand, especially in the SDS. Despite growing momentum behind energy transitions, uncertainty over the trajectory of future demand may hold back company investment decisions needed to achieve orderly energy transitions. Long project lead times exacerbate the risk of a mismatch in timing between demand and the industry's ability to bring on new projects.

Analysis of major mines that came online between 2010 and 2019 shows that it took 16.5 years on average to develop projects from discovery to first production, although the exact duration varies by mineral, location and mine type (S&P Global, 2020). On average, it took more than 12 years to complete exploration and feasibility studies, and 4-5 years for the construction phase. These long lead times raise questions about the ability of supply to ramp up output if demand were to pick up rapidly (although some supply sources such as expansion from existing mines and artisanal small-scale mining have shorter lead times). If companies wait for deficits to emerge

before committing to new projects, this could lead to a prolonged period of market tightness and price volatility.

A further complication is that mining is only one part of the value chain. Whether investment occurs in a co-ordinated manner throughout the value chain is another significant issue, as price signals may not be passed efficiently along the value chain. The recent rise in lithium carbonate prices (and a possible tightening of lithium hydroxide supply) amid ample supply of lithium raw material is one indication of possible strains arising from different parts of the value chain. REE processing is another example of complication, where growth in mined output does not necessarily guarantee greater supply of certain rare earth oxides in high demand (see section on REEs).

Resource quality: Like other commodities, minerals are not free from concerns over the availability of resources. Resources are known metallic concentrations with reasonable prospects for eventual economic extraction, whereas reserves are the economically mineable part of resources under today's circumstances. There are generally no signs of shortages in these areas: despite continued production growth over the past decades, economically viable reserves have been increasing for many energy transition minerals. For example, lithium reserves increased by 30% between 2011 and 2019, while production expanded two-and-a-half times. The volume of copper reserves also rose by 30% in the last 10 years. This is because reserves have been replenished by

exploration activities triggered by growing demand. In Australia lithium reserves increased by 70% in 2017 as price spikes in 2016-17 motivated the country to tap its under-explored resources.

Concerns about resources relate to quality rather than quantity. In recent years, ore quality has continued to decline across commodities as high-quality deposits (and higher-grade parts of the deposits) are exploited earlier. Technological improvement that allows the exploitation of lower-grade deposits has also played a role. For example, the average copper ore grade in Chile has decreased by 30% over the last 15 years. This brings about multiple challenges. Extracting metal content from lower-grade ores requires more energy, exerting upward pressure on extraction and processing costs and carbon dioxide (CO₂) emissions. Lower-grade ores also generate larger amounts of rock waste and tailings that require careful treatment. This means that, over time, strengthened efforts would be needed to offset underlying upward pressures on production costs.

Growing scrutiny of ESG issues: While minerals play a vital role in supporting clean energy transitions, energy is also crucial in the production of minerals. Due in part to declining resource quality, the production and processing of energy transition minerals are energy-intensive, involving higher emissions to produce the same quantity of product. In recent years, mining and processing companies have faced growing pressure to address these and other issues related to their social and environmental performance (see Chapter 4). A growing number of consumers and investors are requesting

companies to disclose targets and action plans on these issues. Tightening scrutiny of ESG issues could have an impact on costs and supply prospects, especially in areas reliant on artisanal mines or where requirements are uneven across different jurisdictions or types of company. For example, around 10-15% of copper, lithium and cobalt production and almost half of nickel production in 2019 came from regions with low governance scores and high emissions intensity.

Exposure to climate risks: In recent years, a combination of more frequent drought events in major producing regions and higher water intensity in ore processing has brought the critical importance of sustainable water sourcing to attention. For example, in 2019 the worst drought in more than 60 years severely affected some operations in Chile, with similar events having occurred in Australia, Zambia and others. The El Teniente mine, the largest underground copper mine in Chile, implemented water rationing to deal with severe droughts (CRU, 2020a).

Among minerals, copper and lithium are particularly vulnerable to water stress given their high water requirements. Over 50% of today's lithium production is concentrated in areas with high water stress levels. Some 80% of copper output in Chile is produced in mines

located in high water stress and arid areas. This has triggered companies to invest in desalination capacity to mitigate the risk. Moreover, the share of mines located in high water stress areas is set to increase over time. As climate change causes more frequent droughts and alters water flows, the availability of high-quality water resources will become a crucial factor affecting stable minerals supplies.

In addition to water shortage, several major producing regions such as Australia, China, and Africa are also subject to other forms of climate risk, including extreme heat or flooding, which pose challenges to ensuring reliable and sustainable supplies. For example, flooding can lead to spills of hazardous waste from mine sites or waste storage, and tailings dam failure, with extensive environmental damage (see Chapter 4; Rüttinger et al., 2020). This requires companies to assess physical risks from climate change in their operations and integrate climate resilience planning in their sustainability strategies. For example, BHP periodically reviews the potential vulnerabilities of their operating assets and investment portfolio to climate risks, and devises strategies to address them.

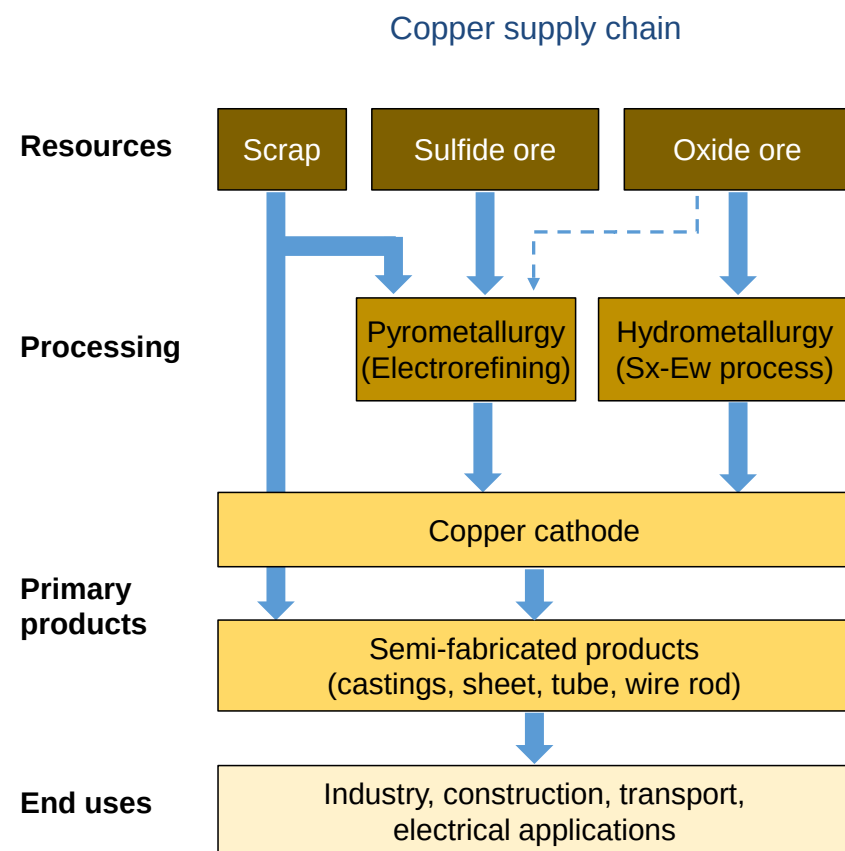
Supply prospects for the focus minerals

Each mineral faces a different set of challenges in ensuring adequate supply

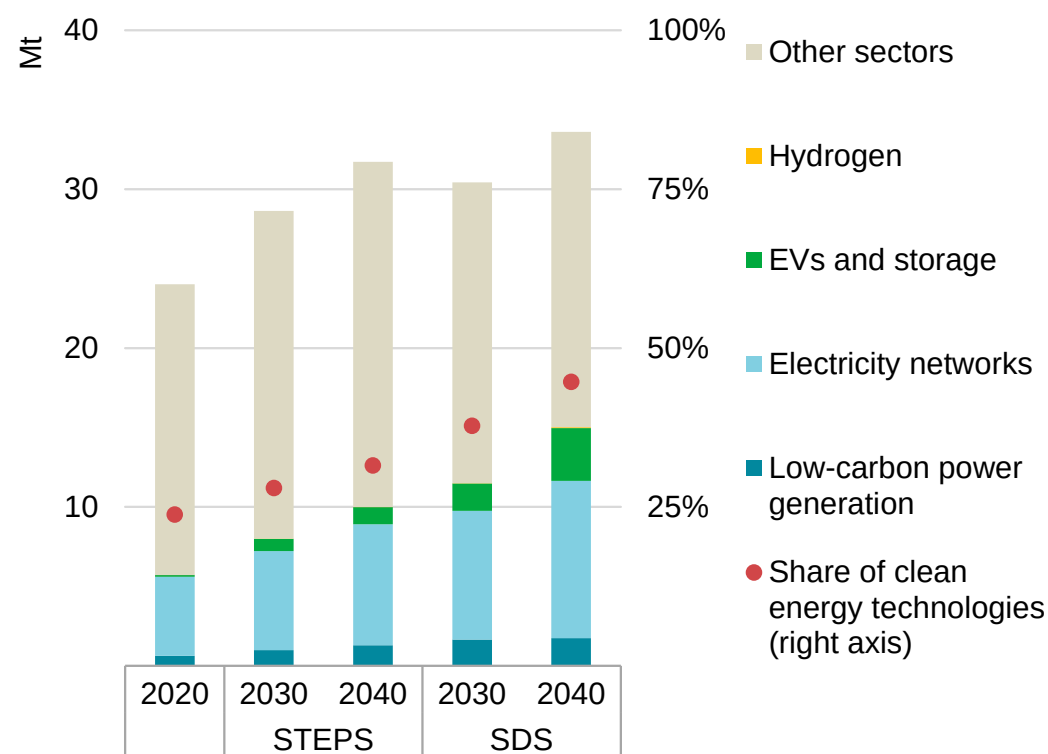
Mineral	Key challenges
Copper	<ul style="list-style-type: none"> • Challenging to substitute due to its superior performance in electrical applications • Mines currently in operation are nearing their peak due to declining ore quality and reserves exhaustion • Declining ore quality exerts upward pressure on production costs, emissions and waste volumes • Mines in South America and Australia are exposed to high levels of climate and water stress
Lithium	<ul style="list-style-type: none"> • Possible bottleneck in lithium chemical production as many smaller producers are financially constrained after years of depressed prices • Lithium chemical production is highly concentrated in a small number of regions, with China accounting for 60% of global production (over 80% for lithium hydroxide) • Mines in South America and Australia are exposed to high levels of climate and water stress
Nickel	<ul style="list-style-type: none"> • Possible tightening of battery-grade Class 1 supply, with high reliance on the success of HPAL projects in Indonesia; HPAL projects have track records of delays and cost overruns • Alternative Class 1 supply options (e.g. conversion of NPI to nickel matte) are either cost-prohibitive or emissions-intensive • Growing environmental concerns around higher CO₂ emissions and tailings disposal
Cobalt	<ul style="list-style-type: none"> • High reliance on the DRC for production and China for refining (both around 70%) set to persist, as only a few projects are under development outside these countries • Significance on artisanal small-scale mining makes the supply vulnerable to social pressures • New supply is subject to developments in nickel and copper markets as some 90% of cobalt is produced as a by-product of these minerals
Rare earth elements	<ul style="list-style-type: none"> • Dominance of China across the value chain from mining to processing and magnet production • Negative environmental credentials of processing operations • Differences in demand outlooks for individual elements bring risk of price spikes for those in high demand (e.g. neodymium) and slumps for those in low demand (e.g. cerium)

Notes: HPAL = high-pressure acid leaching; NPI = nickel pig iron.

Copper: From resource to consumer



Total copper demand by sector and scenario



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Notes: EVs = electric vehicles. Sx-Ew = solvent extraction and electrowinning. High-grade oxide ore is processed in pyrometallurgy. Demand does not include the volume reused in a semi-fabricated form.

Copper: Copper is the most widely used mineral in clean energy technologies

Thanks to its unmatched thermal and electrical conductivity, copper is widely used in a broad range of electronic and industrial applications. Its attributes make it challenging to substitute.

The western part of South America, notably Chile and Peru, is the largest producer of mined copper, responsible for 40% of global output. China, the DRC, the United States and Australia are the other major producing countries.

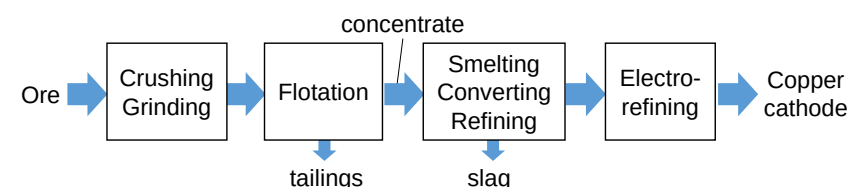
There are two main types of copper ore; copper sulfide (about 80% of production) and copper oxide (about 20%). Sulfide ore is processed via a pyrometallurgical process (known as smelting); the ore is crushed and ground, then transformed into concentrates, which are then exported to China and other countries to produce refined copper through electrorefining. Oxide ore is processed through a hydrometallurgical process known as Sx-Ew (solvent extraction and electrowinning), which extracts copper from the ore to the solvent and then separates copper cathode from the solvent by electrowinning. Sx-Ew processes are usually conducted near mining sites. In addition to mining, recycled scrap also plays a role. Depending on the purity, some scrap (e.g. discarded metal in manufacturing processes) is easily remanufactured, whereas less pure scrap (e.g. post-consumer products) needs to go through a pyrometallurgical process. China is the largest copper refining country, with around 40% market share,

followed by Chile, Japan and Russia. However, as China accounts for 50% of global demand for refined copper, it also imports refined copper products from abroad.

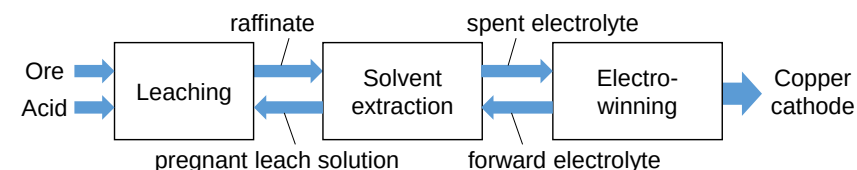
Copper demand for clean energy technologies remains one of the largest both by weight and monetary value. Clean energy technologies are also the fastest growing segment for copper demand. Their share of total copper demand rises from 24% today to 30% by 2040 in the STEPS and 45% in the SDS.

Copper processing processes

Pyrometallurgical process



Hydrometallurgical process



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Sources: Hawker et al. (2014); Forsén et al. (2017).

Copper: New projects under development could bring a sizeable boost to near-term supply, but more is needed to support rising demand

Copper supply has been expanding rapidly over the past decades to satisfy rising demand caused by strong economic growth in emerging and developing economies. More than 250 mines currently operate in nearly 40 countries, producing around 21 Mt of copper. This is 30% greater than 10 years ago.

However, past trends may not be a good guide to what could happen in the coming decades. Production at today's major copper mines has already peaked or is expected to peak in the early 2020s due to declining ore quality and reserve exhaustion. For example, the world's largest copper mine, Escondida in Chile, appears to have reached a peak and its production in 2025 is expected to be at least 5% lower than today (S&P Global, 2021).

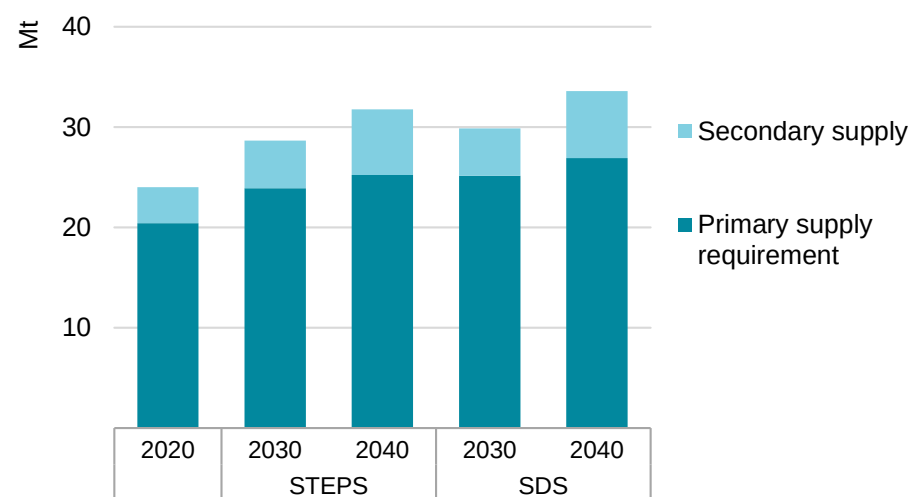
On the back of optimism for copper's role in the energy transition, investment has been picking up. A few large projects, such as Quellaveco in Peru and Kamo-a-Kakula in the DRC are under construction. Several expansion projects such as Oyu Tolgoi in Mongolia are also in progress. These projects could deliver considerable near-term supply, if completed on schedule.

While Chile and Peru remain the largest producers through to 2025, the picture is set to become slightly more diverse, with the DRC and Indonesia increasing their production. As for processing, China is

expected to continue its dominant position in the near term, with its capacity growth to 2025 accounting for nearly half of all planned additions to global capacity. As China's processing share increases (but not its mining share), the country is set to have more influence on the trade and pricing of intermediate products.

Beyond the near term, few projects are planned to start operations in the late 2020s, while output from existing mines is expected to contract further. Meeting rising demand in the longer term would require continued new project development.

Primary supply requirements for copper by scenario



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Copper: Declining ore quality exerts upward pressure on production costs and emissions, requiring additional efforts for technology innovation and efficiency improvement

While there is no shortage of resources (e.g. the size of copper reserves has increased by 30% over the last 10 years), developing new projects has become challenging due mainly to declining ore quality in major producing regions. As noted above, the average grades of concentrate in Chile have decreased by 30% since 2005. The feed for hydrometallurgical processes has also deteriorated in quality. Currently the copper content in Chilean ore is about 0.7% on average. The deposits in some major mines are depleting and developments are moving towards the fringes of exploited deposits.

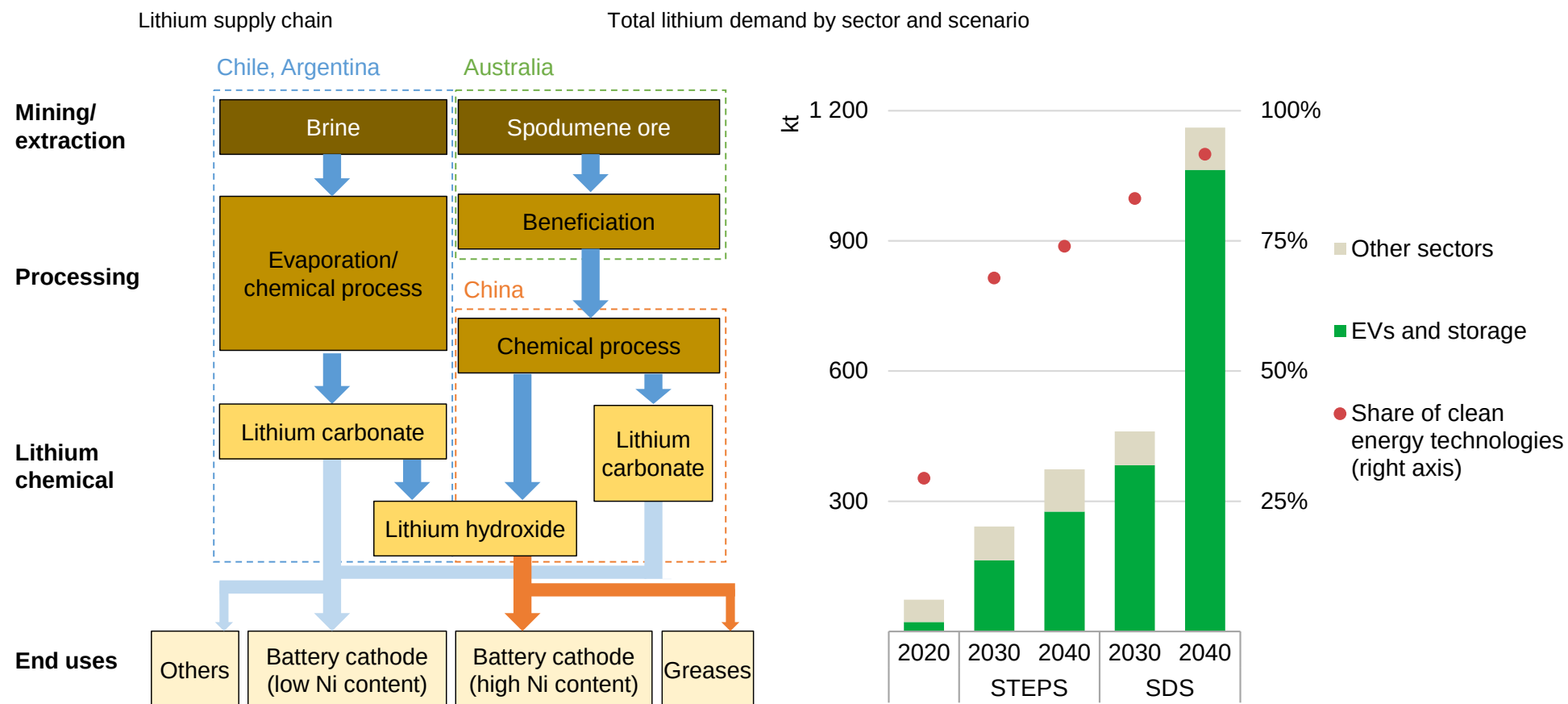
Extracting metal content from lower grade ores gives rise to additional cost and energy use, not just for on-site processing, but also for operations along the value chain (e.g. dust suppression and reclamation). Moreover, the deeper the production site, the more cost and energy are required.

While cost escalations are a major challenge for the copper industry, the impacts of resource depletion can be offset by technology innovation. Until the late 19th century, average ore grades were 10-20%; then they decreased to 2-3% in the early part of 20th century (Henckens and Worrell, 2020). More recently, technologies such as aerial surveys, satellite imagery, geographic information systems and computer models have unlocked new supplies in a cost-effective

manner, enabling a dramatic increase in output (Rötzer and Schmidt, 2018). In particular, the emergence of Sx-Ew processes since the 1970s has allowed greater efficiency in dealing with oxide resources. This process accounts for 20% of global copper production today. As with other minerals, continued technology innovation is pivotal to sustain affordable copper supply.

There are also environmental challenges. Major copper producing areas in South America face water scarcity, as discussed above. Moreover, hazardous elements such as arsenic are highly concerned in the copper industry. Deteriorating ore grades bring a problem of higher impurity including arsenic content, which can cause serious water and air pollution. The average arsenic content in Chilean concentrate has doubled since the beginning of 2000s, leading to higher costs to manage wastewater and mine tailings. Smelters also face challenges to remodel their processes to meet the environmental regulations related to arsenic. For example, new smelters in Chile are required to capture 99.97% of arsenic emissions (COCHILCO, 2018). Some smelters are planning to redesign their processes in response, and others are conducting R&D for copper-arsenic separation technologies.

Lithium: From resource to consumer



Note: Some spodumene ore is directly consumed for ceramic material.

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Lithium: The fastest-growing mineral, driven by surging EV deployment

Lithium is mainly used for lithium-ion batteries, followed by ceramics, glass and grease. It is supplied from two very different types of resource: brine and spodumene (a type of pegmatite).

Brine resources are located in dry areas such as Atacama (northwestern South America) and western China, where the dry climate accelerates brine evaporation and accumulates mineral elements including lithium. Chile has been the largest producer from brine resources. Production occurs in three steps: (i) accumulating lithium contents to about 1-6% through a solar evaporation process in large pools for hundreds of days; (ii) removing other elements (e.g. boron, magnesium) via chemical processes; and (iii) extracting lithium carbonate from the solvent. Lithium carbonate is widely traded as the main material for battery cathodes, especially for relatively low nickel-content cathodes. Another major lithium product is lithium hydroxide, which is made through an additional process of adding slaked lime to heated lithium carbonate.

Spodumene is a mineral composed of lithium and aluminium, and its mines are mainly located in Australia, where lithium concentrate is produced via beneficiation processes. Concentrates are mainly exported to China by offtake contracts and refined to lithium carbonate or lithium hydroxide. Although brine was the dominant source of lithium historically, soaring demand for lithium has recently

spurred the development of spodumene mines. As a result, Australia has emerged as the largest lithium mining country since 2017.

With regard to refining, China accounts for close to 60% of global lithium chemical production, importing increasing volumes of concentrate from Australia. Some companies in Australia are pursuing an integrated scheme to produce lithium chemicals in the country. These are likely to gain traction as producing lithium hydroxide directly from spodumene is less expensive than converting brine resources to carbonate and then to hydroxide.

Lithium demand for clean energy technologies is growing at the fastest pace among major minerals, largely reflecting the dramatic increase in EV deployment. While other minerals used in EVs are subject to uncertainty around different chemistry choices, lithium demand is relatively immune to these risks, with additional upsides if all-solid-state batteries are widely adopted (see Chapter 2). Clean energy technologies represent around 30% of total lithium demand today (up from a minuscule share in 2010), and the rapid uptake of EV deployment raises the share to some 75% in the STEPS and over 90% in the SDS by 2040. While lithium carbonate is currently the main chemical product used in EVs, lithium hydroxide is expected to take its place as it is more suitable for battery cathodes with high nickel content.

Lithium: The adequacy of lithium raw material supply depends critically on the demand trajectories. New extraction technologies could help broaden the supply pool

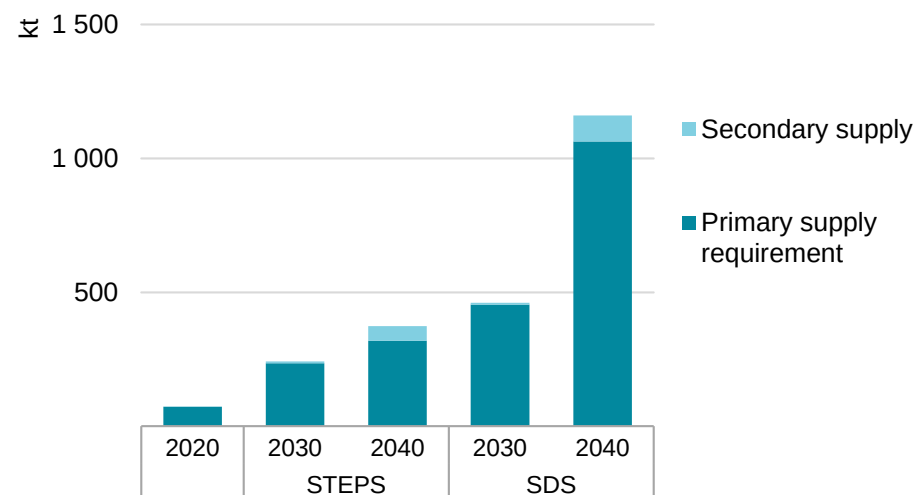
As EV deployment started to take off in earnest in the mid-2010s, surging demand sent major shockwaves through the lithium market, lifting prices threefold between 2015 and 2017. This triggered a wave of investment in supply in Australia and other regions, which resulted in the plunge in prices seen in the late-2010s (lithium resources can be developed with relatively short lead times compared to other minerals).

The production expansion is set to continue until the mid-2020s, with major producers (both brine and spodumene resources) planning to expand their capacity through to the medium term. Both the largest mine and brine production site, Greenbushes in Australia and Salar de Atacama in Chile, are expanding their production capacity by more than 2.5 times. Additional production from these two sites amounts to 320 kt of lithium carbonate equivalent per year, equivalent to over 70% of today's global production. In addition, at least six projects are scheduled to start operations by 2025, including Cauchari-Olaroz in Argentina and Maricunga in Chile. Whether these supplies are sufficient to support demand critically depends upon how demand evolves.

Expected production volumes from existing mines and projects under construction look able to cover projected demand in the STEPS until the late 2020s, but they are not sufficient to support demand growth

envisaged in the SDS. Satisfying SDS demand would require all these projects to be developed and be complemented by additional exploration. There is a host of projects at varying stages of development, with their combined production totalling around 2 500 kt of lithium carbonate equivalent per year.

Primary supply requirements for lithium by scenario



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New types of resources and development technologies may play an important role in the decade to come. Efforts are ongoing to recover lithium from unconventional resources. For example, processing clay

minerals is simpler and less energy-intensive than spodumene as calcination processes are not needed, but their lower ore grades and complicated compositions pose challenges for commercialisation. At least three clay mineral projects are under development in the United States. Rio Tinto has invested AUD 14.5 million (USD 11 million) in a pilot project to produce lithium from waste rock at the Boron mine site in California (The West Australian, 2021).

Direct lithium extraction technologies are also on the horizon. Instead of evaporating all the water and chemically removing all the impurities, this process extracts the lithium directly from an unconcentrated brine to produce a lithium eluate, which can be processed to lithium chemicals without evaporation ponds (Grant, 2019). This holds the potential to reduce cost and lead times as brine accumulation takes more than a year and represents a major part of the capital expenditure of a brine project. Some developers are focusing on technology to recover lithium from oil and gas produced water and geothermal brine. Together, these new technologies could widen the pool of future lithium supply.

New technologies for lithium production

Technology	Mechanism	Developer
Unconventional resources		
Sedimentary rocks	Lithium production from hectorite (clay mineral), lepidolite and searlesite	Lithium Americas, Lepidico, Lithium Australia, Ioneer
Waste rocks	Lithium production from waste of borate production	Rio Tinto
Direct lithium extraction (Brine/oil and gas produced water/geothermal water)		
Phosphate precipitation	Lithium phosphate precipitated upon addition of phosphoric acid	POSCO
Ion exchange	Lithium ions intercalated into layers of metal hydroxide or oxide	Dow, FMC, Simbol, Eramet, JOGMEC, Neometals
Solvent extraction	Selectively recover lithium from diluted water using solvent	Tenova
Nano filtration	Lithium ions concentrated by membrane	MGX
Others	Utilising subsurface technology expertise, etc.	NeoLith Energy (Schlumberger)

Sources: Kumar (2019); JOGMEC (2019a).

Lithium: The supply of lithium chemicals, lithium hydroxide in particular, could become a bottleneck

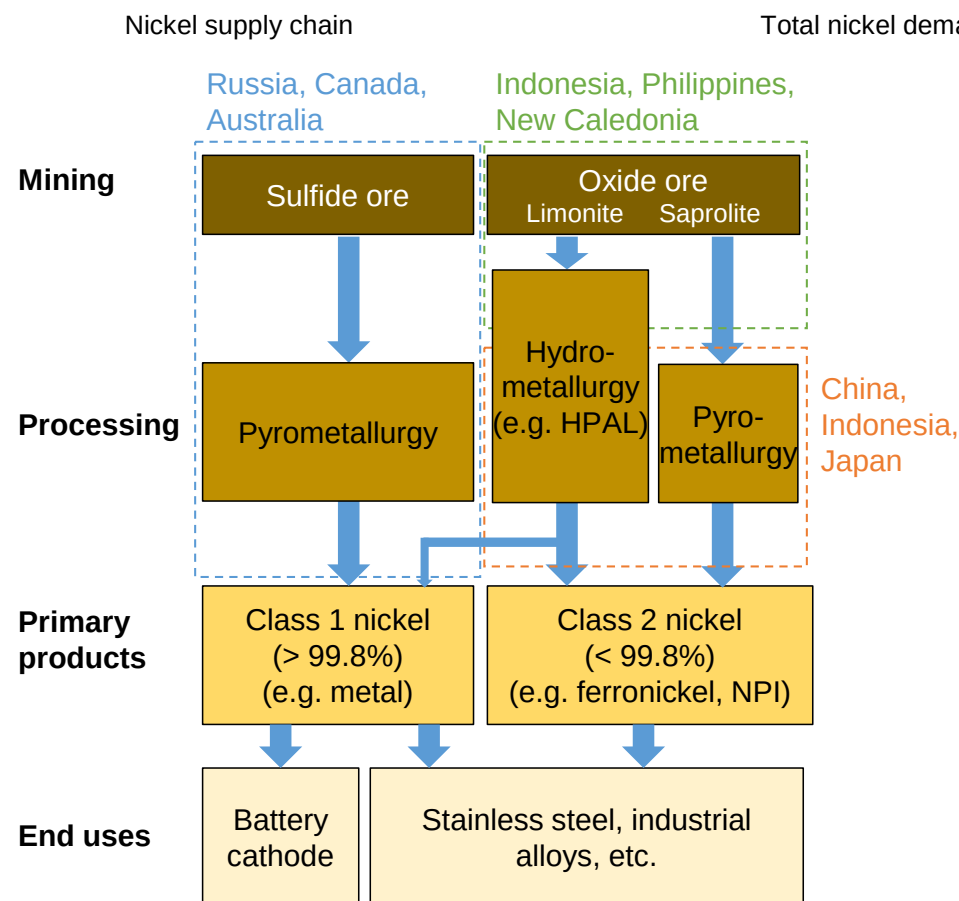
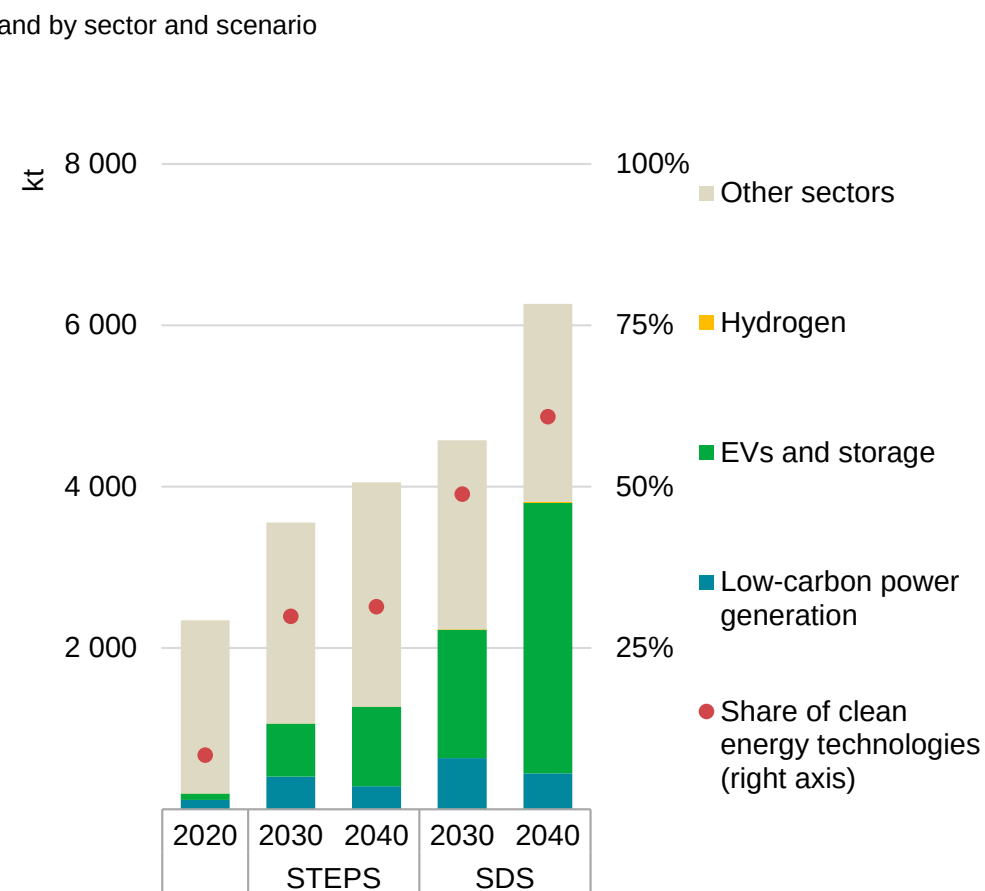
While lithium raw material is expected to remain well supplied in the near term, major strains are likely to come from the midstream value chain that converts raw materials into lithium chemicals. Only a handful of companies can produce high-quality, high-purity lithium chemical products – five major companies are responsible for three-quarters of global production capacity. While several planned expansion projects are in the pipeline, there is a question mark over how rapidly their capacity can come online to keep up with demand growth given that there are few deep-pocketed companies that can finance expansion projects, especially after several years of depressed prices. Many smaller companies are financially constrained and some have delayed planned expansion projects. The recent price rally for lithium carbonate partly reflects the potential concerns. Looking ahead, the strains could be particularly great for lithium hydroxide, which is set to drive future demand growth (as it is favoured for high-nickel cathode chemistries).

A higher level of concentration is another challenge. Close to 60% of global lithium chemicals are produced in China. Chinese companies have also invested in companies in South America. For example, Tianqi Lithium, a large lithium chemical producer in China, acquired a minority stake (23.8%) in Chilean company SQM. The picture is even more skewed for lithium hydroxide – in 2019 over 80% of lithium

hydroxide was produced in China. Some projects to produce lithium hydroxide are being planned in Australia, the United States, the European Union and others, which could help diversify sources of supply, if successfully implemented.

As in the case of copper, mounting water stress poses a further challenge for lithium raw material producers in drought-concerned regions such as South America and Australia. In the case of brine resources, production operations may have adverse impacts on the water balance in the region. Recent studies identified a negative correlation between the continuous expansion of lithium extraction activities and the soil moisture index, a proxy for drought conditions (Liu et al., 2019). New direct lithium extraction technologies could help alleviate pressure around water sourcing.

Nickel: From resource to consumer



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Nickel: A versatile mineral used in a wide range of clean energy technologies

Historically nickel has been used mainly for industrial alloys, to which it contributes corrosion resistance and workability. Around two-thirds of stainless steel currently contains nickel. However, lithium-ion batteries have recently emerged as a new source of demand. They account for around 7% of nickel demand today.

There are two types of primary nickel products: high-purity Class 1 products (containing 99.8% nickel or above) and lower-purity Class 2 products (containing less than 99.8% nickel). Battery cathodes need nickel sulfate, which is synthesised from Class 1 products.

There are complex relationships between different resource types (sulfide, saprolite and limonite) and product types (Class 1 and Class 2).

Sulfide deposits are mainly located in Russia, Canada and Australia, and have been the main source of supply for over a century. Nickel is concentrated in the ore at a relatively high grade, typically in the range of 0.4-3.2%.

Meanwhile, oxide resources (often called laterite) such as saprolite and limonite are located mainly in Indonesia, the Philippines and New Caledonia. Laterite resources are formed by weathering in a high-temperature and humid climate. More weathered upper soil is called limonite, and less weathered lower soil is called saprolite. Nickel is

mainly absorbed in clay in the ore rather than in minerals. Saprolite has a relatively higher grade (1.8-3.0%) than limonite (0.8-1.8%). Due to these differences, methods of producing nickel products differ by resource type.

Sulfide ore is suitable for pyrometallurgical processes, as ore grades are relatively high and it is easy to concentrate the grade by flotation. Currently sulfide ore is the main source of high-purity Class 1 products. Limonite ore is usually processed via hydrometallurgical processes such as HPAL (high-pressure acid leaching), as it is easy to leach the absorbed nickel from clay and has less acid-consuming magnesium than saprolite. Also, there are many existing limonite tailings, which were once discarded during saprolite mining before HPAL technology became commercialised. Although the number of operating HPAL projects is currently small, several new projects are being built or are planned. Saprolite ore is generally not suitable for Class 1 products, and is mainly used to produce Class 2 products for stainless steel (e.g. ferronickel and nickel pig iron).

Around 10% of nickel demand is used for various clean energy technologies, either as a cathode material for batteries or in the form of alloys for renewables and hydrogen. Clean energy technologies' share of total nickel demand grows further to over 30% in the STEPS and to around 60% in the SDS by 2040. In the SDS, batteries take over from stainless steel as the largest consumer of nickel by 2040.

Nickel: All eyes on Indonesia

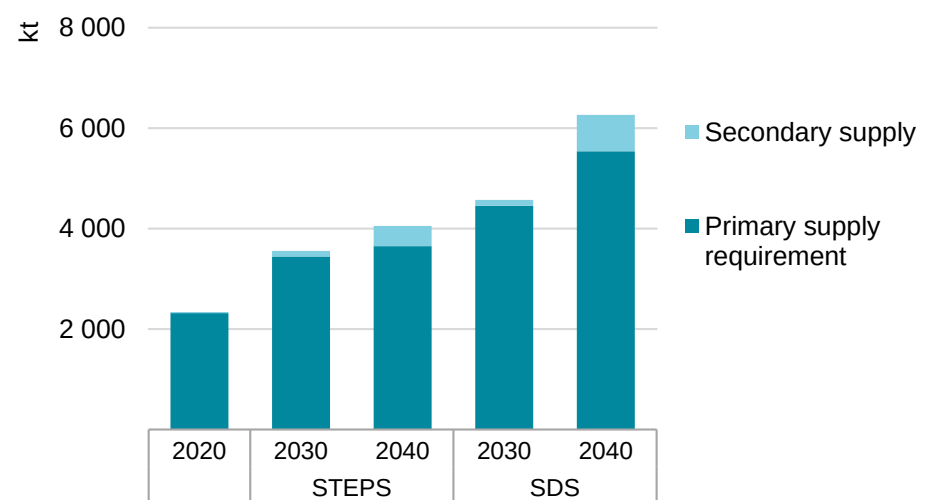
Global nickel production has increased by 20% over the past five years, mainly driven by expansion projects in Asia Pacific, most notably Indonesia and the Philippines. These two countries represent 45% of global output today.

Their domination of nickel production is set to intensify in the coming years, as they are responsible for around 70% of global production growth over the period to 2025. Indonesia alone accounts for around half of the growth. In the longer term several projects are being planned outside Indonesia, such as the Kabanga project in Tanzania (one of the largest nickel sulfide deposits, with 2.6% high-grade ore) and the Wingellina project in Australia.

This suggests that future nickel supply is highly likely to be driven by progress in Indonesia, and therefore global nickel supply chains may be affected significantly by physical events or policy change in Indonesia. On 1 January 2020 the government of Indonesia implemented a ban on nickel ore exports, two years ahead of the previously announced date, with the aim of processing its ore in domestic smelters (instead of exporting to China) and thereby nurturing a downstream industry. In 2020 nickel ore exports to China dropped by nearly 90% and nickel pig iron exports doubled compared to 2019 (Reuters, 2021b). This in turn forced Chinese refiners to find new sources of ore supply from the Philippines or New Caledonia, but also to seek investment opportunities in Indonesia. Chinese

companies invested and committed some USD 30 billion in the Indonesian nickel supply chain, with Tshingshan's investments in the Morowali and Weda Bay industrial parks being the most prominent examples.

Primary supply requirements for nickel by scenario



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Nickel: Quality challenge compounded by resource challenge, with Indonesia pivotal on both

The prospects for nickel supply are mixed. The overall nickel market is likely to remain well supplied, but the picture becomes vastly different for battery-grade Class 1 products. Class 1 nickel is in slight surplus, but the rapid rise in demand from batteries is soon set to change this to deficits. In general, sulfide resources are a good fit for producing battery-grade Class 1 nickel. However, most of the production growth in the coming years is poised to come from the regions with vast amounts of laterite resources, such as Indonesia and the Philippines, which are generally more suitable for Class 2 products.

As such, HPAL is gaining traction as a way to produce Class 1 products from laterite resources. The five hydrometallurgy projects under development in Indonesia all employ HPAL. However, this brings several challenges. First, past HPAL projects have track records of large cost overruns and delays. Second, HPAL is technically difficult to operate stably, as it processes low-grade ore under high temperature and pressure. Third, as HPAL uses acid to leach metals from the deposits, acid production facilities are required on site, which incurs additional cost. Capital costs for HPAL projects are typically more than double those for conventional smelters for oxide ore (BloombergNEF, 2020). And fourth, HPAL projects tend to take four to five years to ramp up to 80% capacity.

HPAL's past track record may not be a good guide to the prospects for Indonesian HPAL projects. They are planned to leverage existing infrastructure, which could help reduce capital costs. Two of the projects are planned to be built at the Morowali Industrial Park, a nickel mining and export hub in Indonesia. As a result, the capital cost of the planned HPAL projects in Indonesia is estimated to be 60% of the average for a typical HPAL project (BloombergNEF, 2020a).

While promising, it remains to be seen if these projects come online as scheduled. The first, PT Halmahera Persada, plans to start operations in 2021. If it comes online successfully, other projects could follow using the first project as a template.

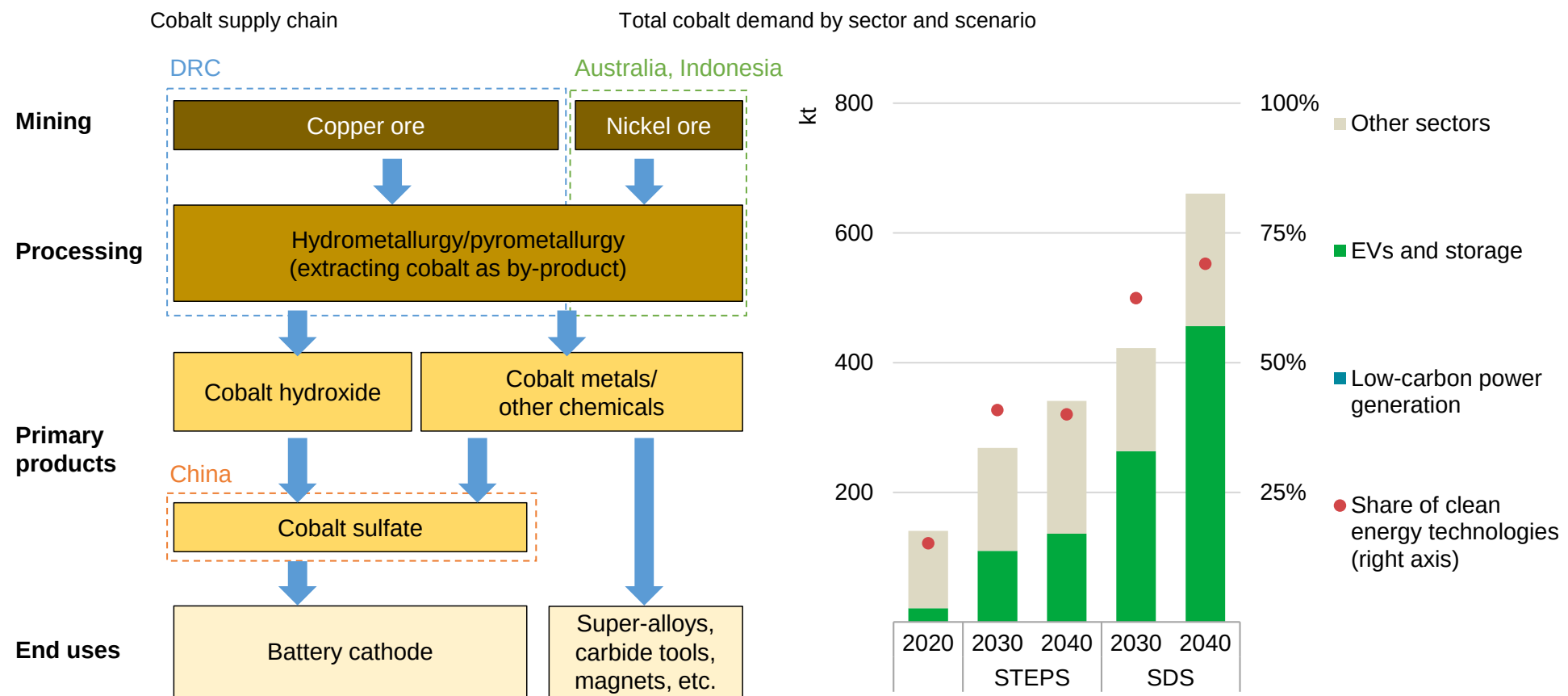
There are environmental issues that need to be addressed, such as higher CO₂ emissions arising from the use of coal-based electricity and tailings disposal. While land-based tailings storage facilities are widely used globally, deep-sea tailings placement is being considered as an option in Indonesia because of the country's unique geographical conditions (e.g. high precipitation and frequent seismic activities) and its lower cost. However, deep-sea tailings placement is causing concern about the marine environment. Economic and sustainable tailings treatment is set to remain a major challenge for HPAL projects in Indonesia.

While the prospects for HPAL projects in Indonesia are crucial, there are other pathways that could meet the demand for Class 1 products :

- Some of the current Class 1 consumption in the non-battery sector could be switched to Class 2, freeing up Class 1 nickel supply for batteries. Higher prices would be required to incentivise such a switch.
- Increasing stainless steel production from scrap materials would make some Class 1 supply available for other uses.
- Conventional oxide smelters, instead of HPAL, could produce Class 1 products from saprolite resources: Tsingshan, the world's largest nickel producer, plans to convert nickel pig iron to nickel matte from its operations in Indonesia, which could then be further refined into Class 1 products (Roskill, 2021a). This is, however, highly energy-intensive and adds more cost.
- Given that Class 2 products are expected to be well supplied, it is conceivable to use Class 2 products such as ferronickel or nickel pig iron as feedstock to produce nickel sulfate for batteries. While technically possible, this process is likely to be cost-prohibitive.
- As explored in Chapter 2, recent movements towards high-nickel chemistries in battery cathode could be slowed if Class 1 nickel supply becomes tight and prices remain elevated, which could instead raise demand for cobalt.

If all planned HPAL projects in Indonesia go smoothly, it would provide sizeable volumes of Class 1 supply, easing pressure on prices in the medium term. Several options are available to satisfy the need for Class 1 products in the case of failure or delay, but all options have some drawbacks and would need higher prices for them to materialise. Given that there is no long list of projects in the pipeline outside Indonesia, progress in Indonesia will be key to future nickel supply for batteries, at least in the near term.

Cobalt: From resource to consumer



Note: There are mines that produce cobalt as a primary product, but volumes are smaller than those produced as a by-product.

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Cobalt: Strong EV-driven demand growth despite uncertainties around cathode chemistry development

Lithium-ion batteries are the main user of cobalt today, followed by super-alloys, carbide tools and magnets. As in the case of lithium, the rapid increase in EV deployment in the mid-2010s shook the relatively smaller cobalt market and underpinned rollercoaster price movement. As rapid demand growth put strains on supply, prices registered a fivefold increase between 2016 and early 2018. This triggered a range of supply responses, both large-scale project investment and a surge in artisanal small-scale mining activities, which helped to stabilise prices.

Some 70% of cobalt is produced in the DRC as a by-product of its copper mines. Cobalt is also produced as a by-product of nickel mines in some countries. The Bou Azzer mine in Morocco is the only major active mine that produces cobalt as a primary product. In the DRC, Glencore produced around 40% of the country's production in 2019, followed by China Molybdenum (12%). In recent years Eurasian Resources Group has emerged as a major producer in the country as its Metakol RTR mine ramps up. While Glencore recently reduced production due to mine maintenance and low market prices, the facilities could restart and expand production capacity once maintenance is completed. Gécamines, a state-owned trading and mining company, is participating in production by owning stakes of

20-50% in certain mines. Some 10-20% of cobalt production in the DRC occurs in the form of artisanal and small-scale mining (Roskill, 2021b).

China processes around 70% of mined cobalt globally, followed by Finland, Belgium and Canada. The DRC exports intermediate chemical products (cobalt hydroxide) to China, which are then converted to cobalt sulfate for use in batteries.

The development of cobalt demand is highly dependent on the direction in which battery cathode chemistries evolve. The composition of cathode chemistries is increasingly shifting towards those with high-nickel content, which could weigh on the appetite for cobalt. However, even under our default assumptions where this trend is sustained, the strong uptake of EVs underpins sevenfold growth in cobalt demand for clean energy technologies in the STEPS and over twenty-fold growth in the SDS over the period to 2040. This raises the share of clean energy technologies in total demand from 15% today to 40% by 2040 in the STEPS and over two-thirds in the SDS.

Cobalt: Production of cobalt is likely to remain concentrated in the DRC and China

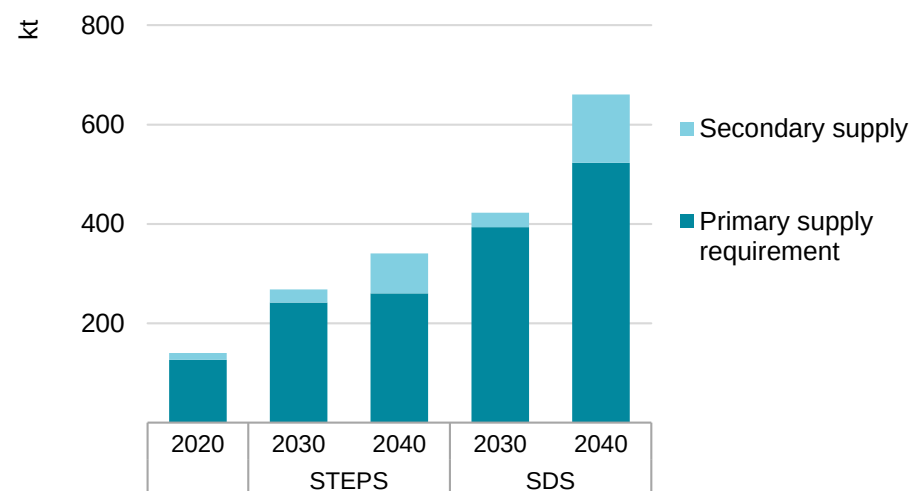
Global cobalt production has increased by 10% over the past five years, mainly driven by the DRC. While some capacity has been subject to temporary suspension due to the recent plunge in prices, two large mines (Kamoto and Metalkol RTR) are under expansion and a new project (Musunoi) is set to start operations in the early 2020s. These projects together would add around 20 kt of annual production by 2025. The Metalkol RTR project alone plans to produce 20 kt by processing cobalt-copper tailings through a hydrometallurgical process. The planned projects in the DRC account for the majority of the current project pipeline, implying that the DRC is set to remain the dominant source of cobalt supply for the time being.

However, outside the DRC, Australia, Canada, Madagascar and Russia have plans to increase cobalt production, mainly through enhanced recovery of cobalt from nickel and copper mines. For example, the CleanTeQ Sunrise project in Australia plans to produce cobalt from one of the world's largest cobalt-rich nickel laterite deposits. Overall, the expected output from existing mines and projects under construction would be sufficient to serve STEPS demand until the medium term, but meeting SDS demand requires a further acceleration in project development.

Mining and processing operations for cobalt are highly concentrated in two countries, the DRC and China, and there is a close tie between

the two countries. The supply chains for cobalt could therefore be highly affected by regional incidents on the trade route or policy changes in these countries. In addition, China has influence over many assets in the DRC through foreign direct investment. It is estimated that one-third of China's imported intermediate products are from mines or smelters in which it has a stake.

Primary supply requirements for cobalt by scenario



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Cobalt: Efforts to formalise the ASM sector and promote enhanced recovery could mitigate negative social impacts while reducing uncertainty around future production volumes

The significant share of artisanal and small-scale mining (ASM) in the DRC is another challenge in cobalt supply. On the one hand, ASM production can have a stabilising effect on markets, as producers are sensitive to price changes and can reduce or ramp up production quickly. On the other hand, ASM may be more vulnerable to economic and social events such as the Covid-19 pandemic. While large-scale mining also has environmental and social impacts, ASM sites often present particular challenges due to their unregulated and informal nature, including unsafe conditions for workers and the presence of child labour.

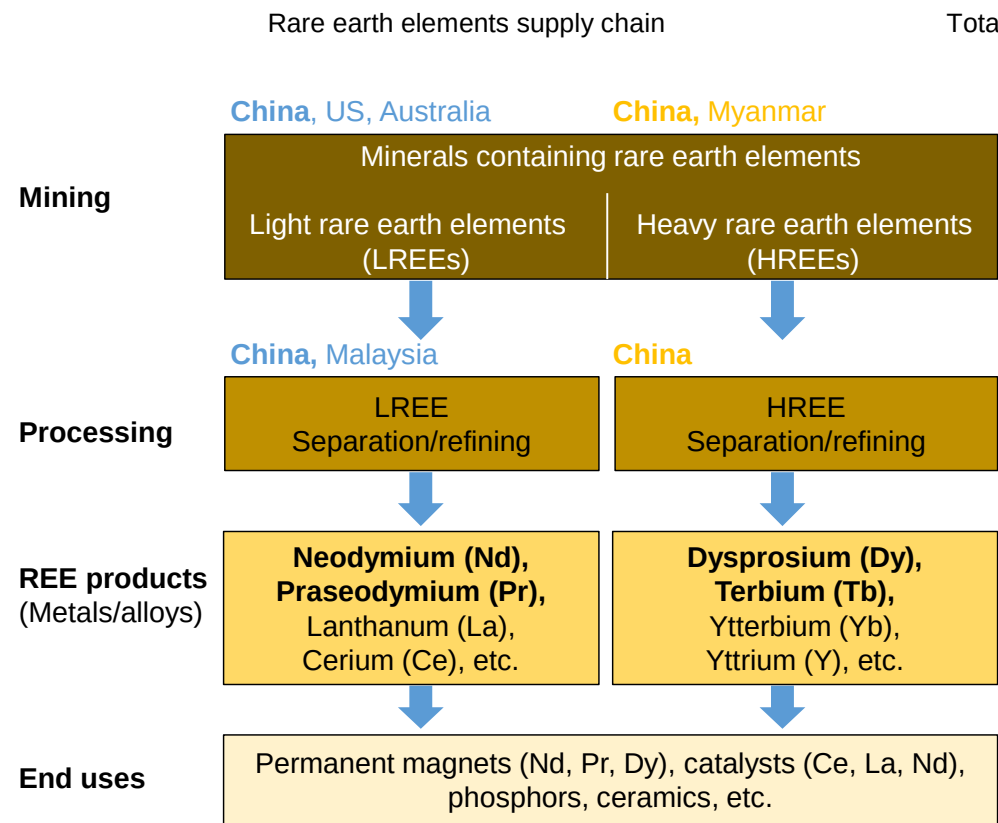
Given these risks, there is a temptation for companies to disengage from the ASM supply chain entirely. However, disengagement may paradoxically worsen the situation. ASM provides an important source of income for many local communities, which, with appropriate mitigation efforts, can help to address the root cause of child labour: poverty. In recognition of this, a growing number of companies are adopting due diligence practices aimed at identifying, assessing and mitigating these risks (see Box 4.8).

Companies and governments are also developing “on the ground” efforts to formalise the sector and prevent irresponsible practices. The DRC government has announced support for formalising ASM through the state-owned Entreprise Générale du Cobalt, and some

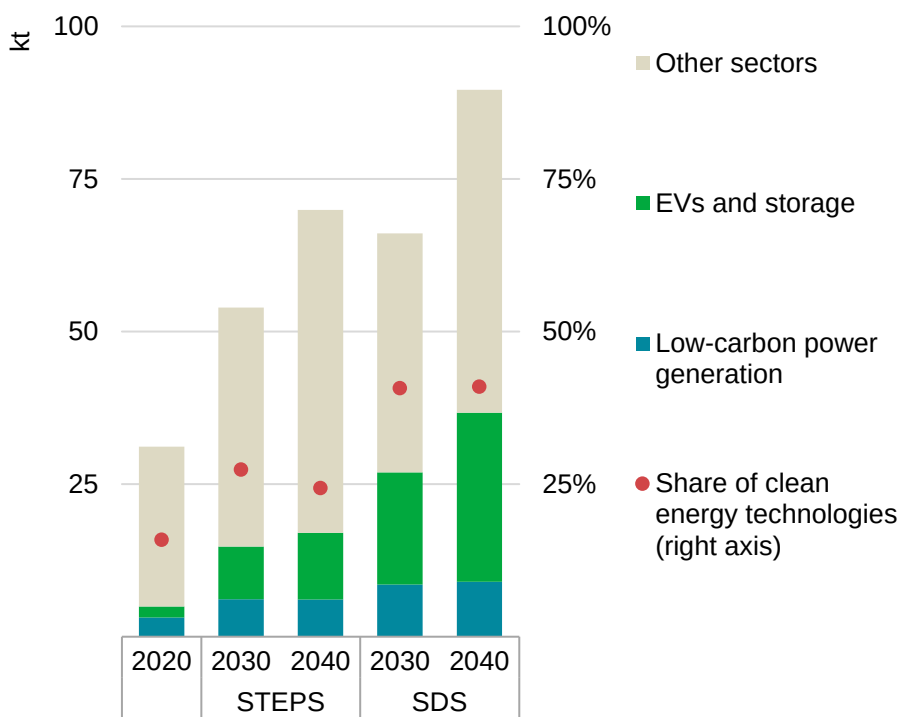
companies have established formalised or semi-formalised ASM pilot projects. However, the long-term viability of this approach is unclear as early pilot projects closed down in 2020 due to the Covid-19 pandemic (Mining Technology, 2020). Separately, a number of industry initiatives exist to provide additional support for formalisation. For example, the “Cobalt for Development” project was launched by BMW, BASF, Samsung SDI and Samsung Electronics (recently joined by Volkswagen), aiming to improve working and living conditions for surrounding communities. However, given the scale of the problem, further efforts would be needed to reduce uncertainty and provide more stability to the market.

Another complication is that cobalt is usually produced as a by-product of copper and nickel. It means that investment decisions for new project development or capacity expansion are not necessarily linked to cobalt market dynamics, but rather more susceptible to the market conditions for copper and nickel. While this raises uncertainty about future supply, efforts to adopt processing methods that maximise cobalt recovery can play an important role in mitigating risks. For example, Kamoto Copper Company in the DRC has adopted a new leaching method – whole ore leach – which improves cobalt recovery rates from 34% to 65% (JOGMEC, 2019b). Methods of this kind have the potential to provide sizeable by-product volumes and ease supply-side pressure if widely adopted.

Rare earth elements: From resource to consumer



Total neodymium demand by sector and scenario



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Rare earth elements: A story of concentration and diversification

REEs are a family of 17 elements comprising 15 elements in the lanthanides group (ranging from lanthanum to lutetium), plus scandium and yttrium. On the basis of atomic weight, among the lanthanides group the lighter six elements are classified as the light rare earth elements (LREEs) and the other nine elements as the heavy rare earth elements (HREEs) (IUPAC, 2005). REEs are contained in the same orebody, the composition of which varies widely by deposit. Typically mined orebodies have LREEs as a large proportion of cerium and lanthanum and a modest amount of magnetic rare earths, plus a small fraction of HREEs (CRU, 2020b). To separate individual elements, mineral concentrate is fed into high-temperature concentrated acids to liberate the REEs they contain and remove radioactive elements (e.g. thorium, uranium).

While each REE is used in different applications, four elements – neodymium, dysprosium, praseodymium and terbium – are of particular importance to the clean energy sector. One of the major uses is permanent magnets for motors. Demand for permanent magnets accounts for the majority of total REE demand today in dollar terms, and is expected to grow faster than any other sector, driven by the strong rise in demand for clean energy technologies. REEs are also used in the catalytic converters of conventional cars to remove pollutants.

Demand for neodymium – one of the most important REEs in the clean energy sector – more than doubles in the STEPS and triples in the SDS, reaching 70 kt and over 90 kt by 2040 respectively. Clean energy technologies represent 15% of total neodymium demand today, and their share is set to increase to 25% by 2040 in the STEPS and over 40% in the SDS.

The United States had been leading the production of REEs until the mid-1990s, when China started to emerge as a major producer. Since then, China's share of global production rose to over 95% in 2010, since when its share has fallen to just over 60% in 2019, as the United States, Myanmar and Australia started to boost production (USGS, 2021).

However, separation and refining operations are still heavily concentrated in China, with almost 90% market share in 2019. There are currently four plants operating outside China, in Malaysia, France, India and Estonia. These plants, however, process only LREEs and the processing of HREEs is entirely dominated by China. This is due in part to the fact that China hosts abundant ion-adsorption clay deposits, which are easy to mine and often rich in HREEs. For example, the highest HREE composition outside China and Myanmar is only 5% (Mt. Weld in Australia), while the HREE content in Xinfeng in China is nearly 50% (JOGMEC, 2020).

While China's share of mining has declined in recent years, its presence in the downstream operations – from processing to metals production to magnet making – has continued apace, with the country holding some 90% market share across the value chain.

China's attempt to limit REE exports in 2010 was an alarm bell for many countries that rely on imports. In the immediate aftermath, prices spiked by more than 10 times for many REEs, although prices subsequently declined. This extreme price movement triggered many countries to consider options to reduce material intensity, find substitutes and diversify sources of production. Japan introduced a comprehensive policy package ("ABCD+R" initiative) that encompasses measures to reduce consumption, secure diversified supply sources and promote recycling. As part of the package, the country offered a USD 250 million loan to Lynas, an Australian REE producer, which was the only sizeable non-Chinese company in the business at that time, to secure non-Chinese supply options.

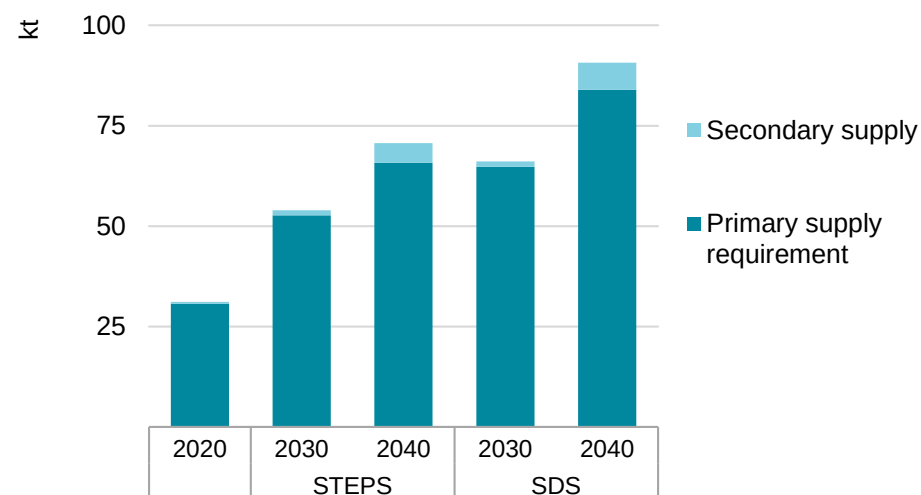
Several new projects have been launched outside China, and today some 20 projects are under development in Australia, Canada and the United States, of which 5 projects plan to start operations in the early 2020s.

On the processing side, a plant in Malaysia run by Lynas is the only large non-Chinese facility in operation today, but several others are under development. In 2020 the US government funded two projects – one by Lynas and the other by MP Materials – while another project

by Texas Mineral Resources is under review. In addition, MP Materials plans to upgrade inactive refining facilities at a mine site.

Meanwhile, the Chinese government has been trying to control the illegal mining of REEs. Before 2014 the country used an export quota to restrict unsanctioned production, which was not effective in controlling production. The quota was lifted in 2014 after the decision by the World Trade Organization (see Box 3.4). In 2015 the country consolidated the REE industry into six state-owned enterprises as part of efforts to bring the industry under control and strengthen environmental oversight. These companies account for 80-85% of REE production in China today and production from illegal mining has registered a notable decline since 2015 (BloombergNEF, 2020b).

Primary supply requirements for neodymium by scenario



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Rare earth elements: Demand soaring to new heights, imbalances looming

While the surge in EV sales and renewables deployment presage a period of booming demand for the four REEs that are vital to clean energy technologies, it is not yet clear if supply can keep up with the demand trajectory as bottlenecks are hampering investment decisions.

A key consideration is China's position along the value chain. A country could open a mine site or build a processing plant, but, as things stand, it would need to bring the output to China for further processing as it would be difficult for a single country to build a presence along the whole value chain. Limited transparency about the market and pricing further complicates investment decisions.

The second issue arises from a unique feature of REEs. All naturally occurring REEs co-exist in the same orebody. They are therefore produced together when processing the ore despite the fact that each element faces different market prospects. While the four elements widely used in clean energy technologies are poised to be in high demand in the years to come, other elements such as cerium and lanthanum, which are used for polishing powders, alloy manufacturing and refining catalysts, do not share the same positive outlook. If a company is to produce neodymium to meet rising demand, it also needs to deal with surplus cerium, the price of which is likely to remain subdued. This could weigh on aggregate profits

from REE production, implying that higher prices for neodymium might not necessarily trigger new investment.

There are also environmental concerns: processing REEs often generates toxic and radioactive materials. These can leak into groundwater, causing major health and safety issues, including fatalities. This has been a serious issue in China. The Chinese government started to tackle this issue, although further efforts will be needed. On 1 September 2020 the country announced the revised law on the Prevention and Control of Solid Waste Pollution, which raised penalties and introduced a credit record system.

Given the rapid rise in projected demand, production would need to increase both within and outside China, but these volumes need to be produced under higher environmental standards. In China tightening environmental regulations would help avoid an influx of unregulated volumes and incentivise investment. At the same time, it would be important to secure diversified sources of supply, which would need international co-ordination and policy support.

New technologies could also unlock additional supply. For example, REEs could be recovered from the deposits of nuclear fuels. The US Department of Energy has funded several projects to develop commercially viable technologies to extract REEs from coal and coal by-product sources.

Box 3.1. Can deep-sea mining be an answer to the need for more critical minerals?

After decades of experience with deepwater oil and gas production, many countries and companies are increasingly eyeing resources beneath the sea as a response to declining high-grade deposits on land. Several exploration projects are progressing in the exclusive economic zones (EEZs) of Japan, Norway and Papua New Guinea. Following the discovery of large sulphide deposits, Norway plans to issue licences to kick-start deep-sea mining as early as 2023, which could place it among the first countries to harvest minerals on the seabed. Around 30 projects are waiting for the formulation of official rules outside the EEZ by the International Seabed Authority (ISA).

Deep-sea mining is the process of exploiting mineral resources from the area of the ocean below 200 metres. There are three main types of deposits: (i) cobalt-rich crust that contains manganese, iron, cobalt, copper, nickel and platinum; (ii) polymetallic nodules which are rich in manganese, nickel, copper, cobalt, molybdenum and REEs; and (iii) sea-floor massive sulphides which contain copper, gold, zinc, lead, barium and silver. In an area of 4.5 million square kilometres in the eastern Pacific Ocean, reserves of polymetallic nodules are estimated at 274 Mt for nickel and 44 Mt for cobalt, multiple times the global terrestrial reserves (Hefferman, 2019).

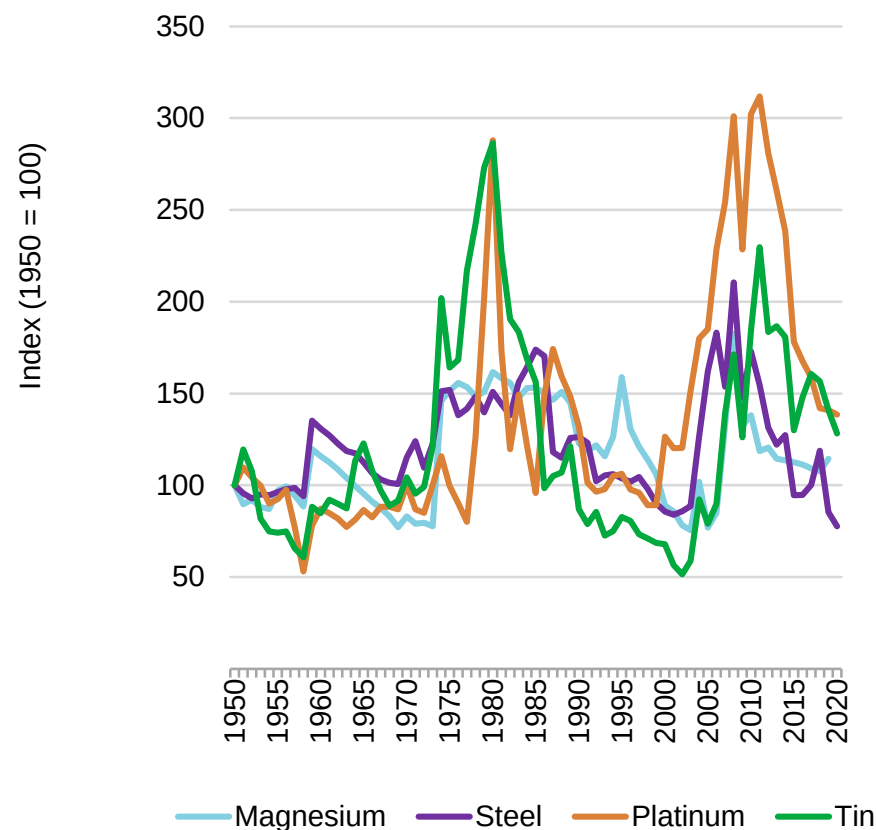
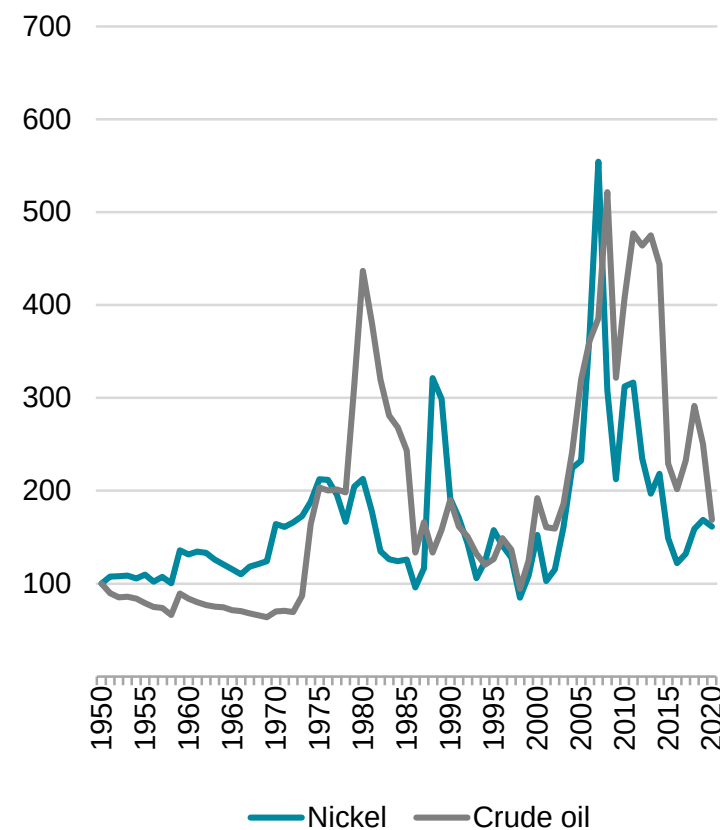
However, there are economic, technical and environmental hurdles. The technologies required are different from onshore mining or deepwater oil and gas extraction. Cutting machines and collecting vehicles need to work remotely under high water pressure, and pumping a mixture of ore and slurry requires different skills from the extraction of oil and gas. While a pilot ore lifting for massive sulfide succeeded in Japan in 2017, further technology development is needed to make the process commercially viable (METI, 2017).

Studies also suggest potentially significant environmental impacts. Machines often cause seafloor disturbance, which could alter deep-sea habitats and release pollutants. Sediment plumes, which arise from stirring up fine sediments, could also affect ecosystems, which take long time to recover. Ecosystems in some old test sites have not yet recovered after 30 years (Hefferman, 2019). The impacts on biodiversity are largely unknown. Despite the vast opportunities, rigorous assessments would be needed to understand the full extent of environmental damage and develop proper regulatory measures. BMW, Samsung SDI, Volvo and Google recently announced moratorium on materials from deep-sea mining until the risks are fully understood (WWF, 2021). The ISA is developing regulatory frameworks for the international seabed, aiming to promote deep-sea mining while minimising environmental risks.

Approaches to ensure reliable mineral supply

Periodic price spikes and volatility have characterised mineral resource markets, just as they have for crude oil

US price trends for several commodities in real terms, 1950-2020



Sources: IEA analysis based on USGS (2013) for historical prices to 2010 and S&P Global (2021) for recent prices.

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Governments and industry responded to previous episodes of supply concern with substitution, innovation and supply responses, but with price increases and time lags

Analysis of historical episodes of tight mineral supply provides useful insight into the factors that could help to mitigate future risks from price spikes. Mitigating activity includes mineral substitution or innovation in supply and demand technologies, although not all price spikes can be avoided entirely. As mineral extraction and processing are often energy-intensive, mineral prices are influenced by trends in energy prices in addition to factors such as geological concentration, production capacity and supply chain bottlenecks.

Lower-grade US iron ore: Time lags limit substitution

When the production of natural iron ore peaked in Minnesota in 1953, research into the extraction of iron from taconite was ramped up in the state (Manuel, 2017). Producing iron from abundant taconite requires processing of over three times more rock than natural ore. Although the quality of iron from taconite had been rejected by the Ford Motor Company in the 1920s, its viability improved as prices of steel rose. A mine was opened in 1955, but this could not prevent the share of Minnesota iron ore in the United States slipping from 68% in 1946 to less than half by 1960. A tax incentive for taconite producers was added to Minnesota's constitution in 1964, but by that time iron ore trade had become more globalised and the problem that taconite mines had sought to address was not as pressing. Most taconite

mines had closed by the 1980s, by which time their favourable tax treatment had also put the natural ore mines out of business.

Trade rules drove (and cooled) magnesium price spikes

Magnesium's military importance has shaped its production since the early 20th century, with all major countries seeking to host a domestic industry. However, not all countries have equal magnesium resources, which has periodically driven intensive research into thermal processes that extract magnesium from ore-bearing rocks and electrolytic processes to extract magnesium from brine. Since 1950 US magnesium prices have surged four times: in response to inflation in 1973; in response to a jump in aluminium demand in 1987; in response to the barring of Canadian imports in 1995; and in response to the closure of plants in Canada and Russia, combined with anti-dumping duties on Chinese imports, in 2007 (USGS, 2013).

Price spikes have largely been resolved by relaxing import constraints, while innovation has not enabled local production despite high prices. The price jolt in 1987 was resolved by new capacity coming online in Canada (though this was itself subject to US anti-dumping measures by 1992). Trade policy-induced volatility continues to affect incentives to invest in new capacity in several major economies.

Aluminium substituted for copper, but with time lags

In electrical cabling, aluminium performs similarly to more expensive copper but has some technical downsides. It became a serious competitor for copper in electrical conductors after World War II, when copper demand could not be met by producer countries. In Germany copper prices rose sixfold in the 20 years to 1966, while aluminium prices were more constant. Aluminium has enjoyed a price advantage ever since, but has not penetrated the market accordingly.

One reason is the time it took for innovation to overcome safety concerns and match the cumulative experience of engineers using copper. Research launched in the United Kingdom in the 1950s took around a decade to resolve key issues, by which time the relative prices had converged and certain applications were using underground cables where the weight advantage was nullified. In the second half of the 20th century, aluminium demand for electrical cabling was seen to respond to copper price spikes, but with a lag of years or decades (Messner, 2002). Its impact was muted by the cyclicity of relative prices and the dominant foothold that copper had already gained.

Aluminium also substituted for tin, notably in packaging. This was initially in response to high tin prices resulting from international cartelisation that was intended to benefit tin producers and user countries. It provides a lesson in the unanticipated effects of such measures.

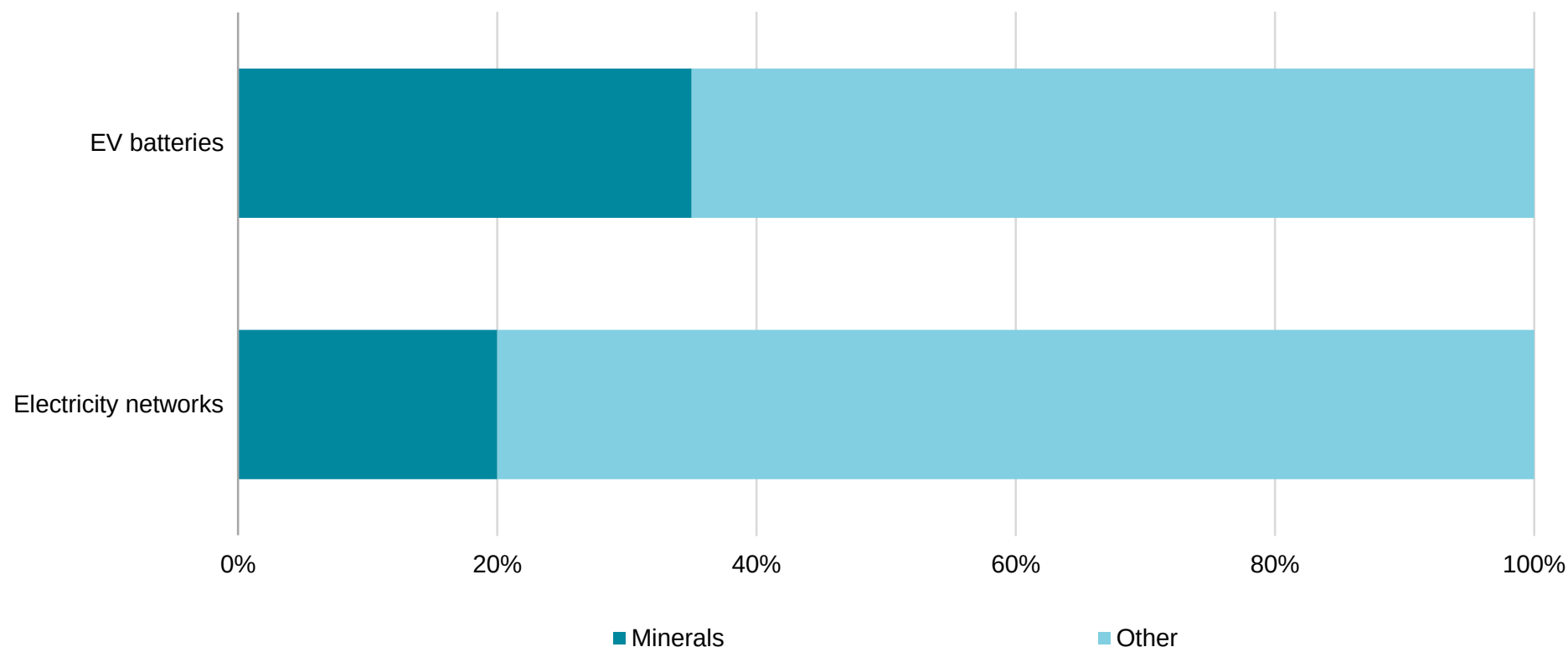
As total aluminium demand has risen, technological advances have made it possible to use lower-grade resources – the maximum allowable silica content of bauxite has doubled in 30 years – without prices ever reaching more than 40% above their 1950 level in real terms. Due to price advantages, major consumers such as the United States continue to rely on imports rather than exploit advances in the use of bauxite-containing clays and non-bauxite sources.

Platinum prices spurred innovation in substitution

Since 1979 the automotive sector has been the principal platinum consumer for catalytic converters. Initial platinum purchases by car companies fuelled speculation that pushed up prices. One response to higher prices was more commodity trading and fewer bilateral trades with South African producers. However, volatile platinum prices remained an issue for the automotive sector in the 1980s, spurring research into substitution (USGS, 2013). In 1988 Ford announced a platinum-free catalyst, and by the late 1990s catalytic converters for gasoline cars contained more palladium than platinum. However, a subsequent spike in the palladium price caused producers to return to platinum briefly, before platinum prices outpaced those of palladium again when catalytic converters for diesel engines were introduced. While today's relative prices would suggest a return to platinum in gasoline catalytic converters, this is not widely expected for reasons of well-established designs and supply chains, and past experiences of cyclical prices.

The biggest risk from inadequate mineral supply could be less affordable and delayed clean energy transitions

Current share of mineral cost in total investment in selected clean energy technologies



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Note: Mineral cost for EV batteries (based on 40 kWh NMC622) covers copper, lithium, cobalt, manganese, nickel, graphite and aluminium, and that for electricity networks covers copper and aluminium.

Source: IEA analysis based on Argonne National Laboratory (2020), BatPac 4.0.

Countries and regions are stepping up efforts to ensure reliable supplies, although their policy approaches differ

While policy makers have been concerned about critical minerals since the 1950s, export restrictions on REEs introduced by China in 2010 triggered many countries to adopt formal strategies and implement measures to ensure reliable supplies of minerals. Over the past decade, the European Union, the United States, Japan, Canada and Australia have all introduced critical material strategies. The issue of critical minerals has risen further up the policy agenda due to growing momentum behind clean energy transitions. Although ensuring undisrupted supplies is a common feature of the strategies, specific directions and policy priorities vary depending on national or regional circumstances.

Meanwhile, China has emerged as a major force in global supply chains for critical minerals and clean energy technologies over recent decades. The country's rise to becoming the kingpin of clean energy supply chains has largely been underpinned by its long-term industrial policies, such as five-year plans for economic development, the Made in China initiative and the Belt and Road Initiatives. In this section, we examine major policy directions and approaches to ensuring mineral security across global regions.

The European Union: Diversified and sustainable supplies to support clean energy transitions

In September 2020 the European Commission published a set of policy documents to make Europe's raw materials supply more secure and sustainable. It updated its policy directions from previous studies to align with new 2030 and 2050 climate ambitions. The policy package extended the list of critical minerals to 30, compared to 14 in 2011. Together with bauxite, titanium and strontium, lithium was added to the list for the first time in 2020, reflecting the region's ambition to nurture a battery and EV manufacturing industry. Some EU member states have a strong metal refining and manufacturing base. Finland refines around 10% of global refined cobalt output. There are major manufacturers of solar PV components, wind turbines and EVs in the region. However, the region is almost entirely reliant on external mining supplies for many energy transition minerals such as lithium, cobalt and REEs.

The European Union plans to seek opportunities for sourcing critical minerals domestically, for example by tapping opportunities for enhanced metal extraction in post-mining regions. The EU Action Plan estimates that this could lead to 80% of Europe's lithium demand being supplied from European sources by 2025 (European

Commission, 2020a). Other measures include encouraging circular uses of resources, including establishing advanced recycling capacity, strengthening efforts for sustainable product sourcing, and promoting technology innovation for material substitution. Europe holds a leading position in recycling critical minerals, with over 50% of its base metals coming from recycled sources (Eurometaux, 2019). To implement the plan, the European Union established the European Raw Materials Alliance, which involves industrial actors along the value chain, member states and regions, trade unions, civil society, research organisations, investors and non-governmental organisations. The alliance aims to diversify supply chains, attract investment into the raw material value chain, foster technology innovation and create an enabling framework for the circular economy.

The United States: Revitalising domestic production and building resilient supply chains

From the 1960s until the late 1980s, the Mountain Pass mine in California was the largest source of rare earth oxides in the world. In 1992 China surpassed the United States as the world's largest producer. Since then, China has dominated the global supply of REEs. After the Chinese export embargo in 2010, the US Department of Energy issued its first Critical Materials Strategy that year. The strategy identified 14 critical minerals, which were extended to 35 in later years. Since then, critical minerals have become a prominent

feature in US national security and defence strategies, highlighting the interdependence of economic security with national security.

The 2019 Federal Strategy to Ensure Secure and Reliable Supply of Critical Minerals highlighted that the country is reliant on imports for 31 of the 35 critical minerals, and has no domestic production for 14 of them. The strategy included 24 policy goals under the six major “calls to action” categories, alongside over 60 recommendations aiming to revitalise production and processing operations in the country and alleviate vulnerability against supply disruption. In addition to rebuilding domestic production, the strategy acknowledged the important role of strategic partnerships with other regions such as Canada, the European Union, Australia and Japan.

The Energy Resource Governance Initiative (ERGI), launched by the Bureau of Energy Resources of the US Department of State in June 2019, expanded the scope further to engage other major producers across the globe. Its aim is to promote sound mining sector governance and resilient global supply chains for critical minerals. This initiative brings countries together to engage in advancing governance principles, sharing best practices and encouraging a level playing field for investment. The founding partners – Australia, Botswana, Canada, Peru and the United States – released [the ERGI Toolkit](#) to share and reinforce best practices.

Japan: Securing critical mineral deposits overseas and investing in demand-side innovation

Due to its natural circumstances and highly industrialised economy, Japan realised early on that it had to meet its demand for natural resources through active foreign engagement and emergency preparedness. This has been the case both for oil and natural gas and also for critical minerals. In accordance with Ministry of Economy, Trade and Industry policy, it defined over 30 minerals as “rare metals” to ensure security of supply. Although Japan has no domestic resources, it does have a significant REE processing and refining industry, including 15% of global permanent magnet production (CSIS, 2021). Japan’s official target is to raise the self-sufficiency rate of mineral resources (base metals) to more than 80% by 2030. For this, the country has been taking action on both demand and supply sides. For example, in the aftermath of the Chinese export ban in 2010, Japan introduced a comprehensive policy package (“ABCD+R” initiative) that encompasses both supply and demand to reduce the risk of REE supply disruption.

On the supply side, Japan has been operating a strategic stockpiling programme since 1983, through Japan Oil, Gas and Metals National Corporation (JOGMEC). The government also provides financial support (loans, guarantees and equity) to Japanese companies working to develop overseas critical mineral resources, through JOGMEC. JOGMEC also directly conducts exploration activities in co-operation with foreign companies. These activities tend to be linked to direct supply guarantees for Japanese manufacturers.

Japan is also eyeing the potential of mineral resources on the seabed and conducted the first probe exploration in 2017.

The government also supports R&D for recycling, material efficiency and substitution technologies to reduce the primary supply requirements. These have been among the most active areas of Japan’s co-operation with the United States and the European Union.

Canada: Aiming to be a supplier of sustainable and responsible minerals for global markets

Canada holds some of the world’s most substantial reserves of many minerals, including some 15 million tonnes of rare earth oxides (NRCAN, 2020). The Canadian Minerals and Metals Plan released in 2019 sets a policy vision for establishing Canada as the leading mining nation of sustainable and responsible minerals. In response to growing momentum for clean energy transitions, it aims to bolster Canada’s standing as an exploration and mining powerhouse, increase foreign direct investment, promote the competitive mining service industry, and therefore boost the local economy. An additional task identified in the plan is to assess Canada’s recycling capacity to determine how it can support sustainability and competitiveness.

In January 2020 Canada and the United States signed a Joint Action Plan on Critical Minerals Collaboration to advance mutual co-operation. Additionally, Canada joined the US-led ERGI to advance its goals of securing sustainable supply chains for critical

minerals. The country also has strong bilateral relations on critical minerals with both the European Union and Japan through regular policy dialogue. It is also working with the Global Battery Alliance to develop a circular and sustainable EV battery value chain.

The country is putting a strong focus on sustainable development of minerals. It implemented a range of initiatives aiming to accelerate R&D for green mining technologies and promote sustainable development practices under the umbrella of the Green Mining Innovation initiative by the Department of Natural Resources. In 2016 CanmetMINING, a research branch of the department, initiated an internal programme called Mining Value from Waste to examine opportunities to reprocess mine waste to recover minerals and repurpose other inert materials. The Mining Association of Canada *Toward Sustainable Mining Initiative* is a widely recognised sustainability programme that supports mining companies' efforts to manage environmental and social risks. It was among the first to set a sustainability standard requiring site-level assessments.

Australia: Strengthening the critical minerals sector to support its economy through foreign investment, infrastructure and innovation

Australia is a major producer of many critical minerals: it is the world's largest producer of lithium and zirconium concentrate, and the fourth largest producer of REEs. The country is well placed to support global clean energy transitions as a reliable and responsible supplier of

many minerals that are vital to clean energy technologies. Australia's Critical Minerals Strategy 2019 outlines the government's ambition to expand this potential by promoting investment into its minerals sector. The focus includes downstream processing and refining, boosting innovation to lower production costs, and connecting mineral development projects with infrastructure development. At the beginning of 2020 the government established the Critical Minerals Facilitation Office within the Department of Industry, Science, Energy and Resources. The office's main goals include: (i) enabling and attracting investment; (ii) partnering internationally on global supply chains; (iii) helping finance prospective domestic critical minerals projects; and (iv) facilitating critical minerals research.

In March 2021 Australia launched the Resources Technology and Critical Minerals Processing road map and allocated funds under the government's AUD 1.5 billion Modern Manufacturing Strategy. The intention is to help manufacturers increase their competitiveness and build scale in the global market in the areas of resources technology and critical mineral processing. The road map aims to enhance the country's critical mineral processing capabilities, develop processing and refining industries, and maximise the value of country's resources.

China: A major force in the global supply chain for critical minerals through decades of industrial policies

China's recognition of the strategic value of minerals dates back to the seventh National Five-Year Plan for Rare Earth Industry (1986–

1990), which highlighted the need for research and production of advanced rare earth applications and new materials (CSIS, 2021). During the 1990-2010 period the focus was to secure resources to serve the country's burgeoning appetite for infrastructure build-out. Where domestic resources were lacking, China pursued a "going out" strategy and invested in overseas mining projects. A combination of state-directed investment and financing support based on long-term strategic plays saw Chinese firms take major positions in supplies of minerals from other countries, often in higher-risk jurisdictions. It is estimated that China today owns or has influence over half of the DRC's cobalt production through large stakes in its mining industry (FP, 2019).

At the same time, the country has been active in nurturing downstream capacity through supportive regulation, state-backed financing and subsidies. In some cases (e.g. REE), export and production quotas were used to favour companies that create additional value through processing, although export restrictions were lifted following the decision by World Trade Organization. The country currently accounts for some 40-70% of global copper, lithium and cobalt refining and almost 90% of REE processing.

While these approaches enabled China's rise in the critical mineral supply chain, in some cases they were accompanied by side effects such as financial losses, overcapacity and weakened environmental performance. As such, approaches in the 2010s shifted gear from large investment in bulk materials to focused investment in strategic

"new materials", reflecting the changing pattern of consumption and the evolving ambition in the clean energy space (STRADE, 2018).

In 2015 the government announced the Made in China 2025 initiative, which identified the "new materials" industry as one of ten important areas for government support. The new materials included permanent magnets (made from REE) that are central to many clean energy applications such as EV motors and wind turbines. While recent investment in overseas mineral assets does not appear to be as large as before, strategic investment continues. Examples include Tianqi Lithium's equity acquisitions in Chilean company SQM (23.8%) and Australia's Greenbushes lithium mine (51%).

Due to the strong foothold of its downstream industries, China's consumption of mined material has been increasing, often at a faster pace than domestic production growth (e.g. copper, REE). This triggered the country to introduce policies to mitigate risks from potential supply disruption. China's National Mineral Resource Plan for 2016–2020 called for a warning mechanism to safeguard its REE supply chains against potential disruption, and a more systematic demand and supply analysis of mineral products. More recently China passed a law to allow export controls on items considered to be critical to the state's interest and security. The country also announced draft legislation to strengthen the approval process for REE development projects (CSIS, 2021).

IEA's six pillars of a comprehensive approach to mineral security

While each country has different motivations and approaches to the issue of critical minerals, their experiences provide useful lessons for designing frameworks to ensure reliable mineral supplies. Past approaches have varied depending on whether the country is a producer or a consumer, but this distinction is increasingly becoming blurred as producer countries strive to build a domestic industry to produce clean energy equipment, and consumer countries seek to revitalise domestic production or secure overseas production assets. This suggests that an approach to ensuring reliable mineral supplies needs to be multi-faceted, covering a wide range of aspects from supply to demand to recycling.

Based on the IEA's long-standing experience in energy security, we identify **six pillars of a broad approach to minerals security**, complementing countries' existing initiatives. They are: (i) ensuring adequate investment in diversified sources of new supply; (ii) promoting technology innovation at all points along the value chain; (iii) scaling up recycling; (iv) enhancing supply chain resilience and market transparency; (v) mainstreaming higher environmental and social standards; and (vi) strengthening international collaboration between producers and consumers.

Beginning with adequacy of supply, the supply of minerals and metals needs to keep up with the rapid pace of demand growth to ensure orderly energy transitions. This requires strong growth in investment

to bring forward new supplies at the right time. Governments can take a variety of measures to attract investment into the sector, but the foremost action is to provide clear and strong signals about energy transitions. As noted in Chapter 2, the largest uncertainty around demand comes from questions about countries' real commitment to their climate ambitions. If companies do not have confidence in countries' climate policies, they are likely to make investment decisions based on much more conservative expectations. Given the long lead times for new projects, this could create a bottleneck when deployment of clean energy technologies starts to grow rapidly, as envisaged in the SDS.

Governments can also play a role in creating conditions conducive to investment in the mineral supply chain. Measures could include strengthening national geological surveys, streamlining permitting procedures to shorten lead times and, in some cases, providing financing support to de-risk strategic projects (which can be defined according to each country's own assessment of which, and how much, critical minerals they might need in the future). They can also support the unlocking of additional sources of supply by supporting enhanced metals recovery from low-grade ores and waste streams or revisiting the potential of abandoned mines. Further, governments can work together to improve data availability and comparability across regions, and raise public acceptance.

Box 3.2. What would be the right metrics to assess mineral security?

Any efforts to improve security of supply start with understanding where we stand and what progress is being made. The rising importance of critical minerals in energy transitions raises a question about the right metrics to measure the status and progress of mineral security.

The most commonly used metrics today are (i) import dependency and (ii) the level of supplier concentration. Import dependency is calculated as the amount of imported material as a percentage of domestic consumption. The level of supplier concentration is often measured using the Herfindahl–Hirschman Index, a widely used metric to assess the level of market concentration. In some cases, these are complemented by measurement of the economic importance of a certain mineral, such as the contribution of minerals to the value added of end-use sectors. Many countries have defined a list of critical minerals using variations of this approach.

While these remain highly valuable, most of the metrics naturally focus on the sovereign boundary, and the question remains as to how these measures can trigger action to improve security of supply. Given the need for a wider security approach, there may be scope to develop metrics that encompass wider aspects of supply, demand, resilience and sustainability to complement the traditional criticality indicators.

For example, to assess the adequacy of future supply, the actual level of investment spending against the level required to meet long-term demand could be measured, as has been done for the energy sector in the IEA's *World Energy Investment* reports. This could give an indication of possible market tightness.

Public R&D spending on technologies that can reduce material intensity, allow substitution and unlock new supplies can be assessed. The IEA's *Energy Technology RD&D Budgets* report assesses this for energy technologies in IEA member countries. There is scope to track material intensity in clean energy technologies in a systematic manner. This will be crucial for a more accurate view about future material requirements.

On supply chain resiliency, the measurement of supplier concentration could be expanded to include the processing and refining value chain. Some countries assess the political and social risks of the major producers, which can be a useful complement. Finally, progress on recycling (e.g. collection rates and the share of secondary production) can be an important part of security metrics.

Both traditional and complementary metrics will require greater data transparency. Governments have a role in collecting and disseminating reliable data in this regard.

Stepping up efforts for technology innovation and recycling can yield multiple benefits

History suggests that innovation in demand-side technology can play a major role in alleviating strains on supply and reducing material costs, which could in turn help enhance the affordability of clean energy technologies. As noted in Chapter 2, costs associated with raw materials are likely to represent a larger portion of total investment costs for clean energy technologies in the future as other cost components continue to decline thanks to technology learning and economies of scale. This underscores the important role of innovation in demand-side technology to mitigate upward cost pressure.

There are many positive examples. Efforts to reduce the use of silver and silicon in solar cells have helped to enable a spectacular rise in solar PV deployment in recent years. Technology advances in aluminium helped ease strains on copper supply in the 1950s and tin supply in the 1980s. A host of emerging technologies have the potential to reduce the use of critical minerals, if successfully commercialised (e.g. induction motors or switched reluctance motors to reduce REE consumption). There is, however, a need to assess trade-offs that substitution could trigger (e.g. all solid-state batteries reduce the need for nickel and cobalt, but require more lithium).

The possible contributions of technology are not confined to the demand side. Innovation in production and processing technologies can unlock sizeable amounts of new supplies and contribute to

reducing primary supply requirements. The emergence of Sx-Ew processes in the 1970s opened up the possibility to tap into extensive copper oxide resources. More recently, emerging technologies such as direct lithium extraction, or enhanced metal recovery from waste streams or low-grade ores, could lead to a step change in future supply volumes. Technologies that help reduce water use or energy consumption can also bring additional environmental and operational benefits. In 2021 the US Department of Energy announced USD 30 million in funding research to secure domestic supply chains. Countries endowed with huge resources are naturally putting more effort into supply-side technology innovation, but consumer countries can also benefit from reduced import dependency.

Policy support to scale up recycling efforts can bring multiple benefits. It can help reduce primary supply requirements and alleviate the environmental burdens associated with primary supply. Also, the security benefits of recycling can be far greater for regions with wider deployment of clean energy technology, as they stand to benefit from greater economies of scale. Government support may be necessary to incentivise recycling at the end-of-life stage of products, support collection and sorting activities and fund R&D into new recycling technologies. In the last section of this chapter, we examine the prospects and policy approaches to scaling up recycling in more detail, with a focus on batteries and electricity network

Governments can play a role in enhancing supply chain resilience and market transparency

Ensuring that critical minerals enable clean energy transitions requires a broad view of the supply chains, from mining to processing. Even if raw materials from mining are well supplied, a bottleneck in processing capacity could elevate prices for refined products and affect clean energy investment. In addition, a higher degree of concentration of production implies that disruption can have wider ripple impacts on the entire value chain.

Periodic stress-tests coupled with emergency response exercises can help policy makers identify points of potential weakness, assess potential impacts and devise necessary actions. For example, some European countries conduct a regular “N-1” stress test to assess the resiliency of gas supply infrastructure. The test assumes the loss of the single largest element of supply infrastructure and evaluates the impact on the country’s energy supply. Another example is the emergency response exercises the IEA regularly organises with its member countries to ensure quick and effective responses to major supply disruptions. Safeguarding security of oil supply has been the main focus so far, but the concept is expanding to encompass other areas as well. In 2016 the IEA worked with the Japanese government to conduct a gas resiliency assessment, aimed at identifying risks and challenges related to natural gas supply in Japan.

Voluntary strategic stockpiling, where applicable, can also help countries weather short-term supply disruption. Some countries have

been operating stockpiling schemes for many years as a tool to ensure supply security. Such programmes need to be carefully designed, based on a periodic review of potential vulnerabilities. In general, such schemes can be more effective for minerals with smaller markets, opaque pricing and a concentrated supply structure than those with well-developed markets and ample liquidity.

There is scope to improve market transparency. Many base metals such as copper are widely traded in the market with reliable pricing mechanisms. However, this is not the case for some energy transition minerals with smaller markets, such as lithium and cobalt (see Box 3.3). These minerals have been historically regarded as “minor minerals” and traded on a bilateral basis, resulting in low pricing transparency and liquidity. Buyers need to rely on information provided by suppliers, making it difficult to manage price risks and affecting investment decisions down the value chain. However, as demand grows, end users will increasingly call for more transparency around pricing to hedge risks. Establishing reliable price benchmarks will be an important step towards enhancing market transparency and supporting market development. While this process takes time, the experience in the LNG market shows the potential benefits: the rise of hub-based pricing for LNG, alongside long-term supply contracts, has made gas markets more responsive to changes in global and regional supply-demand balances.

Box 3.3. Towards a transparent pricing system: A story of lithium and cobalt

The predominant approach to trading lithium has not changed much over the past few years. Lithium has not been listed on an exchange and does not have a reliable benchmark price. The vast majority of lithium raw materials and chemicals are sold under bilateral long-term contracts between suppliers and end users. There is a spot price index based on Chinese custom data, but a question mark remains as to whether the index reflects market dynamics in an accurate and timely manner. It is rarely used for large-scale negotiation or hedging in practice (McKinsey, 2018).

However, there are signs of change. The duration of contracts is becoming shorter, and the London Metal Exchange (LME) introduced a tradeable price benchmark in partnership with Fastmarkets, a price reporting agency. The LME also plans to launch the LME lithium futures contract in the first half of 2021 – the first of its kind. These developments are expected to allow stakeholders to mitigate against price volatility.

There are, however, challenges. While a growing number of buyers are entering the market, only four companies supply the majority of lithium raw materials. The ambiguity of standards and classifications is another obstacle. Lithium is a speciality chemical that comes in a variety of material grades. This calls for a standardised methodology to enable comparability and accuracy of prices.

Cobalt is currently traded on the LME and the Chicago Mercantile Exchange (CME). The LME launched a physically settled contract in 2010, followed by a financially settled contract in 2019. CME launched new cash-settled cobalt futures contract in 2020. So far, the LME's physically settled cobalt contract has not been widely accepted by industry participants as a tool for hedging. The financially settled contracts faced similar issues. The major barriers to cobalt trade have been the lack of liquidity in the spot market, as well as cargo heterogeneity.

However, the situation is clearly improving with more pricing information being available. Fastmarkets releases a daily metal price and twice-weekly hydroxide payable assessment. These have been adopted into the majority of cobalt contracts. Some companies started to hedge cobalt exposure through financial swaps and banks are also getting involved.

Over time, as demand grows and more market participants enter the market, more liquid contracts are likely to be evident in the market. The development of new financial instruments will be important to provide some level of risk mitigation and increased levels of transparency (Lee et al., 2020).

Improved environmental and social performance contributes to enhanced mineral security

As a sector, mining is often cited as having the greatest exposure to ESG risks (S&P Global, 2019b). Recognising this, investors, consumers and civil society increasingly push companies to source minerals that are sustainably and responsibly produced, with institutional investors particularly visible in these efforts. It is becoming increasingly difficult for mining companies to ignore these concerns. Higher environmental and social performance is also crucial for governments to gain public acceptance for project development.

There is a significant degree of variation in environmental and social performance in the market. This makes it challenging for consumers to exclude poor-performing minerals as there may not be sufficient quantities of high-performing minerals to meet demand. Efforts to improve environmental and social performance can therefore contribute to enhanced mineral security by increasing volumes produced with higher environmental and social standards and lowering the cost of sourcing them.

Poor environmental and social performance can also lead to supply disruption. Production sites may be shut down or disrupted due to disputes over water access or as a consequence of regulatory actions to enforce child labour or human rights violations. Meanwhile, dam failures at tailings storage facilities can lead to extended

shutdowns and large remediation and repair costs. At the same time, criminal and civil liability related to environmental damage or corrupt practices can raise the cost of production, with severe reputational and financial implications for the companies concerned.

A level playing field

Environmental and social performance tends to be better for minerals produced in countries with well-developed regulatory systems, strong enforcement and institutionalised transparency practices. At the same time, some of the worst social impacts caused by mining, such as child labour, are ultimately a product of widespread poverty. To address these impacts, co-ordinated policy efforts will be needed: (i) to provide technical and political support to countries seeking to improve legal and regulatory practices; (ii) to incentivise producers to adopt more sustainable operational practices; and (iii) to ensure that companies across the supply chain undertake due diligence to identify, assess and mitigate these risks (see Chapter 4).

Establishing a level playing field may also help to support innovative strategies to address these risks, which can ultimately lead to greater diversification among supply. If strong environmental and social performance is rewarded in the marketplace, new entrants will have an incentive to develop new approaches to addressing these risks.

International co-operation is vital for ensuring reliable and sustainable mineral supply

As noted above, many governments have developed strategies to ensure the reliable and sustainable supply of minerals. While encouraging, given the complex nature of the mineral supply chains spanning across the globe and involving multiple minerals, no individual country will be able to drive the necessary changes on its own. For example, in the case of REEs, while there is growing interest in securing diversified supply options, it would be challenging and cost-prohibitive for a single country to build a presence along the entire value chain and some efforts so far have given rise to trade disputes (see Box 3.4).

Governments can steer better market outcomes and improve the security of mineral supply by working together. For the moment, there is no overarching international governance framework for critical minerals and co-ordinated policy action is lacking. Individual efforts are often fragmented and tend to focus on narrow issues. There is a strong case for strengthened international co-operation to ensure reliable and sustainable mineral supply. To this end, the UN Environmental Programme's International Resource Panel highlighted the need for a framework to inform policy strategies and co-ordinate international efforts surrounding mineral security (IRP, 2020).

There are many ways in which a multilateral framework could play a role in ensuring reliable and sustainable mineral supply:

- Provide clear market signals on decarbonisation targets to reduce demand uncertainty and help de-risk investment decisions.
- Facilitate a dialogue between producers and consumers to identify key bottlenecks and co-ordinate investment decisions.
- Mobilise public funds to accelerate R&D efforts for technology innovation.
- Conduct regular assessments of potential vulnerabilities across the supply chains and discuss collective action to respond to potential disruption.
- Promote knowledge and capacity transfer to spread sustainable and responsible development practices to a wide range of countries.
- Strengthen environmental and social performance standards through international standardisation and other mechanisms, to maintain a social license and ensure a level playing field.
- Co-ordinate diplomatic efforts to prevent restrictive export policies.
- Collect reliable data to assess the level of risk and help informed decision-making.

Box 3.4. Export restrictions on critical minerals

As security of supply comes into sharper focus, potential distortions to the free trade of critical minerals become increasingly sensitive. Export restrictions introduced by China, Indonesia and the DRC reflect the varying objectives being pursued, and the mixed results achieved. Quantitative restrictions are largely prohibited under GATT article XI, but may be justified under certain limited exceptions such as environmental conservation or national security.

China started introducing export restrictions on REEs in 2006, which resulted in an increase in prices and the United States filing a WTO case in 2012. Plaintiffs argued that the export controls were part of a deliberate industrial policy, and not resource conservation efforts. In 2014 the WTO Appellate Body ruled in their favour and China lifted the measures (WTO, 2015). Moves by third countries to invest in non-Chinese sourcing, the subsequent collapse in prices and the ultimate WTO ruling underline the mixed benefits of such measures. In January 2021 the Chinese government issued its draft version of the Regulations on Rare Earth Management. The regulations aim to protect national security and prohibit unsustainable practices such as illegal mining and environmental degradation. Exports would become subject to government approval through the Chinese Export Control Law (China Briefing, 2021). The compatibility of any potential measures with WTO provisions remains unclear.

Policies aimed at adding local value are also subject to economic conditions and WTO rules. For instance, while Indonesia's nickel ore export prohibition has been successful at enticing the construction of smelters (UNCTAD, 2017), it has not attracted a diverse investment profile, with mostly Chinese companies investing so far, and the European Union is now challenging it at the WTO (DG Trade, 2021). The DRC pursued a similar strategy through an export ban on copper and cobalt concentrates starting in 2013. However, this ban has largely stalled due to operators' inability to develop local processing facilities (Africa Oil & Power, 2020). This reflects the inherent challenges to interventionist trade policies in commodity-dependent countries.

These examples illustrate how growing concerns over local development and environmental conservation could lead to an increase in export restrictions. However, importing countries are likely to dispute them as a proxy for industrial or geopolitical strategies. Empirical evidence also shows that despite the limited geographic scope of production and/or processing of certain minerals, export restrictions often have limited effect in the long run due to potential diversification of supply (IRENA, 2019).

Focus on recycling

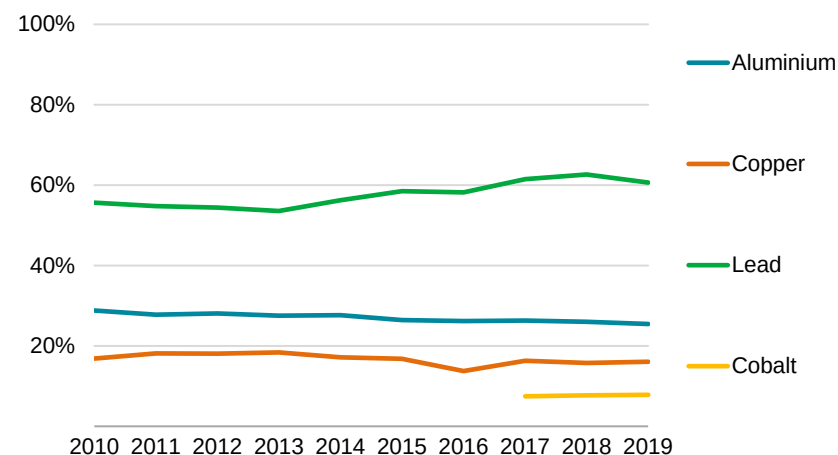
Growing recycled volumes have only managed to keep up with demand growth

Metal recycling has the potential to be a significant source of secondary supply, although it comes with its own set of challenges. Recycling comprises the physical collection and separation of metals, and metallurgical processing to recover them. Taken together, these combine multiple pathways with a wide range of technologies and practices. Potential sources for recycling include tailings from processing, scrap used in manufacturing and fabrication and scrap from end-of-life products. For some metals, such as aluminium and copper, global stock and recycling pathways are relatively well established. However, for many metals, global stock assessments are scant or only examine discrete sub-sectoral applications, making recycling potential difficult to assess.

As noted in Chapter 1, recycling rates are typically measured by end-of-life recycling rates and recycled input rates. End-of-life recycling rates refer to the share of material in waste flows that is actually recycled, and recycled input rates assess the share of secondary sources in total supply. Both rates differ substantially by metal and region. Higher end-of-life recycling rates do not necessarily mean higher recycled input rates, as each end-use product has a different lifetime and shows a varying pace of demand growth. For example, a beverage can typically enters the waste stream within a month after

consumption, whereas building materials take over 40 years to be collected. The fact that collected products are often reused in a semi-fabricated form makes an additional difference. For many metals such as copper and aluminium, recycled input rates have not changed much in recent years, meaning that improved recycling activities have only managed to keep up with demand growth.

Recycled input rates for selected metals and minerals



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Notes: Share of secondary production in total refined product consumption. Does not include scrap volumes that are reused in end-use applications. Source: World Bureau of Metal Statistics (2020).

Scaling up recycling can bring considerable security and environmental benefits

Physical collection is a primary limiting factor on the level of recycling. Metals such as aluminium, iron, nickel and often copper have been able to achieve high rates of recycling for simple, bulk products or for industrial applications that are easier to collect and more homogeneous in nature. As a result, these metals have a higher potential for continuous recycling and maintaining global stock.

Many new products such as personal electronics or alloyed materials make physical and metallurgical separation difficult. New iron and copper alloys, for example, bring superior functionalities but result in energy-intensive recycling pathways. Recycling of these products may require the physical, chemical and metallurgical separation of over 50 materials with different thermodynamic and metallurgic considerations from a single product.

Recycling technologies need to take into account current available stock and anticipate stock changes. Minerals that enter stock today may not be recoverable for decades depending on product life. Technologies must adapt to the stock life and the nature of the stock's evolving thermodynamic and metallurgical properties. While stock descriptions are moderately robust for copper, aluminium and nickel at a global level, most critical minerals lack information and description of stock at country, regional or global levels. For many energy transition minerals, stock descriptions and estimates are

needed to inform policy measures to efficiently support the development of new markets (Nicolli et al, 2012).

But the potential for increased secondary supply from recycling, while challenging, is apparent. Recent analysis indicates that recovery of key minerals (copper, palladium, gold and silver) from printed circuit boards could require as little as 5% of the energy as compared to primary supply from mining (Seabra and Caldeira-Pires, 2020). In a world increasingly looking to reduce emissions, this is an important advantage. Critical to achieving these potential rates are increased collection rates, developing knowledge of global and regional stocks, market incentives, and collaboration, often beyond country borders, to encourage secondary market development. The digital revolution is also seeing its mark across recycling processes. Approaches span from the use of data analytics to track and understand global and regional metal stocks to the use of new sensors to improve physical collection and separation.

In addition to established waste streams (e.g. industrial applications), emerging waste streams from clean energy technologies (e.g. batteries, solar panels) could be a significant source of secondary supply after the 2030s, although they do not eliminate the need for continued investment in the primary supply of minerals.

Enhanced metal recovery from mining and processing waste provides additional opportunities for secondary supply

Enhanced metals recovery from mining and processing waste (e.g. mining residues, slag, sludges and tailings) provides a clear opportunity to increase supply. Better treatment of waste streams can also reduce the risk of hazardous materials entering the environment. Governments are increasingly taking notice of the opportunities to improve metal recovery from waste streams, as shown by Australia's recently announced National Manufacturing Priority roadmap (DISER, 2021) aimed at increasing the country's share of critical mineral supply.

New technologies, coupled with in-depth assessments of the potential from mining and processing waste, can help generate further supply and reduce the dependence on imported materials. For example, the Kiruna iron ore mine tailings in Sweden are estimated to contain approximately 5 000 parts per million of REEs after beneficiation and are considered a new REE resource for the European Union (Peelman et al., 2016). US scientists found that waste rock from long-closed iron ore mines in the eastern Adirondack Mountains, New York, may provide valuable REEs. This is triggering further analysis of the potential of waste rock and tailings from old mines, although there are challenges associated with the proper

handling of radioactive elements (e.g. thorium) (USGS, 2020). Rio Tinto is tapping an opportunity to extract lithium from waste rocks at its Boron mine in the United States (see section on lithium). Several laboratory studies demonstrated the potential of bioleaching to recover copper, cobalt, nickel and others from mine tailings and other secondary sources (e.g. electronic waste) in Germany, Spain, Serbia, Iran, China and Uganda (Schippers et al., 2014, Zhang et al., 2020).

Similarly, stockpiled and annually produced bauxite residue can be considered a resource for extracting REEs, titanium and vanadium. In the European Union the combination of enhanced metal recovery from low-grade ores, fine grained landfilled sludges, iron-rich sludges from metal production (from zinc production) and fayalitic slag (mostly from primary and secondary copper production) could yield additional volumes of zinc, nickel, copper, cobalt and others, with a combined market value estimated at EUR 2.9 billion per year (Eurometaux, 2019).

While secondary supply from waste streams is becoming increasingly cost-competitive with primary sources (Spooren, 2020), challenges remain to be addressed such as minimising emissions from recycling processes and removing hazardous substances.

Policy intervention may be necessary to build demand for secondary supply...

In certain contexts, secondary markets for specific metals have developed in recent years even in the absence of policy support. This has occurred where market prices were high enough to encourage investment in recycling and a sizeable, readily available supply of waste stock existed. This is not currently the case for many minerals and metals that are vital for energy transitions. Barriers to further development of secondary supplies include competition from primary supply (the prices of which often do not account for negative environmental externalities), information deficits and limited waste collection (Nicolli et al, 2012; Söderholm, 2020). In these cases, a range of policy options can support the development of secondary supply markets and consequently reduce many of the environmental and social impacts associated with mining.

Support for secondary supply markets

Many countries have set overall recycling rate targets for consumer products – particularly for end-of-life vehicles and electronic waste. However, these product-specific recycling targets are less likely to encourage recycling of energy transition metals than more targeted, metal-specific policies. Weight- and volume-based metrics that are not metal-specific may allow companies to meet the targets by focusing on high-volume materials that are more readily recyclable than those found in small or trace quantities (UNEP, 2013).

Targeted policies, including minimum recycled content requirements, tradeable recycling credits and virgin material taxes all have potential to incentivise recycling and drive growth of secondary supplies (Söderholm, 2020). Alternatively, governments can consider direct subsidies for recycling. California's Covered Electronic Waste programme, for example, charges a fee to consumers on purchases of electronics, which is used to offset the cost of recovery and recycling. Each of these policy options increases the cost of using non-recycled materials vis-à-vis secondary supplies.

While these policies can, in theory, all yield similar outcomes, their impacts may vary in practice depending on the specific market dynamics (e.g. how a certain tax level would affect prices for primary products and in turn the uptake of secondary supply in each market). It is therefore crucial for policy makers to choose policy tools based on an understanding of the specific market context in order to adequately account for the costs of negative externalities.

International co-ordination will be critical because of the global nature of metal markets. If policies designed to stimulate demand for secondary supply are enacted unilaterally, they may have unintended consequences that lead only to a geographical change in use rather than a change in market supply. In addition, collaboration between countries or regions may be needed to sufficiently understand market stock, costs and dynamics.

...and to ensure a sufficiently large waste stream to justify infrastructure investment

In addition to policies driving demand for secondary supplies, it will be important for policy makers to address other potential externalities associated with secondary supplies. They include supporting the development of collection and sorting programmes and incentivising manufacturers to develop products that are easier to recycle.

Enhanced support for collection and recycling

Economies of scale play a major role in improving the economic viability of recycling, and increasing collection and sorting rates is a crucial starting point. In this context, government policies can play a major role in facilitating waste collection. For example, although traditionally applied to drinks containers, deposit-refund schemes may have potential to increase collection rates of electronics and batteries. Denmark introduced such a system in the 1990s to increase collection of nickel-cadmium batteries (OECD, 2014). Lower-volume minerals, such as cobalt, lithium or REEs, may require collaboration across country boundaries, for example across the European Union, to drive sufficient waste streams to warrant infrastructure investment. Furthermore, concerted action may be needed to discourage waste from being exported for the purpose of avoiding recycling requirements and to ensure that products exported for secondary use are held to similar end-of-life standards in the destination country – for example, batteries contained in exported used cars.

Extended producer responsibility

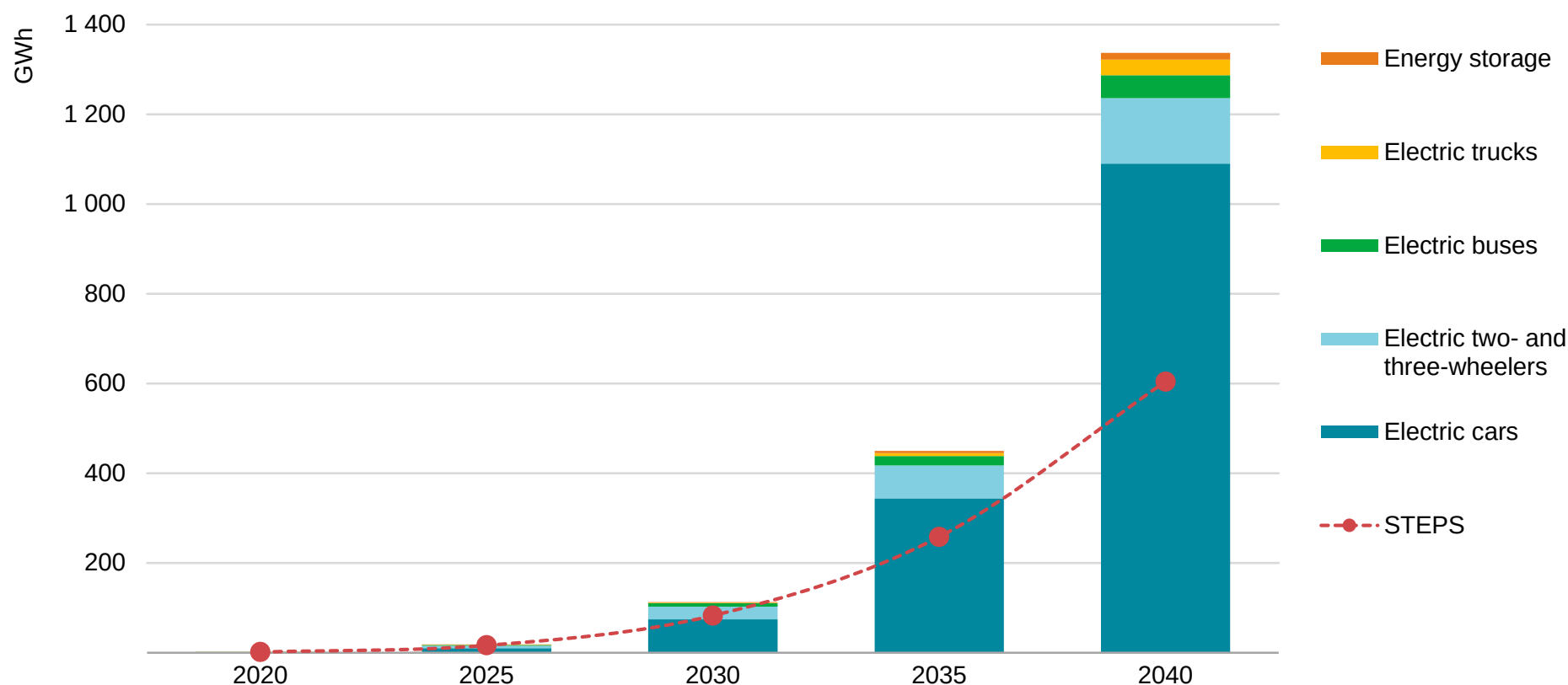
Waste collection can also be encouraged by making the manufacturer responsible for the treatment or disposal of post-consumer products. In addition to incentivising collection, this encourages manufacturers to reduce waste and to adopt product designs that facilitate recycling processes. Schemes like these have been deployed across a number of different product types, including batteries, tyres, vehicles, packaging and electronic waste. Although some extended producer responsibility schemes have led to very high recycling rates, there can be major differences in performance depending on policy design (Bio by Deloitte, 2014). Therefore, it is important that policy makers set clear definitions and objectives, apply those criteria equally to all market players, and take an active role in enforcement.

Ultimately, a mix of policies will be necessary to ensure that companies across the value chain incorporate recycling into their business activities. Depending on the market and national/regional considerations, combinations of trading credits, subsidies and other policy instruments can successfully support regional secondary supply value chains that ultimately influence global markets.

In the remainder of this section, we will consider two potential recycling cases in greater depth: batteries and electricity networks.

Battery recycling: The amount of spent EV and storage batteries reaching the end of their first life is expected to surge after 2030, reaching 1.3 TWh by 2040 in the SDS

Amount of spent lithium-ion batteries for EVs and storage by application in the SDS



Note: GWh = gigawatt hour.

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Battery recycling: The battery recycling industry is in its nascent stages, but the picture is set to change significantly from 2030 as an influx of spent batteries arrives

Although the volume of lithium-ion batteries available for recycling or reuse today is modest and largely dominated by batteries in waste electronic products, the fast-paced growth of EV sales and the demand for energy storage are poised to alter this situation significantly by the end of the decade. As the share of electric cars in the total car stock grows from today's 1% to 18% in the STEPS and 50% in the SDS by 2040, an influx of spent batteries is expected to arrive in the market, and is likely to pose serious waste management challenges. For example, when all the electric cars sold in 2019 reach the end of their lifetime, this would result in 500 000 tonnes of unprocessed battery pack waste (Harper et al., 2019).

The total amount of spent batteries from EV and storage applications is under 2 GWh today. Under the *WEO 2020* EV and energy storage deployment trajectories, the volume reaching the end of their first life rises modestly over the period to 2030 to the tune of 100 GWh, and grows rapidly thereafter to reach 600 GWh in the STEPS and over 1.3 TWh in the SDS by 2040. This represents over 20% of new battery requirements in that year. At over 80%, the majority of these spent batteries under the SDS in 2040 come from electric cars, while over 10% will be from electric two- and three-wheelers, more than 5% from buses and trucks, and just over 1% or about 15 GWh from the energy storage domain.

There are two main ways to deal with the stream of spent lithium-ion batteries – recycling and reuse. The first route involves recycling the used batteries to recover the valuable minerals like cobalt, lithium and nickel. This approach has several advantages. Recycling materials can curb the volatility of the supply chain and prices of raw materials for battery manufacturing, and can therefore play a pivotal role in alleviating the energy security concerns of countries that are heavily dependent on imports of these minerals.

It could also reduce the environmental, social and health impacts arising from mining large quantities of these minerals that are needed to meet the expanding demand for batteries. Further benefits of recycling include reducing the energy used for and emissions from the production of lithium-ion cells. Argonne National Laboratory found that the use of recycled materials reduces both (Gaines et al., 2018). The study reported that the most sizeable reductions in energy use come from the recovery of the metals, whose initial extraction from low-concentration ores is very energy-intensive. Additionally, sulfur dioxide emissions arising from cobalt, nickel and copper developments can be reduced by 65% to 90% depending on the recycling process employed.

Battery recycling: The projected surge in spent volumes suggests immense scope for recycling

Several methods for recycling lithium-ion batteries are currently in use either commercially or at the pilot level. Before being recycled, battery packs must be first discharged, stabilised and then dismantled to at least the module level. Once discharged, the cell components can be separated into different material streams for further processing. Three broad categories of techniques, either employed alone or in combination, are currently used for battery recycling. These are mechanical pretreatment, pyrometallurgical processes and hydrometallurgical processes.

Mechanical pretreatment primarily involves shredding and sorting plastic fluff from metal-enriched liquid and metal solids. However, it must be combined with other methods (usually with hydrometallurgy) to recover most cathode materials, other than copper, aluminium and steel casings. Few companies focus on this process: they include AkkuSer (Finland), Retrie Technologies (United States) and Li-cycle (Canada).

Pyrometallurgical recovery uses high-temperature smelting to reduce the component to an alloy of cobalt, nickel and copper. It is a frequently used method to extract valuable metals such as cobalt and nickel, despite its environmental drawbacks (such as the production of toxic gases) and high energy costs. Hydrometallurgical recovery uses aqueous solutions to leach metals from the cathode. This could be followed by solvent extraction and/or chemical precipitation to

recover lithium, nickel and cobalt. Umicore (Belgium) and JX Nippon Mining and Metals (Japan) are some of the representative companies that use both pyrometallurgical and hydrometallurgical technology, while Brunp (China) and Valdi (France) use mechanical and hydrometallurgical technology.

Additionally, an emerging recycling method known as direct recycling removes the cathode or anode from the electrode for reconditioning and reuse in a remanufactured lithium-ion battery without breaking them down into individual materials elements. Although this has the major benefit of avoiding long and expensive purification steps, there is a limitation that recovered cathodes can only be used for the manufacturing of the same battery type (Northvolt, 2019; IEA, 2020; Harper et al., 2019).

Currently, the global capacity for battery recycling is around 180 kilotonnes per year (kt/yr). China accounts for almost 50% of this capacity and it is expected to retain its dominant position given the large amount of additional capacity it has announced, amounting to 1 000 kt/y (BloombergNEF, 2019). Most of the companies involved today are independent refiners, but a broad spectrum of players from battery manufacturers, original equipment manufacturers, miners and processors are beginning to show interest in entering the market, especially in Europe.

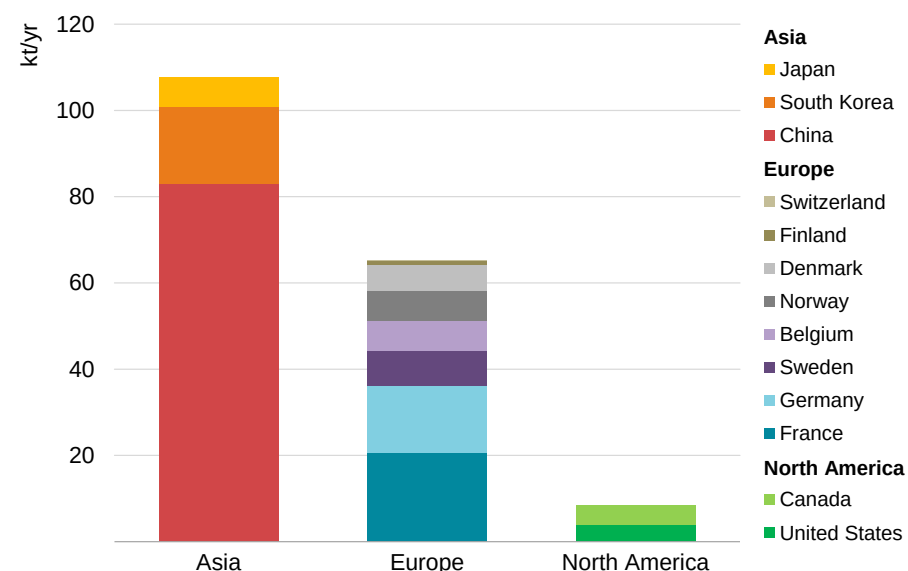
Battery recycling: The reuse of EV batteries for second-life applications offers additional scope for reducing primary supply requirements

A complementary measure to recycling is the reuse of the rapidly growing pool of EV batteries for “second-life” applications. Spent EV batteries tend to have terawatt hours of unused energy that no longer meet the standards for usage in an EV, although they typically maintain up to 80% of their total usable capacity (IEA, 2020). Repurposing used EV batteries could generate significant value and ultimately help bring down the cost of EV charging stations, residential and even utility-scale energy storage to enable further penetration of renewable power into electricity grids. Initial trials for second-life batteries have already begun. For example, in January 2020 Nissan Motor Co. and American Electric Power launched a pilot study in Ohio that reuses expired Nissan Leaf batteries to test their stationary storage characteristics. BMW introduced a plan to sell stationary storage products for peak load reduction and backup power storage in homes by reusing batteries from the i3 EV model.

However, a number of technological and regulatory challenges remain for second-life applications to grow at scale. Chief among them is their ability to compete on price given the rapidly falling cost of new systems. Retired batteries need to undergo costly refurbishing processes to be used in new applications, and a lack of transparency regarding the state of used batteries (e.g. storage condition,

remaining capacity) further complicates the economics. Clear guidance on repackaging, certification, standardisation and warranty liability of used EV batteries would be needed to overcome these challenges.

Existing and announced lithium-ion battery recycling capacity to come online by 2021 by region



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Sources: IEA analysis based on company announcements, press research and Swedish Energy Agency (2019).

Battery recycling: Scaling up battery recycling needs to overcome various technological and commercial challenges

While many companies are active or showing interest in the field, lithium-ion battery recycling has yet to reach the maturity of technology needed to scale up sufficiently and become economically profitable. The commercial viability of recycling depends on the costs of collecting and disassembling the batteries, as well as the value of the materials recycled. Unlike the lead-acid battery recycling industry, which is already mature, the lithium-ion battery recycling industry still needs to address several challenges in order to reach scale and profitability. Some of these are technical constraints, and others involve economics, logistics and a lack of streamlined policies.

Although some companies and organisations collect spent batteries, there are no comprehensive systems that dictate and guide the material collection processes at a national level in most countries. In 2006 the Battery Directive proposed by the European Union was an important step in this direction, but not all members have reached the mandated collection targets and the directive did not include specific targets for each mineral present in spent EV batteries. In December 2020, the European Commission proposed a new Batteries Regulation as an update to the older directive, which placed a particular emphasis on lithium-ion batteries. The proposed new regulation suggests mandatory sustainability and safety requirements (e.g. carbon footprint rules, minimum recycled content,

labelling and information) and end-of-life management obligations (e.g. producer responsibility, collection targets and obligations, recycling efficiency targets) (see Box 3.5).

Specific guidelines or regulations for discharging, disassembling and storing spent batteries are also lacking in most countries. China is one of the few with some technical guidelines on dismantling and restoring spent EV batteries, and retraining staff at carmakers (MIIT, 2018).

Transport logistics for end-of-life lithium-ion batteries pose another challenge. The high energy density of their cells, coupled with the presence of flammable organic electrolytes, creates a risk of thermal runaway. This requires more stringent safety measures to handle and transport spent EV battery packs.

Technology bottlenecks include the lack of standardisation of designs for battery packs, modules and cells. Different vehicle manufacturers have adopted different battery chemistries, especially for the cathode, and they tend not to disclose information on their cell designs and chemistries. This wide variety of cell types and chemistries in the market poses a major challenge to recycling, and especially to the automation of recycling processes, as each battery pack and module type requires different approaches for disassembly.

Battery recycling: Policy can play a pivotal role in preparing for the exponential growth in volumes of waste EV and storage batteries

While there is no standard policy framework that governs the end-of-life management of lithium-ion batteries globally, several policies have been announced, mainly in the European Union, China, Japan and at a state level in the United States. Recent progress also includes the founding of the Global Battery Alliance in 2017, which aims to establish a sustainable battery value chain, from sourcing, to repurposing and recycling.

Policy makers can consider three specific actions: (i) facilitating the efficient collection and transport of spent batteries; (ii) fostering product design and labelling that help streamline the recycling process; and (iii) harmonising regulations on international movement of batteries.

Firstly, clear guidance on collection, transport and storage of end-of-life lithium-ion batteries is crucial. Policies enabling the exchange of data between key stakeholders in the process, including original equipment manufacturers, will be necessary. For example, BMW, Umicore and Northvolt have recently embarked on a joint project that aims to create a “closed life cycle loop” for battery cells. In this technology consortium, the EV maker (BMW) collects and deposits its end-of-life batteries directly at the recycler (Umicore), then the recycler uses the recovered material to produce active cathode material. This material is then shipped to the cell maker (Northvolt),

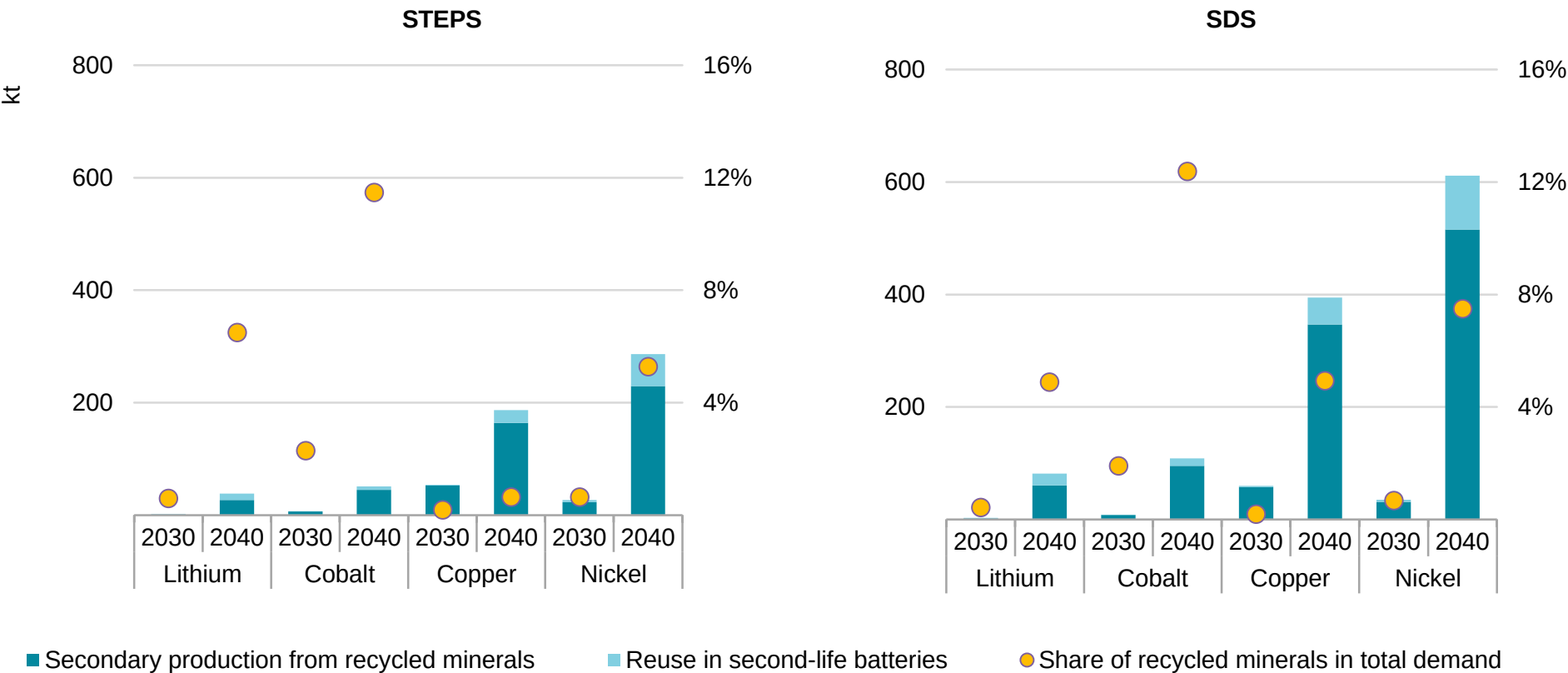
which closes the loop by supplying batteries to the OEM (Umicore, 2018).

Secondly, early action in the product engineering and design phase can help facilitate an efficient recycling process. The current design of battery packs is not optimised for easy disassembly. A more standardised battery design with recycling in mind will allow easier dismantling and automation. Measures such as including labels or QR codes on battery cells or battery packs, with information on the battery components, chemistries and substructures, would not only help streamline the recycling process, but also enhance safety by better preventing fire hazards and explosions during battery disassembly and smelting (SAE International, 2016; USABC, 2014).

Lastly, concerted regulatory action across countries to ensure the safe, eco-friendly and affordable transport of batteries is essential. The Global Battery Alliance has launched the concept of a “battery passport,” which is a digital representation of a battery that contains information about all applicable lifecycle requirements of a sustainable battery, making it easier to identify and track batteries throughout their lifecycle. This could not only support data sharing on battery chemistries, origin and the state-of-health of spent batteries, but also help countries harmonise their regulatory actions on transboundary movement of spent lithium-ion batteries (WEF, 2020).

Battery recycling: By 2040 recycling and reuse of EV and storage batteries could reduce the primary supply requirement for minerals by up to 12%

Contribution of recycling and reuse of batteries to reducing primary supply requirement for selected minerals by scenario



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Battery recycling: Recycling and reuse of batteries can bring significant security and environmental benefits, although the need for continued investment in primary supply remains

We analysed the possible contributions from recycling and reuse of spent batteries to reducing primary supply requirements for lithium, nickel, cobalt and copper under base-case chemistry assumptions. Key inputs to the model are the lifetime of the different batteries, the battery collection rate, the yield rate for each mineral, the reuse rate and the reuse efficiency. We assumed the collection rate to increase gradually to 80% by 2040, and the yield rate to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries faces many technical and regulatory obstacles.

The recycled mineral volumes are negligible in the 2020s, but they start to make larger contributions to the total supply from 2030 and become much more significant by 2040. While recycling and reuse assumptions are identical in the STEPS and the SDS, the higher absolute deployment of EV and storage in the SDS makes the contribution of the recycled minerals far more sizeable than under the STEPS.

In the SDS, recycled quantities of nickel, copper, cobalt and lithium from spent EV and storage batteries in 2040 are around 500 kt, 350 kt, 100 kt and 60 kt respectively. By 2040 secondary production from recycled minerals accounts for up to 12% of total supply requirements for cobalt, around 7% for nickel, and 5% for lithium and copper. The projected contribution of reused batteries is relatively smaller, reaching only 1-2% of total supply requirements for each mineral in 2040.

This implies that the recycling of end-of-life lithium-ion batteries to recover the valuable minerals, and to a smaller extent their reuse as second-life batteries, can relieve a proportion of the burden from mining them from virgin ores. Although this does not eliminate the need for continued investment in primary supply of minerals, the contributions from recycled minerals could be even more prominent in the total supply if effective recycling policies are adopted more widely across the globe, with larger benefits particularly for the regions with higher EV deployment.

Box 3.5. EU Sustainable Batteries Regulation

In line with the European Union's circular economy and European Battery Alliance objectives, the [proposed regulation](#) addresses the social, economic and environmental issues related to all types of batteries, including those imported into the bloc. The proposal covers the entire battery life cycle, and directly applies to lithium, cobalt, nickel and copper supply chains. The shift from a directive to a regulation is aimed at increasing harmonisation and legal certainty by giving the instrument binding legal force in all member states. The Commission states that the regulation sets out "mandatory requirements for the greenest, safest and most sustainable batteries on this planet" (EURACTIV, 2020). It is scheduled to enter into force on 1 January 2022.

Proposals for mandatory requirements range from sustainability and safety, end-of-life management, labelling, electronic exchange of information and digital passports. The aim is to enhance separate collection of portable batteries to achieve 70% collection by 2030, against less than 50% in 2018 (EUROSTAT, 2020) and prohibit any landfilling. It also places obligations on economic operators for product requirements and supply chain due diligence. The OECD Due Diligence Guidance is incorporated into the legal instrument, ensuring that sustainable batteries do not come at the expense of responsible and sustainable supply chains (see Box 4.8).

The regulation's general objective is to mitigate the environmental impact of batteries and their effects on climate change and public health by controlling toxic substances and mandating waste management. As part of the EU Sustainable and Smart Mobility Initiative, it aims to facilitate the transition to cleaner mobility by contributing to a 90% reduction in transport-related GHG emissions by 2050. The deployment of clean batteries reduces GHG emissions while improving air quality. The proposal sets out minimum levels of recycled content (12% cobalt, 4% lithium and 4% nickel by 2030) and material recovery (90% cobalt, 90% copper, 35% lithium and 90% nickel by 2026) which will gradually increase. Batteries sold in the European Union will have to carry a carbon intensity performance label and comply with carbon footprint thresholds. The carbon footprint, recycled content and responsible sourcing will be verified by recognised third-party entities. The Commission is supporting research on batteries in line with these objectives, in particular through H2020 projects receiving approximately EUR 500 million (European Commission, 2020b).

The regulation is a critical step towards achieving both clean mobility and high penetration of renewables, ensuring a fully circular economic model. By facilitating a market for recycled products and waste, it lays the groundwork for sustainable minerals development.

Grid recycling: Unlocking copper and aluminium from today's electricity networks

Transmission and distribution systems contain a large amount of “locked-in” copper and aluminium. Analysis of the globally installed base of overhead lines, underground cables and transformers suggests that 150 Mt of copper and over 220 Mt of aluminium are present in these grids today. These volumes are roughly seven times higher than current annual copper demand and three times higher than that for aluminium. With current technologies, the locked-in volume is projected to grow by almost 60% in the STEPS and some 75% in the SDS by 2040. When efficient collection and processing operations are put in place, these volumes can provide a sizeable source of supply to the market, via recycling or reuse.

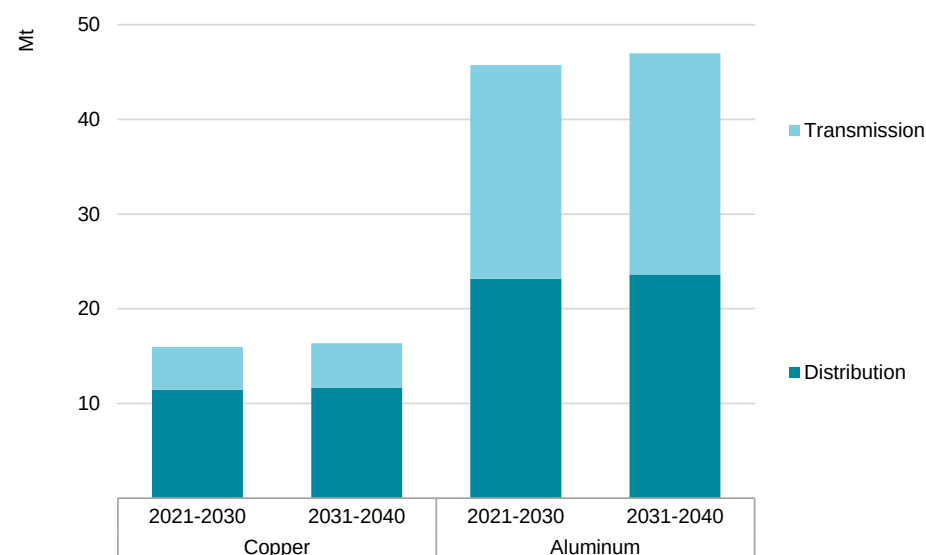
Overhead lines, underground cables and transformers in electricity grids have usually a design lifetime of around 40-60 years. After this period, these assets need to be replaced. The displaced grid assets can then be reused in a semi-fabricated form or the locked-in copper and aluminium can be recycled. Over 60 Mt of aluminium and copper attached to grid infrastructure needs to be replaced by 2030 and a similar amount between 2031 and 2040.

High end-of-life recycling rates are essential to reduce primary supply requirements for grid expansion and replacement. Copper has a high end-of-life recycling rate: current estimates of copper recycling from electricity grid infrastructure are around 60% (higher than the average copper recycling rates). But the potential end-of-life recycling rate of

copper is over 85% (Henckens, 2021). Achieving this would reduce primary copper supply requirements by over 9 Mt in 2040 in the SDS.

Aluminium has a global recycling rate of around 40% (UNEP, 2011). The potential end-of-life recycling rate of aluminium is estimated to be around 75% (IAI, 2020). Achieving this would reduce primary supply requirements by around 32.5 Mt in 2040 in the SDS.

Copper and aluminium demand for grid replacement



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Sustainable and responsible development of minerals

Failure to manage environmental and social impacts from minerals development will slow clean energy transitions

The growth of mineral supply not only plays a vital role in enabling clean energy transitions, but also holds great promise to lift some of the world's poorest people out of poverty. Mineral wealth can, if exploited responsibly, contribute to public revenue and provide economic livelihoods for many. However, if poorly managed, mineral development can lead to a myriad of negative consequences, including:

- Significant greenhouse gas (GHG) emissions arising from energy-intensive mining and processing activities.
- Environmental impacts, including biodiversity loss and social disruption due to land use change, water depletion and pollution, waste-related contamination and air pollution.
- Social impacts stemming from corruption and misuse of government resources, fatalities and injuries to workers and members of the public, human rights abuses including child labour and unequal impacts on women and girls.

In addition, these risks may lead to supply disruption, which could slow the pace of clean energy transitions. It is therefore imperative for both companies and governments to manage the environmental and social impacts of mineral production.

Companies have a clear business case to address these harms to reduce risk and maintain a social licence to operate. Consumers and investors are increasingly demanding that companies take these issues seriously. Failure to respond to these social demands could not only undermine reputation, but also lead to difficulties in raising capital or even to legal liability.

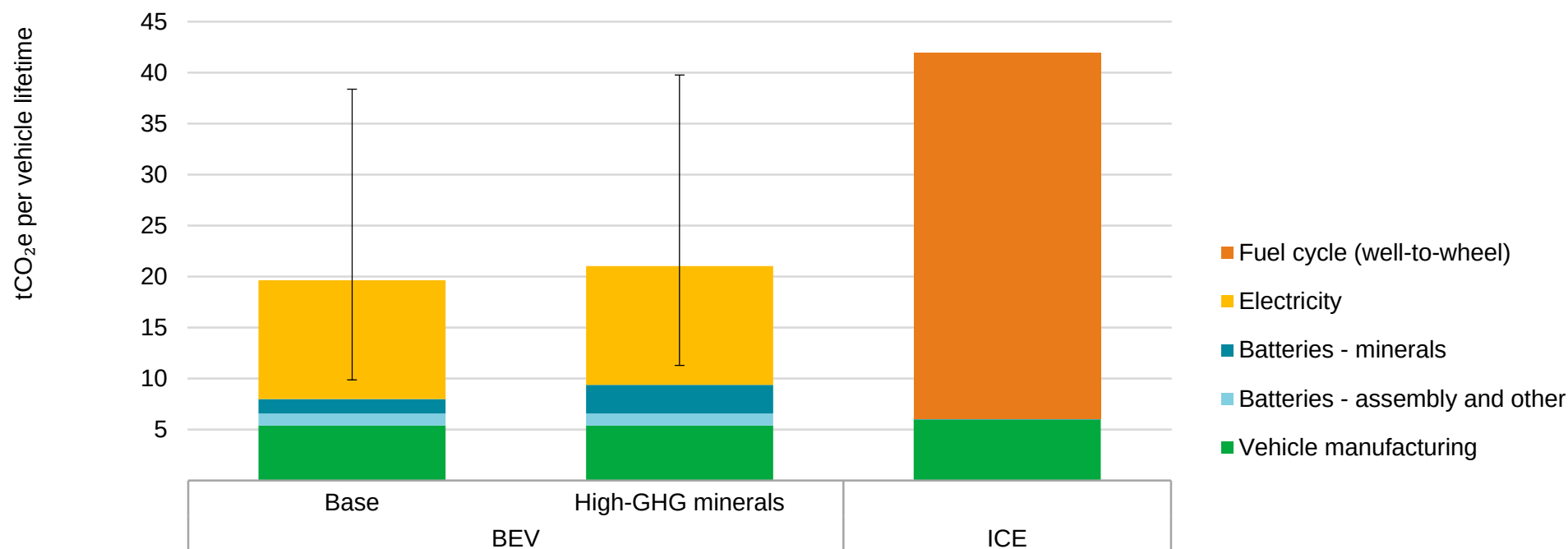
Companies have increasingly implemented responsible practices over the years. The adoption of corporate responsibility policies and processes at company level and via industry-wide initiatives has led to improvements throughout mineral supply chains. However, performance varies significantly among industry actors, with some segments showing limited effort and more progress being needed across the board. Challenges are more substantial where regulatory safeguards are inadequate, and where systemic issues such as labour informality, weak fiscal capacity and high inequalities are persistent, such as in artisanal and small-scale mining (ASM).

Governments play an important role in promoting improvements in environmental and social performance. As supply chains become more global, international co-operation to apply appropriate standards will be critical to ensuring that the extraction and trade of minerals are carried out sustainably and responsibly, and that the supply of energy transition minerals remains uninterrupted.

Mineral development and climate change

Emissions from minerals development do not negate the climate advantages of clean energy technologies

Comparative life-cycle GHG emissions of a mid-size BEV and ICE vehicle



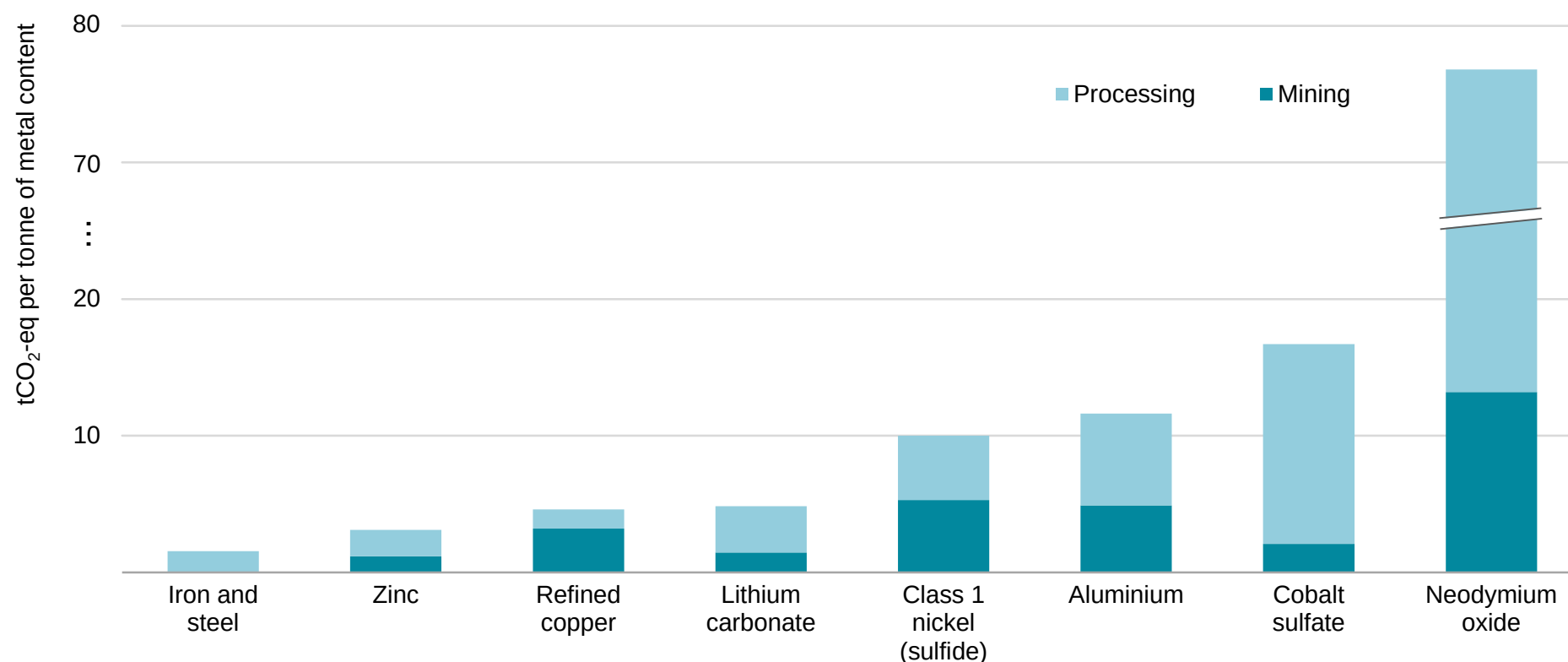
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Notes: The “High-GHG minerals” case assumes double the GHG emissions intensity for battery minerals (70 kg CO₂-eq/kWh compared to 35 kg CO₂-eq/kWh in the base case; other assumptions are the same). The values are for a vehicle manufactured from today’s manufacturing lines assuming dynamic global average grid carbon intensity in the SDS (including transmission, distribution and charging losses, weighted for mileage decay over a 20-year lifetime). The ranges shown for BEV represent cases for charging with a static low-carbon (50 g CO₂-eq/kWh) and high-carbon electricity mix (800 g CO₂-eq/kWh). Vehicle assumptions: 200 000 km lifetime mileage; ICE fuel economy 6.8 Lge/100 km; BEV fuel economy 0.19 kWh/km; BEV battery 40 kWh NMC622. BEV = battery electric vehicle; ICE = internal combustion engine; NMC622 = nickel manganese cobalt in a 6:2:2 ratio; g CO₂-eq = gramme of CO₂-equivalent; kg CO₂-eq = kilogramme of CO₂-equivalent; tCO₂-eq = tonne of CO₂-equivalent; km = kilometre; kWh = kilowatt hour; Lge = litre of gasoline-equivalent.

Sources: IEA analysis based on IEA (2020a); Kelly et al. (2020); Argonne National Laboratory (2020).

However, there is a growing imperative to tackle emissions from mineral development as energy transition minerals involve higher GHG emission intensities

Average GHG emissions intensity for production of selected commodities



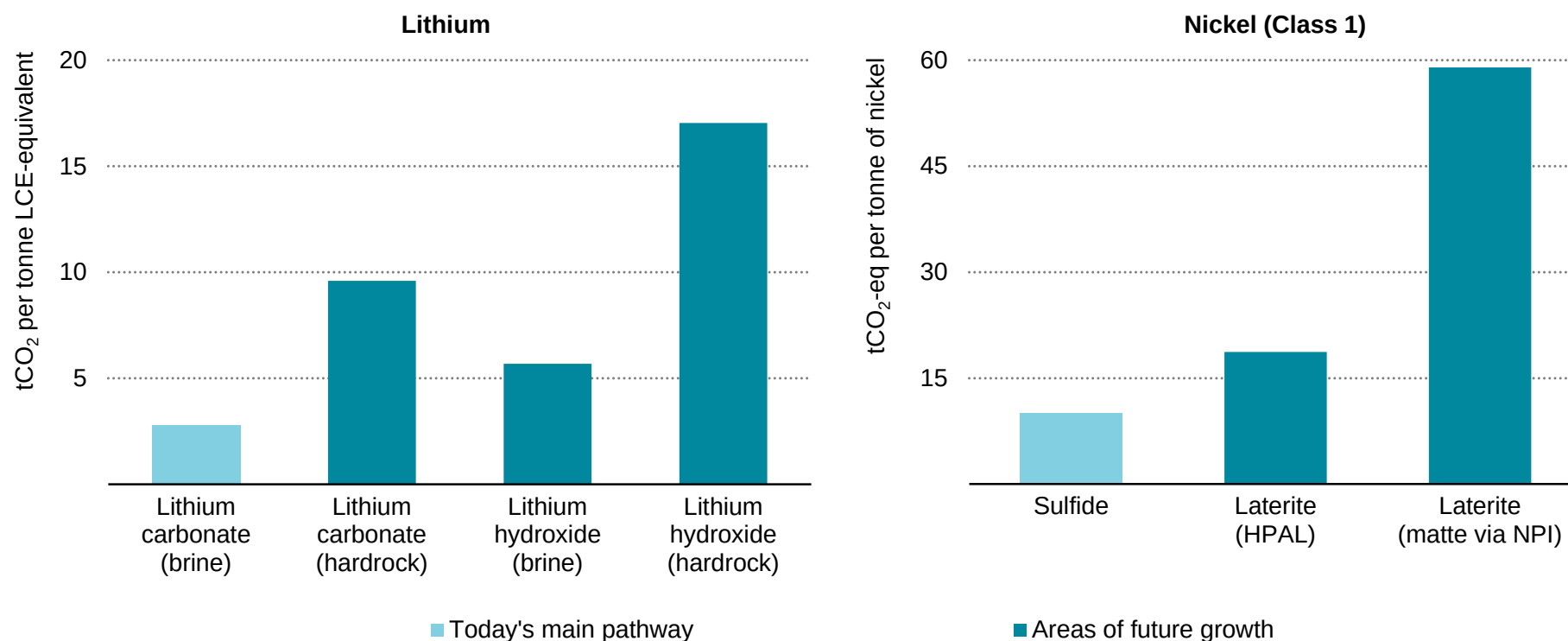
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Notes: Includes both Scope 1 and 2 emissions of all GHGs (the majority of which are CO₂) from primary production. The values for lithium carbonate refer only to CO₂ emissions based on the weight average of brine and hard-rock production (denoted on a lithium carbonate-equivalent basis).

Sources: IEA (2020b) and Rio Tinto (2020) (steel); Nuss and Eckelman (2014) (zinc); data received from Skarn Associates (copper and nickel); Roskill (2020) and S&P Global (2021) (lithium); IEA (2020b) and Tost et al. (2018) (aluminium); Argonne National Laboratory (2019) (cobalt); Marx et al. (2018) (neodymium).

Changing patterns of demand and types of resource targeted for development are set to exert upward pressure on emissions

GHG emissions intensity for lithium and nickel by resource type and processing route



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Notes: LCE = lithium carbonate-equivalent; HPAL = high pressure acid leaching; NPI = nickel pig iron. Includes both Scope 1 and 2 emissions from mining and processing (primary production). For lithium hydroxide, the value of brine is based on Chilean operations and the value for hardrock is based on a product that is mined in Australia and refined in the People's Republic of China ("China").

Source: IEA analysis based on Roskill (2020), S&P Global (2021) and Vulcan Energy (2020) (lithium); data received from Skarn Associates (nickel sulfide and laterite HPAL) and Trytten Consulting Services (nickel matter via NPI).

Stronger action will be required to counter upward pressure on emissions from mineral production

The process of producing various commodities, such as fossil fuels and steel, is a significant contributor to global emissions. For the moment, emissions from producing minerals vital for clean energy technologies are relatively small, due to their low production volumes. However, these minerals require much more energy to produce per unit of product, which results in higher emissions intensity than other commodities. For example, emissions from producing the average tonne of lithium carbonate and Class 1 nickel are three and ten times higher, respectively, than those from producing a tonne of steel.

The higher emissions relate to the fact that most energy transition minerals have a lower metallic concentration in ore. While the metal content in iron ore is typically 50-70% (IEA, 2020c), the average ore grade for nickel is less than 2% and under 1% for copper. Lower grade ores require more energy to extract the valuable fraction, and to move and treat the waste fraction (the “gangue”).

The effects are aggravated by deteriorating ore quality. The average ore grade for copper in Chile declined from 1.25% in 2001 to 0.65% in 2017. As a result, fuel and electricity consumption per unit of mined copper increased by 130% and 32% respectively over the same period (Azadi et al., 2020). Given their large electricity consumption, refining and smelting operations are also a major contributor to emissions, especially when relying on coal-based electricity.

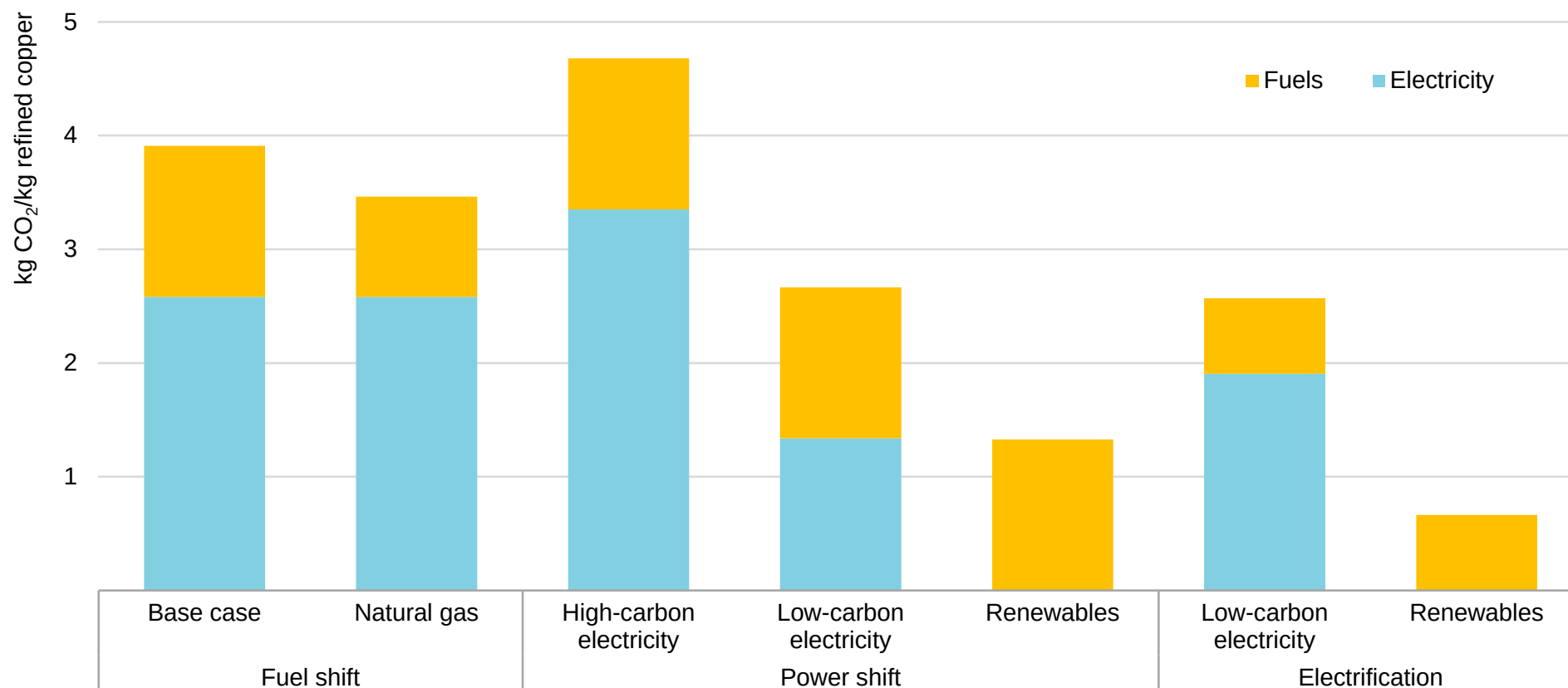
Future production is likely to gravitate towards more energy-intensive pathways. Lithium production has been moving from brine-based recovery (mostly in Chile) to mineral concentrate production from hardrock (mostly in Australia). The emissions intensity of hardrock-based lithium carbonate production is three times higher than that of brine production. This is due in part to higher energy requirements in mining and also in refining, the latter being mainly carried out in China where coal plays a dominant role in the power mix. In this context, several companies in Australia are looking to integrate projects within the country to lower these emissions.

There is also additional pressure from changing demand patterns for lithium. Demand is moving from lithium carbonate towards lithium hydroxide, as the latter is more suitable for batteries with higher nickel cathode chemistries. However, lithium hydroxide involves more emissions as it requires an additional processing step to convert lithium carbonate to lithium hydroxide (when produced from brine resources).

Battery-grade nickel faces a similar situation. While sulfide resources played a major role in the past, future growth is increasingly coming from laterite resources, which require more energy to produce. These underlying pressures highlight the need for companies to take stronger action to address emissions across their value chains.

The emissions intensity of production can vary considerably across companies and regions...

Energy-related CO₂ emissions intensity for an indicative refined copper production project under different energy consumption scenarios



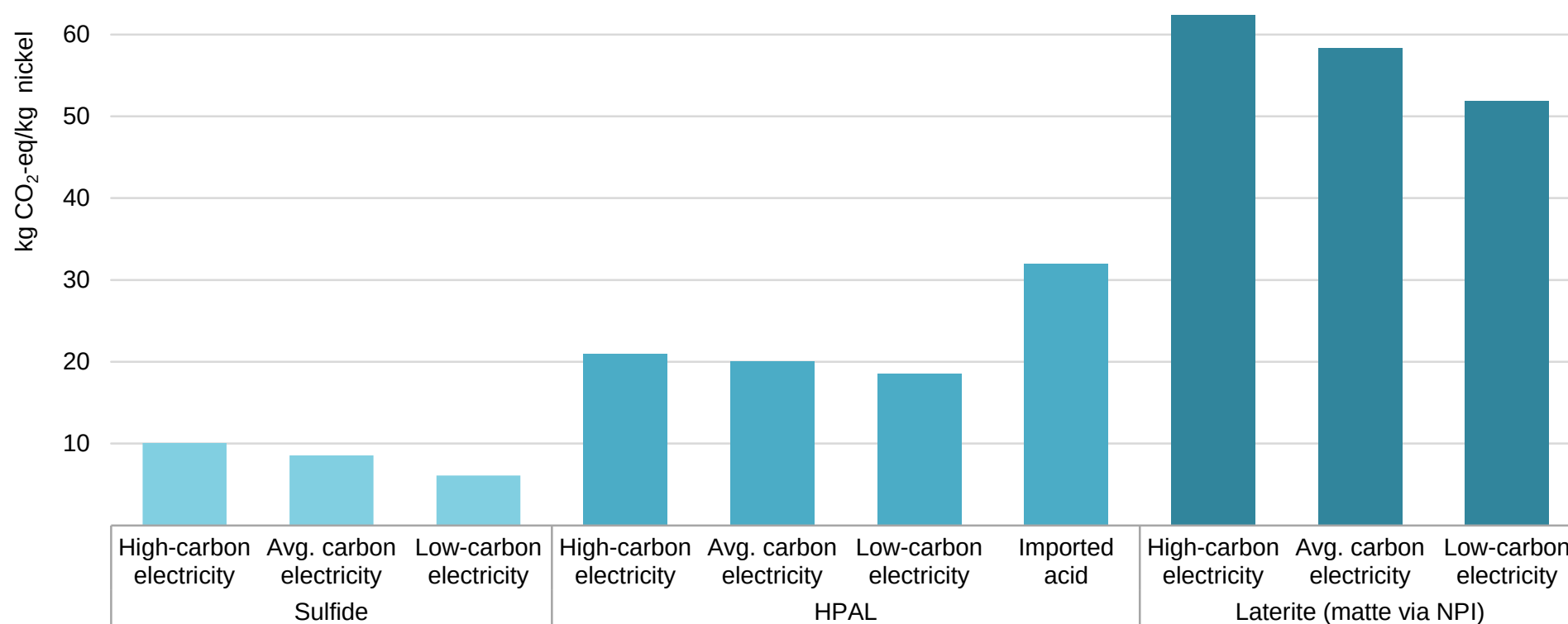
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Notes: The base case assumes a fuel mix of 33% coal, 33% diesel and 33% natural gas with a global average emissions intensity for electricity (463 g CO₂/kWh). The high-carbon and low-carbon electricity cases assume 600 g CO₂/kWh and 240 g CO₂/kWh, respectively, and renewables are assumed to be carbon neutral. The electrification case assumes 50% of the energy demand from fuel consumption becomes electrified.

Source: IEA analysis based on Cochilco (2020).

...depending on operational practices, power sources and production pathways

GHG emissions intensity for an indicative nickel production project under different grid scenarios and production pathways



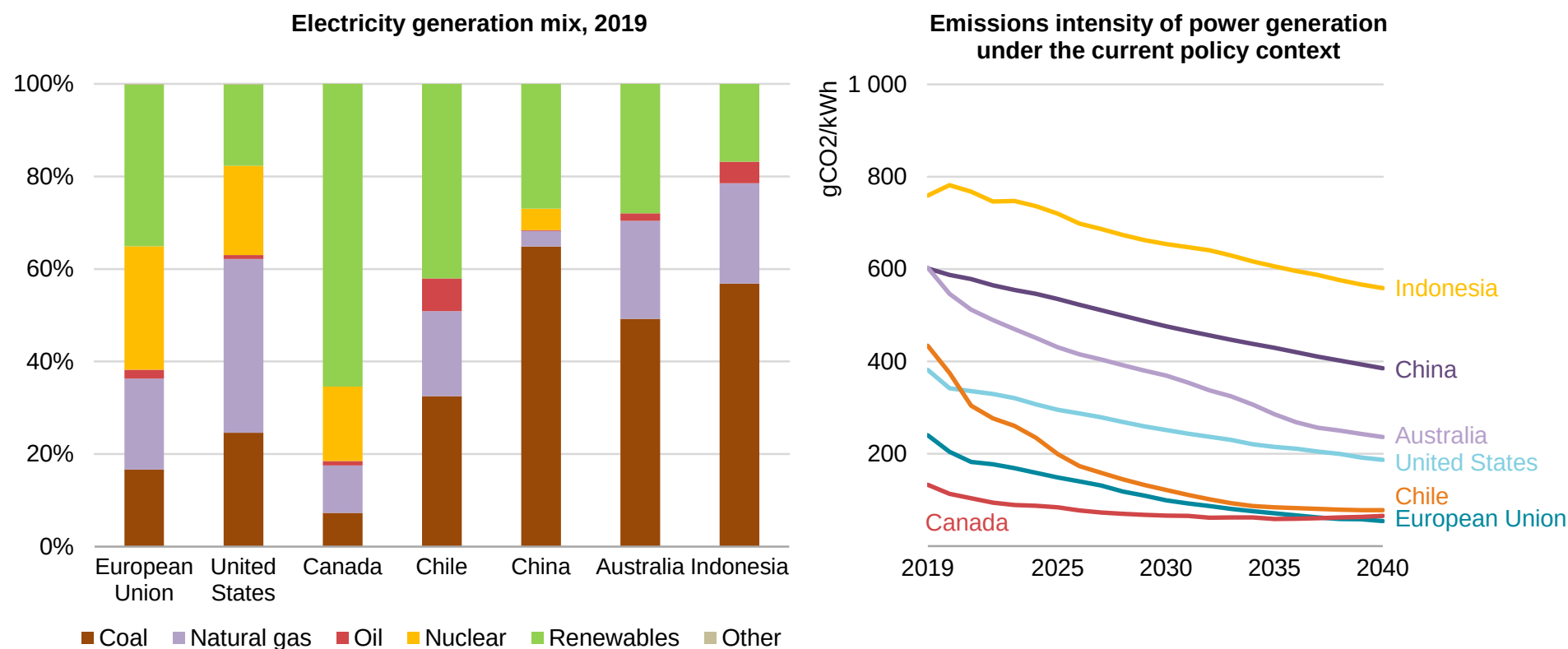
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Notes: Avg. carbon electricity = global average emissions intensity for electricity (464 g/kWh). The high-carbon and low-carbon electricity cases assume 600 g CO₂/kWh and 240 g CO₂/kWh, respectively. Includes both Scope 1 and 2 emissions from mining and processing. Imported acid HPAL assumes average electricity carbon intensity.

Source: IEA analysis based on data received from Trytten Consulting Services.

The carbon footprint of the electricity mix and the pace of future decarbonisation have significant impacts on the emissions profile of mineral production

Electricity mix and emissions intensity of power generation in selected regions



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Notes: The emissions intensity under the current policy context is based on the projections in the Stated Policies Scenario. The values for Australia also cover New Zealand as the two countries are modelled together in the World Energy Model.

Source: IEA (2020b).

Minerals are needed for clean energy transitions, and sustainable mineral development needs clean energy

Many aspects of mineral production contribute to climate change, and foremost among these are direct and indirect sources of GHG emissions. Direct emissions, also called Scope 1 emissions, include vented CO₂ from waste rocks, emissions from fuel used in mining and refining operations and GHGs from acid neutralisation, mineral beneficiation (e.g. flotation), extraction and waste streams (e.g. tailings). Indirect emissions are either associated with the generation of purchased energy (e.g. electricity, steam and heat) (Scope 2) or any other emissions that occur in the products' value chain (Scope 3). Overall, Scope 3 emissions are the largest source of GHG emissions from the mining sector, representing well over two-thirds of the total (McKinsey, 2020), which is why many companies are taking steps to curb these emissions by partnering with end users, such as the steel industry.

Even within similar production routes, GHG emission intensities vary greatly between operators, depending on the technologies employed and mine characteristics. For instance, a time-series life-cycle assessment study, which looked at copper mining and smelting in Australia from 1940 to 2008, indicated that the carbon footprint of copper produced at all sites over the time period ranged from 2.5 to 8.5 kg CO₂-eq/kg copper (Memary et al., 2012).

In the context of Scope 1 and 2 sources, emissions from mineral production are largely driven by electricity consumption and fuel use. Electricity serves multiple purposes throughout mineral development, but refining activities are particularly electricity-intensive, representing a large share of emissions that are linked to the grid's carbon footprint. Comminution, the process of crushing and grinding solid materials, is estimated to consume up to 3% of all the electricity generated in the world (NRCAN, 2016). Meanwhile, fuels are mostly used by vehicles (e.g. diesel consumption by trucks in ore hauling and loading operations) and to generate heat for processing steps.

Emissions from mineral development can be significantly reduced by a shift in fuel sources and by using low-carbon electricity. A simulation of an indicative refined copper production project under different energy consumption profiles reveals a wide variation in emissions intensity depending on the type of fuel used and the intensity of electricity supplied by the grid. Shifting all fuels to natural gas would bring emissions down by 10%, while using renewable-based electricity reduces CO₂ intensity by about two-thirds. Further reductions could be achieved through the electrification of fuel use. When combined, electrification and renewable-based electricity have the potential to reduce emissions intensity by almost 80%. Similar trends are also visible in nickel production.

Fuel switching, low-carbon electricity and investment in energy efficiency can significantly reduce the emissions footprint of mineral production in the near term

Near-term strategies to reduce energy-related emissions include increasing the share of low-carbon electricity, acting on energy efficiency and switching to cleaner fuels.

Emissions from electricity use can be lowered by using low-carbon electricity via corporate power purchase agreements (PPAs) or on-site renewable generation. Glencore, for example, built a 3 megawatt wind turbine at its Raglan Mine in Canada to replace diesel power generation. The project received funding from the Canadian government to couple leading-edge storage technologies with an Arctic-grade wind turbine and demonstrate that such a system can operate reliably (NRCan, 2021). Meanwhile, BHP stepped out of nearly 800 million dollars in contracts for coal-fired power in Chile and established 6 terawatt hour renewables power purchase contracts (Reuters, 2019a). Of note, PPAs need to go hand-in-hand with efforts to lower the grid's carbon intensity to be more effective. For better results, low-carbon electricity can be coupled with higher power demand resulting from increased electrification of equipment and the incorporation of batteries to safeguard flexibility in operations.

Additional emission reductions can be achieved through investment in energy efficiency, for example through digitalisation, automated process management and technological improvements (e.g. using high-efficiency burners in furnaces). Glencore's Nikkelverk refinery in

Norway, for example, implemented a portfolio of energy management technologies to save over 30 gigawatt hours annually (Eurometaux, 2019). The plant reduced its energy consumption by installing new tanks, electrical contacts and energy-efficient anodes. Moreover, waste heat from its sulfuric acid plant replaced previously electrically generated steam.

In the medium term, reducing or displacing diesel use in trucks is an important element of many companies' efforts. Options include optimising material handling practices, using other transport means (e.g. conveyors) or switching to electric trucks. Some companies are also exploring the possibility of using hydrogen. For example, Anglo American is partnering with ENGIE to develop a hydrogen-powered mine haul truck (Anglo American, 2019).

Companies are also increasingly reviewing options to tackle Scope 3 emissions, by shifting their business portfolio away from polluting fuels (such as coal), using low-carbon fuels for shipping and working with customers to co-invest in emission reduction measures. Another option to reduce emissions is to scale up secondary production. An assessment of current copper production routes in China shows that producing copper from scrap has the potential to reduce GHG emissions intensity to about a quarter of conventional routes (Dong et al., 2020).

An increasing number of mining companies are committing to reduce emissions...

Net CO₂ emission reduction pledges for top 20 mining companies

Company	Scope 1 and 2		Scope 3	
	2021-2030	Long term	2021-2030	Long term
Vale	33%	100%	-	15%
BHP	30%	100%	30-40% ⁱ	-
Rio Tinto	30%	100%	15%	-
Glencore	40%	100%	40%	100%
Freeport-McMoRan	15%	-	-	-
Codelco (Corporación Nacional del Cobre)	70%	-	-	-
Fortescue Metals Group	26%	100%	-	-
Norilsk Nickel	25% ⁱ	-	-	-
Barrick Gold	10%	-	-	-
Southern Copper	-	-	-	-
Newmont	30%	100%	15%	100%
Hancock Prospecting	-	-	-	-
KGHM Polska Miedź	-	-	-	-
Teck Resources	33%	100%	-	-
AngloGold Ashanti	-	-	-	-
First Quantum Minerals	-	-	-	-
Zijin Mining Group	-	-	-	-
Anglo American	30%	100%	-	-
Sibanye-Stillwater	27%	-	-	-
Mitsui	50%	100%	50%	100%

Notes: Reductions can account for CO₂ removal (e.g. through afforestation or direct air capture) and emission credits (generated by emission reductions in other sectors). Long-term targets include pledges to be fulfilled in 2035, 2040 or 2050. i = intensity target.

Source: IEA analysis based on company filings or websites.

... but a wider range of companies needs to come on board if overall emission levels are to follow a sustainable development path

With mounting pressure from investors, governments and other stakeholders, the industry is increasingly aware of its environmental footprint. The [Responsible Mining Index](#) reports that the vast majority of companies track their performance on Scope 1 and 2 GHG emissions, with over half disclosing comprehensive tracking data against publicly stated targets. However, fewer companies review the effectiveness of measures taken to manage emissions, and fewer still take actions to respond to such reviews.

Announced emission reduction targets have proliferated in recent years among major mining companies. Two-thirds of the top 20 mining companies have established Scope 1 and 2 emissions reduction targets for 2030. A further one-third have extended targets to include long-term and Scope 3 reductions, with Glencore, Mitsui & Co. Ltd, and Newmont Corp. setting full net-zero targets.

While encouraging, companies with emission pledges account for only a small proportion of global mining output – 25% for cobalt, and less than 20% for copper and nickel. Greater pressure from governments, investors and end-use customers is needed to expand emission reduction initiatives across sectors and regions, to include junior miners, refiners and Chinese players. Major companies, via their influence in non-operated ventures, can also influence the performance of the sector as a whole.

Mineral development can also contribute to clean energy transitions in other sectors. It can act as an anchor consumer for renewable power, support demand response and export residual energy to nearby users. In Chile, copper mines consume substantial amounts of electricity in an area with one of the world's highest levels of solar irradiation. This, coupled with the declining cost of renewables, has led to an increase in renewable power capacity, which contributed to reducing the carbon footprint of the grid (OECD, 2019a). Moreover, in the refining sector, many electricity-intensive facilities provide services to the power grid (e.g. grid stabilisation and peak attenuation) by allowing for temporary interruption of power supply or demand reduction in instances of lower supply. Automated process management helped these services become competitive in many countries, such as France and Germany, particularly for aluminium, zinc and copper production (Eurometaux, 2019).

To achieve net-zero targets, mining companies will have to address all GHG sources in their value chain, including those hard-to-abate sources. In this context, carbon offsets may complement direct emission reduction measures. However, for offsets to be effective, mining companies must verify that they result in permanent, additional, real and verified emission reductions.

Industry and market-driven disclosures are starting to improve transparency on sourcing and sustainability...

Industry sustainability initiatives have pushed companies towards voluntary environmental impact disclosures, bridging the gap between consumer and investor expectations and regulatory processes. For example, the Mining Association of Canada's Towards Sustainable Mining (TSM) initiative has developed an assessment tool, the [TSM Energy and Greenhouse Gas Emissions Management Protocol](#), which calls for companies to develop a comprehensive GHG emissions management system, track and report GHG emissions metrics and set reduction targets. The Initiative for Responsible Mining Assurance's GHG emissions requirements in their [Standard for Responsible Mining](#) similarly encourage companies to quantify and report emissions and to develop specific emission reduction strategies.

Market mechanisms

Trading platforms and metal purchasers can also play an important role in encouraging companies to adopt voluntary approaches to reduce emissions. The London Metal Exchange (LME) trading platform is aiming to provide consumers with greater transparency of the carbon footprint of traded metals, building on recent efforts to incorporate responsible sourcing standards into its brand listing requirements. The new voluntary disclosures will be introduced in

2021 starting with aluminium, in the form of an "LME passport" and a spot-trading platform so that producers can substantiate their carbon emission claims. This digital passport will then be phased in for all LME's physically settled metals requiring certificates of analysis, including cobalt and nickel from 2023 (LME, 2020). Public disclosure of sustainability metrics can incentivise producers to measure emissions in a credible manner, and ultimately lower their carbon footprint to meet consumer demands. This in turn may eventually support a price premium for low-emission metals. It can also act as an indicator to policy makers to assess industry and consumer buy-in (IGF, 2018a).

These industry initiatives actively support greater disclosure of emissions data, but it will take time for them to mature enough to provide consistent data and indicators. Moreover, further effort is needed to develop standardised accounting frameworks to ensure emissions data is comparable across companies. So far, industry sustainability standards remain voluntary, and thus their impact is limited to companies that choose to implement them. Although governments can encourage companies to adopt these standards – as Canada does for TSM – policy support will be needed to provide incentives for further uptake of transparency norms.

...while regulatory approaches to reduce mining emissions are often incomplete

Once an industry standard is broadly accepted, governments can play a key role in turning voluntary commitments into legal requirements. For example, the EU Batteries Regulation will mandate disclosure of key sustainability metrics already reported on a voluntary basis under industry standards (see Box 3.5). Voluntary climate-related financial disclosures, such as the Task Force on Climate-related Financial Disclosures, are also being progressively incorporated into law, for instance in the United Kingdom and New Zealand (Davies et al., 2020).

Inconsistent reporting frameworks

Governments also have a role to play in driving standardisation among emissions accounting frameworks. Although companies are increasingly expected to disclose GHG emissions, including any indirect emissions in the value chain (Scope 3), the lack of consistency in reporting makes it challenging to compare data. Even under the Greenhouse Gas Protocol, which is designed explicitly to create a corporate standard allowing comparable reporting, companies are free to choose which values to report, emission category boundaries and relevant categories. Empirical research on the copper supply chain demonstrated that GHG accounting protocols were often lacking and differed dramatically between companies (Lee et al, 2020). As such, policy support to standardise accounting principles is necessary to bolster emission disclosures.

A suite of policy options for mining emissions

Government policies can drive companies to adopt emission reduction strategies across their operations, including fuel switching and investing in low-carbon electricity and energy efficiency. These can be addressed through a suite of policies such as renewable portfolio standards, energy efficiency mandates, emission regulations and carbon pricing. In particular, allowing independent power producers to enter the market could facilitate less emission-intensive power generation. For instance, in 2015 Chile mandated power distribution companies to conduct tender processes to provide energy to regulated customers, thus facilitating the successful development of renewable-powered mines (CCSI, 2018).

R&D and innovation support is also key to lowering emissions in mining. For instance, in the context of the European Battery Alliance, the European Union financially supports a “Zero Carbon Lithium” project in Germany to find less water- and carbon-intensive ways to extract the mineral (Energy Storage News, 2020). The Australian Renewable Energy Agency and other government entities also provided financial support for solar-powered energy generation at the DeGrussa copper mine in Western Australia, which has the potential to meet up to 90% of the mine’s daytime demand (CCSI, 2018). Clean fuel standards can also impact mining operations given their use of liquid fossil fuels and freight services (Government of Canada, 2020).

Carbon pricing can complement other policies by providing incentives to reduce emissions

Carbon pricing holds potential to become an important component of climate governance, at both national and international levels. Carbon taxation and emissions trading schemes can be an effective tool for driving reductions in emissions in line with the “polluter pays” principle while encouraging innovation. However, so far the impact of carbon pricing mechanisms on the minerals sector has been limited to only a handful of contexts.

In many cases, the impact of carbon pricing mechanisms on minerals has been limited to the indirect effects of carbon pricing applied to electricity or fuel use. This indirect effect is small as long as carbon prices remain low. The carbon tax in Chile is a good example of these limits. The tax applies to power generation, which may ultimately be passed on to mineral producers in electricity contracts. The actual impact is minimal due to the low level of the price: USD 5 per tonne CO₂-eq (ICAP, 2021). Further, the mining sector has sometimes been exempted or received free allocation of allowances due to carbon leakage and competitiveness concerns.

However, there are encouraging efforts to apply carbon pricing directly to mining and mineral processing operations. Canada’s output-based pricing system, which applies to provinces and territories that do not have their own carbon pricing systems with comparable stringency and coverage, targets large industrial emitters. Among the sectors covered, the system puts a price on

emissions occurring from mining and refining base metals such as nickel, copper, zinc, lead and cobalt, in addition to a charge on fossil fuels (Government of Canada, 2019). By combining direct and indirect carbon pricing, such schemes can provide further incentives to lower emissions.

For carbon pricing to have a more widespread impact on the mining sector’s emissions, rigorous implementation will be needed and governments should send clear policy signals to this effect. For instance, the Canadian government has proposed increasing the federal carbon price by CAD15 per year from 2023, reaching CAD170 per tonne CO₂-eq in 2030 (Government of Canada, 2021a). Such policies can incentivise investment in emissions reduction measures in project planning. However, uncertainty over carbon pricing in different jurisdictions complicates the picture for companies.

Some companies have established an internal carbon price within corporate account systems. For instance, BHP has established a “shadow” carbon price ranging from USD 10 to USD 110/t CO₂-eq. It uses the price in scenario modelling to determine the competitiveness of fuels across sectors, to inform investment decisions and asset valuations (BHP, 2020). The use of shadow prices within company decision-making is a positive step to track and reduce emissions, but clear signals from governments on carbon pricing remain crucial.

Sustainable minerals development

A holistic approach can help integrate sustainable practices in mineral development

Mineral development affects the local and regional environment in different ways. Related interactions must be managed carefully to mitigate negative impacts and reduce associated risks. In this section, we focus on three chief challenges that are present throughout the mining value chain:

- Land use change – This is the main source of direct and immediate impacts on people, biodiversity and ecosystems. It can result in the displacement of communities and the loss of habitats that are home to endangered species.
- Water use – Mining generally requires large volumes of water for its operations. It can also be a source of water contamination, be it through acid mine drainage, wastewater discharge or the disposal of tailings.
- Waste generation – Mineral development results in massive amounts of residues, both during extraction and after utilisation, some of which are hazardous to human health.

Mineral development also entails other environmental aspects and impacts, including air pollution from particulate matter (e.g. mine dust) and gaseous emissions (e.g. sulfur and nitrogen oxides), and noise pollution due to blasting and transporting activities.

Experience suggests that it is possible to manage these impacts effectively via a combination of policy measures, robust project management and technological solutions. In particular, integrating environmental concerns at the early stages of project planning can go a long way to ensuring sustainable practices do not come at a high cost.

In this context, employing a holistic approach enables an integrated assessment of the drawbacks and benefits of different project alternatives. Often there are trade-offs between different environmental objectives. Open-pit mining, for example, has lower energy requirements than underground mining, generally leading to lower emissions, but results in more land use change. However, there are also cases where an alternative presents synergistic outcomes. The recovery of minerals from waste streams (e.g. reclaimed copper production) illustrates this, as it can reduce the amount of waste that needs to be disposed of, lessen the ecotoxicity of effluents and lead to lower GHG emissions (Hong et al., 2018).

Furthermore, taking an integrated approach to sustainability can enable better resource use and systemic innovation, often resulting in lower overall energy needs (Lèbre and Corder, 2015). For example, extracting multiple minerals from the same ore or reworking tailings to maximise recovery rates are ways to increase production, reduce pollution and often minimise other risks in parallel.

Land use: Mining can displace communities and threaten natural habitats

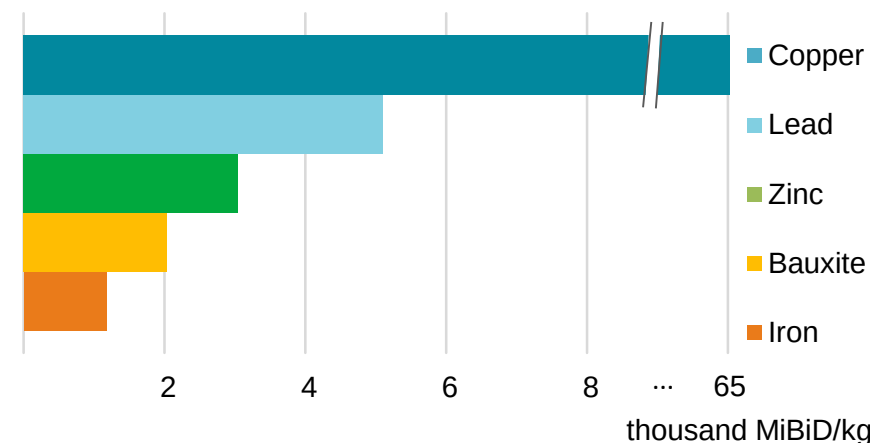
Mining brings major changes in land cover. Open-pit mines, in particular, can spread across several kilometres and usher in dramatic changes to the surrounding environment. Underground mines have a lower surface impact, but still generally require areas for processing, waste management and transport systems that have a sizeable aboveground footprint. Furthermore, mining activities can have spillover effects in nearby regions, such as increased urbanisation or the conversion of land to plantation forestry, which is used in the supply chain of related industries (Sonter et al., 2014). Global estimates for the area disturbed by mining activities lie between 0.3% and 1% of total terrestrial land surface (Tost et al., 2018).

The amount of land needed for mining varies significantly according to the technologies employed, the minerals produced and project characteristics. A recent study used satellite image analysis to assess land use change at three copper mines, showing results ranging from below 5 to about 20 hectares of built-up land needed per thousand tonnes of copper ore extracted (Murakami et al., 2020). The highest values were tied to an open-pit mine in a mountainous and forested location in Indonesia, which aggravated spatial requirements and related impacts, whereas the lowest values came from an underground mine in a Chilean desert. Other influencing

factors included mine productivity, ore grade and afforestation initiatives.

Impacts from land use change have a cumulative nature and can cause far-ranging repercussions. In sensitive areas, such as habitats of endemic species or traditional indigenous territories, engaging in new mining developments might present a lower societal value than maintaining healthy ecosystems.

Intensity of mining pressure on biodiversity for selected minerals



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Note: MiBiD is a non-dimensional index based on data regarding land cover, protected areas and mining operations.

Source: Kobayashi, Watando and Kakimoto, 2014.

Land use: The effects of mining projects on people and biodiversity

Activities, impacts and risks of mineral development related to land use change

Segment	Activities	Impacts	Risks
Production	<ul style="list-style-type: none"> The installation of a mine involves the clearing of an area for exploration, initial processing and logistics Open-pit mines expand as production progresses, while underground mines remain mostly with the same superficial area throughout their development Tailings (waste materials left over after target minerals are extracted from the ore) are often stored in large dams 	<ul style="list-style-type: none"> Noise pollution from operating machines and the transport of materials Habitat reduction and fragmentation, resulting in the loss of fauna, flora and ecosystem services Potential displacement of communities in the area of the project Landscape change and labour migration with impacts on local social settings and lifestyles 	<ul style="list-style-type: none"> Biodiversity loss, sometimes increasing endemic species' vulnerability to extinction Loss of cultural heritage sites Soil erosion can lead to changes in topography, soil quality and water pollution Failure of underground mine excavations can lead to surface subsidence
Processing	<ul style="list-style-type: none"> Refining involves large facilities and substantial material flows 	<ul style="list-style-type: none"> Landscape change Noise pollution from trucks and machines 	<ul style="list-style-type: none"> Spills of hazardous materials or the deposition of toxic dust can lead to soil contamination
Distribution and use	<ul style="list-style-type: none"> Railways and waterways are the main means of transporting minerals 	<ul style="list-style-type: none"> Habitat fragmentation Noise pollution (both in land and aquatic environments) 	<ul style="list-style-type: none"> Accidents during transport can harm people and fauna

Land use: Appraisal and management systems can ensure projects follow a sustainable profile

Mitigating the damage from land use change requires the potential land use issues to be considered before a project is approved. Integrated management of environmental and social impacts can help ensure projects conform to regulatory requirements.

Environmental and social impact assessments (ESIAs), which evaluate project alternatives with regard to their environmental impacts, can support decision making by providing an understanding of present environmental conditions and future consequences of proposed actions. Thus, ESIAs may identify areas that should remain untouched or options to reduce environmental impacts. For example, the Carajás S11D iron-ore project in Brazil is a case where the ESIA and project appraisal process led to reduced impacts on a national reserve, the use of technologies that do not require tailings dams and a transportation system without trucks (IBAMA, 2016).

ESIAs are now mandatory for most mining developments; however, their implementation still faces major challenges related to poor integration in project planning, monitoring and community engagement (IGF, 2019). The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development has released a [guidance document](#) for governments on improving ESIA-related legal frameworks. Project appraisal can also provide an avenue for public participation and enable conflict resolution at an early stage of the development process. To support citizen engagement, the

Environmental Law Alliance Worldwide published a [guidebook](#) for evaluating mining project ESIAs.

A major component of ESIAs is a set of measures addressing both the mitigation of impacts and their eventual compensation, such as the provision of alternative settlements for displaced populations. These are consolidated in environmental management plans (EMPs), which integrate regulatory requirements and company mitigation efforts, such as pollution control, environmental monitoring, compensation projects and risk management. EMPs commonly take a continuous improvement approach to ensure that problems are identified, corrected and procedures improved to prevent similar occurrences in the future. These plans should be present in all project phases. For example, before the start of an activity, they may provide for wildlife relocation. During operations, EMPs can address issues such as fugitive dust emissions control and the management of hazardous materials. Lastly, a major concern for mining undertakings is closure and relinquishment. There are hundreds of thousands of abandoned mines across the world, posing multiple hazards – from collapsing tunnels to soil and water contamination – with entities in charge of site clean-up often either foregoing remediation or restricting actions to highly affected areas (Gutierrez, 2020). Closure plans are a part of EMPs that help mitigate these risks by outlining costs, strategies and activities related to decommissioning.

Box 4.2. Mine closure: Australia's Leading Practice Sustainable Development Program

Australia is a major mineral resources holder, with over 300 mining projects in operation and the world's second-largest reserves of cobalt, copper, nickel and lithium (Australia Minerals, 2021). It is also home to biodiversity hotspots and reference environmental management initiatives. One of these is the [Leading Practice Sustainable Development Program for the Mining Industry](#), a series of handbooks developed by experts, industry, government and non-governmental representatives to serve as a reference both to mine operators and regulators.

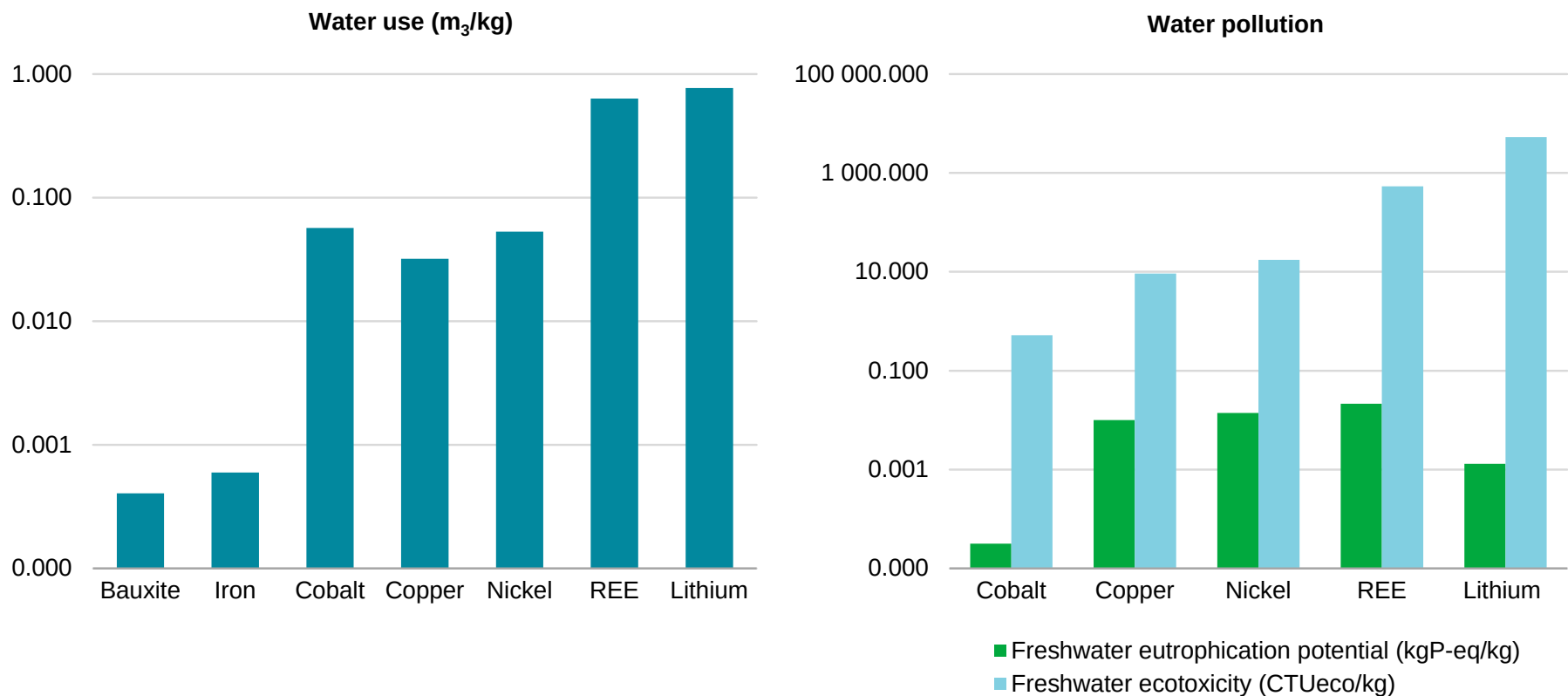
Australia has about 60 000 abandoned mines and often it falls to the authorities to address these sites, such as in 2015, when the Western Australian government took on responsibility for a recently abandoned nickel mine (Campbell et al., 2017). The mine closure handbook sets out approaches on how to prevent or minimise adverse long-term impacts from mining. It states that most Australian jurisdictions require mine closure planning as part of the approval process for mining activities. Moreover, regulators usually have significant enforcement powers over company commitments, often linked to financial securities. Post-mining land use planning is thus incorporated in project design, including measures to minimise disturbance, establish stable non-contaminated landforms, ensure progressive rehabilitation and enable subsequent use.

Closure plans should reflect local circumstances and build on local strengths, which are often a key factor for a successful transition after relinquishment. Future uses may comprise agricultural activity, industrial development, ecosystem conservation or community use. In this sense, planning for mine closure and rehabilitation requires a holistic approach and stakeholder engagement. Furthermore, it is an essential part of the various phases of a mining development's life cycle, from feasibility studies to project design throughout operations and decommissioning. This involves: continuous planning efforts; progressive allocation of financial resources, asset review and divestment evaluations; and implementation of closure, including remediation and monitoring, until agreed-upon completion criteria are met.

Even after infrastructure removal and site rehabilitation, there is still a need for ongoing management and monitoring until final relinquishment is approved and new users take ownership and responsibility for the land. Poorly closed and derelict mines provide a negative legacy for governments, communities and companies, while also leaving lasting environmental impacts. Best practice recognises that the mining sector is a temporary user of land and that sites should be returned to a state that enables the sustainable development of present and future generations.

Water management: Energy transition minerals have high water requirements and pose contamination risks

Indicators for water use and water pollution for selected minerals



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Notes: REE = rare earth element; CTUeco = comparative toxic unit for ecosystems; kgP-eq/kg = kilogramme of phosphorous-equivalent per kilogramme; m³/kg = cubic metres per kilogramme. Lithium data is for brine-based resources. REE refers to neodymium iron boron (NdFeB) magnet.
Source: IEA analysis based on Farjana, Huda and Mahmud (2019) (cobalt, copper, nickel); Jiang et al. (2020) (lithium); Marx et al. (2018) (REE); Tost et al. (2018) (bauxite and iron).

Water management: Mining is a major water user and can cause long-lasting water pollution

Mining is a water intensive activity. Copper facilities alone withdrew over 1.3 billion cubic metres of water in 2006 (Gunson et al., 2012). Water is used along the production value chain, from exploration to processing (e.g. flotation uses water to concentrate mineral ores) and transport. It is a major input of many standard operations, such as cleaning, cooling, dust control and pumping. Energy transition minerals often have higher water needs than other commodities, although this varies according to the production process. Water consumption levels for nickel and copper production, for example, are more than double in hydrometallurgy compared with the more common pyrometallurgical method (Northey et al., 2014).

However, the most long-lasting impacts from mining do not come from water consumption. Acid mine drainage, resulting from water flows coming into contact with sulfide-rich materials, can persist long after a mine has been closed. Moreover, tailings ponds pose a risk of contamination to downstream water bodies, including extensive damage resulting from potential dam failure. Meanwhile, mines that employ dewatering operations (when groundwater inflows are pumped out to maintain access to the site) can cause a decrease in the surrounding water table or contaminate communicating aquifers.

Water pollution is particularly worrisome in the processing stage, where grinding, milling and concentration methods generate toxic effluents loaded with heavy metals and chemicals.

The associated contamination potential varies significantly among different resources, processing routes and means of disposal. Lithium production involves the highest eco-toxicity risks, mostly due to its leaching process. Moreover, the shift from traditional brine-based production to rock-based lithium leads to an almost tenfold increase in eco-toxicity values (Jiang et al., 2020). Water pollution is especially problematic in China, where REE production was conducted illegally or in unregulated small-scale activities until recently. There are numerous wastewater ponds, formerly used for leaching activities, abandoned near mining sites. China is taking steps to change this picture by remediating polluted areas and enacting stricter regulations to prevent new sources of contamination.

Mineral development can also affect the marine environment. Seabed mining can lead to significant water pollution through the release of dewatering waste or side cast sediment with fine particles and heavy metals (Miller et al., 2018). Deep-sea tailings placement, which involves the dumping of tailings in the ocean, also poses high contamination risks. Indonesia is one of the few remaining countries with mining activities that still use this disposal method. Legislation from 2001 outlawed marine tailings disposal, but two copper developments that already used deep-sea disposal before this remain in operation and a new nickel project is applying for a permit despite the existing regulatory framework (BloombergNEF, 2020).

Water management: The effects of mining projects on water resources

Activities, impacts and risks of mineral development related to water

Segment	Activities	Impacts	Risks
Production	<ul style="list-style-type: none"> Water is required for exploration (e.g. drilling), extraction, initial processing (e.g. ore crushing) and related operations Mining frequently encounters water resources, such as aquifers, creating the need for mine dewatering Mining often encompasses a large area subject to rainfall and related drainage Tailings with high water content are typically stored in artificial ponds 	<ul style="list-style-type: none"> Reduced availability for other uses due to increased overall demand or lower quality of sources Pollution of water bodies by discharged effluents, including leachate, process water and other effluents Acid mine drainage and sediment build-up in nearby waterbodies 	<ul style="list-style-type: none"> Increased water stress in the area and depletion of groundwater resources Contamination of aquifers or downstream water by acids, sulfates and metals Reduced surface water storage capacity
Processing	<ul style="list-style-type: none"> Water is used to separate and concentrate minerals as well as for operational needs such as dust control 	<ul style="list-style-type: none"> Processing operations reduce water availability and generate effluents rich in chemicals and metals 	<ul style="list-style-type: none"> Increased water stress in the area Contamination of freshwater bodies
Distribution and use	<ul style="list-style-type: none"> Water is used in pumping and to transport minerals through pipelines 	<ul style="list-style-type: none"> Pollution of water bodies 	<ul style="list-style-type: none"> Spills can occur during the transport of minerals by ship, rail or pipeline

Water management: An integrated approach can help to address water needs sustainably

Water availability and demand depend on geographical conditions, the number of users and their different needs. That is the reason why water management increasingly requires an integrated catchment approach, addressing water systems at a basin level to better co-ordinate water uses and flows. This generally involves engaging stakeholders to address two major topics in a participatory manner.

Fulfilling water needs

There are several policy options to regulate surface and groundwater use, including the control of withdrawal through permits, economic instruments – such as pricing and setting a market for water rights – and defining standards for efficiency of use. These regulations often rely on monitoring systems that cover related flows and reservoir levels, to both verify compliance and ensure the sustainability of water sources.

Mining can improve its water footprint by reducing its water needs or by using alternative sources. Efficiency can be gained by reducing losses (e.g. minimising wet areas, filtrating tailings, monitoring pipelines), using dry processing technologies and by replacing evaporative cooling with less water-intensive methods. Furthermore, mining operations can often use water that has lower quality, such as water from mine dewatering and surface runoff, as well as recycled process water, treated wastewater or desalinated seawater. The

Mining Association of Canada's TSM initiative has a [Water Stewardship Protocol and Framework](#) that sets benchmarks for company water management programmes.

Ensuring water quality

Effluents from the mining industry contain toxic substances, such as residual metals and chemicals used for extraction and processing. Comprehensive standards for the discharge of wastewater are a way of guaranteeing that polluting substances remain within acceptable limits, with acidity and metal toxicity being two key parameters to address (Opitz and Timms, 2016). These can be complemented by quality norms for water bodies, which align uses with required conditions and support the monitoring of affected ecosystems.

To reduce the load of pollutants discharged and meet established standards, mining facilities can reduce the volume of water that is contaminated (e.g. by managing runoff or covering waste rock and ore piles) and prevent it reaching waterbodies (e.g. implementing a drainage system or designing the project to avoid contact with groundwater). Furthermore, multiple treatment technologies allow the industry to remove the different contaminants present in its effluents. These include both simple measures (e.g. pH correction and the use of coagulants to precipitate metals) and advanced technologies, such as membrane filtration or photochemical oxidation.

Box 4.3. Managing groundwater: Lessons from Chile, where copper mines stand next to earth's driest non-polar desert

Chile is the world's largest copper producer, responsible for about 28% of global supply in 2019. It is also the most water-stressed country in the Americas, ranking 18th globally in terms of baseline water stress (WRI, 2021). Moreover, most of its copper mines are located in the Andean mountain range in the dry northern part of the country, with approximately 54% of copper production occurring in the Antofagasta province (Lutter and Giljum, 2019), which lies next to the Atacama desert.

In this region, groundwater faces competing interests from agricultural, domestic and industrial activities, including mining. The development of copper, in particular, not only demands water for dust control and the extraction, separation and transport of ore, but can also potentially contaminate the scarce water resources due to acid mine drainage, dewatering and the disposal of tailings.

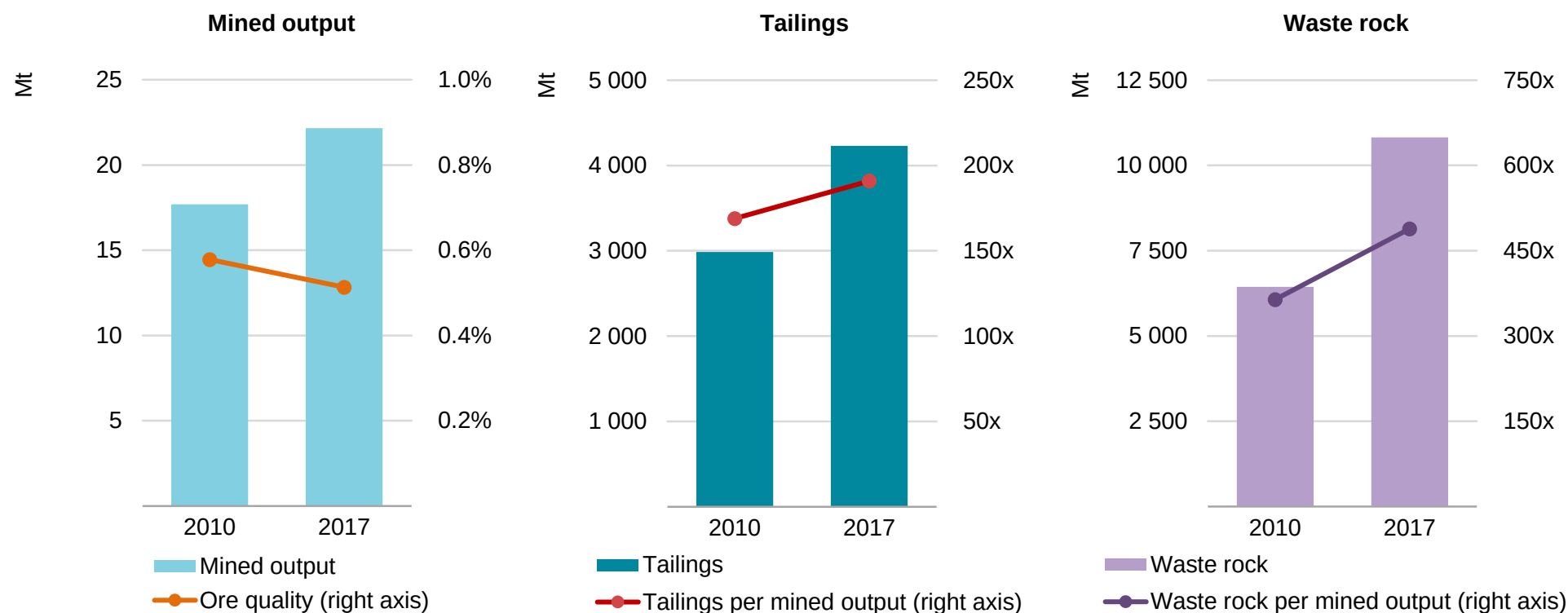
However, until the mid-2000s Chile did not have a specific legal framework to regulate groundwater use. The Water Code of 1981, which implemented a water permit trading scheme, was designed to address surface water use. In 2005 this legislation was amended to include procedures related to groundwater management (Donoso, Lictevout and Rinaudo, 2020).

These included defining and allocating groundwater property rights, regulating its use, establishing user associations and enabling the reallocation of rights through market mechanisms. Restrictions on use apply when there is a decline in reservoir levels, exploitation generates a risk of contamination, and to safeguard water flows for sensitive ecosystems. The industry has been looking to keep pace with these developments. Anglo American, for example, took measures to allow its Los Bronces mine to recycle over 78% of the water it uses, upgrading a water transport system and using an automated circuit for recirculation (Copper Alliance, 2021).

Chile has put in place new legal instruments to address water stress. However, it could still benefit from a more integrated approach to water management, as it is not able to manage resources at river basin level or involve multiple stakeholders in co-ordination efforts (Donoso, 2018). Moreover, it faces a number of implementation challenges, such as inadequate monitoring and enforcement, often leading to the over-allocation of use rights (Donoso, Lictevout and Rinaudo, 2020). This is aggravated by the fact that many reservoirs were already overexploited before the relevant legislation came into place, highlighting the importance of regulating groundwater at the early stages of its use.

Waste: Growing production volumes and declining ore quality are leading to a substantial increase in waste volumes from mining operations

Waste generation from copper and nickel mining



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Source: IEA analysis based on data updated and expanded from Mudd and Jowitt (2016).

Waste: Mineral development generates vast volumes of residues that have, on more than one occasion, led to large-scale environmental disasters

Mining is generating increasing volumes of waste. This includes overburden (materials covering mineral resources), waste rock (uneconomic materials removed in ore extraction), and tailings (fine-grained materials left after separating the valuable fraction of the ore). The total amount of residues generated during mining can vary depending on the extracted commodity, methods employed and resource conditions (e.g. ore grade), but is usually quite significant. In 2018 the mining and quarrying sector accounted for over a quarter of the total waste generated in Europe (Eurostat, 2021).

Typically, the volume of waste rocks is governed by the stripping ratio, which refers to the amount of material removed to extract one unit of ore. This ratio spans from 2:1 to 8:1 in surface extraction and is much lower in underground mining (EC JRC, 2018). Waste rocks are often stored close to the mine, in piles or heaps. Meanwhile, the amount of tailings is related to the ore grade (i.e. the share of valuable minerals in the ore). For copper and nickel, of which ore grades are low, the waste rock and tailings generated to produce one tonne of product amounted to almost 700 tonnes in 2017, 30% more than in 2010 due to deteriorating ore quality and the predominance of surface mining. Tailings are usually transported through pipes to a tailings storage facility. The number of these facilities are estimated at around 32 000 globally – among active, inactive and abandoned

facilities – containing around 223 billion tonnes of tailings (World Mine Tailings Failures, 2020). The most common type is an embankment dam that is designed to retain tailings and the associated water.

These facilities pose contamination risks for nearby soil and water bodies and the hazard of dam failure. The locally called Rare Earth Lake, for example, covers over 10 square kilometres of Bayan Obo, a mining town in China, and the soil surrounding it is highly enriched with heavy metals (Pan and Li, 2016). In 2019 the collapse of the tailings storage facility at Vale's mine in Brumadinho, Brazil, led to mining waste surging across the surrounding areas and the death of over 270 people (see Box 4.6). In 2015 Brazil had already seen the collapse of the Fundão dam, which released 43 million cubic metres of iron ore tailings, polluting 668 km of watercourses from the Doce River to the Atlantic Ocean (Carmo et al., 2017).

Mining and mineral processing also generates hazardous waste, an output related not only to the metals and chemicals handled in these activities, but also to the presence of naturally occurring radioactive material (NORM) in some ores. NORM can be further concentrated during mineral processing and end up in waste, with the highest activity concentrations having been found in scales from wet chemical processes and in precipitator dust from high-temperature processes (IAEA, 2005).

Waste: The impact of mining operations on residues

Activities, impacts and risks of mineral development related to waste

Segment	Activities	Impacts	Risks
Production	<ul style="list-style-type: none"> Excavation removes overburden, while initial processing generates waste rock and tailings Seabed mining might discharge plumes of contaminated waste sediments and slurry in the seafloor 	<ul style="list-style-type: none"> Formation of waste piles, often with the potential to result in acid drainage Generation of hazardous waste, including heavy metals and, in some cases, radioactive material (NORM) 	<ul style="list-style-type: none"> Soil contamination due to the leaching of waste piles Pollution of downstream water bodies, including adjacent aquifers
Processing	<ul style="list-style-type: none"> The beneficiation of minerals frequently requires the use of chemicals and the comminution of ores (e.g. grinding) Processing equipment can concentrate NORM, resulting in technically enhanced substances (TENORM) 	<ul style="list-style-type: none"> These processes generate waste streams with fine metal particles and, in many cases, high toxicity Waste with higher radioactivity (TENORM) generally must be disposed of through permanent storage in specialised facilities 	<ul style="list-style-type: none"> Hazardous waste poses health threats to workers as well as environmental contamination potential
Distribution and use	<ul style="list-style-type: none"> Products that reach their end of life are discarded by users 	<ul style="list-style-type: none"> Generation of hazardous waste, often with mixed substances, such as a combination of plastics and metals 	<ul style="list-style-type: none"> Improperly managed waste can end up being handled in unsafe environments or contaminating ecosystems

Note: TENORM = technologically enhanced naturally occurring radioactive material.

Waste: A robust waste management framework can ensure that companies take steps to reduce waste generation and handle waste safely

Sustainable waste management can ensure that instead of causing environmental harm, mining residues are used as resources and support economic development. This usually follows a “reduce, reuse and recycle” hierarchy, with disposal as a last resort.

Policies and plans to manage waste

Effective waste management policies ensure that companies take action to reduce the risks to the environment and public health from waste streams, take steps to reduce waste generation and undertake proper disposal or recovery. The European Union’s [Directive on Management of Waste from Extractive Industries, 2006/21/EC](#), for example, requires the use of best available techniques, including techniques to reduce the volume of extractive waste and use of residues for backfilling or construction purposes. In addition, the EU directive requires operators to develop waste management plans that cover all aspects of waste management, including waste reduction, storage, transport, monitoring and reporting, for each phase of production.

Waste management plans typically involve establishing procedures for each type of residue. The International Finance Corporation indicates measures for management of key mining waste categories in their [Environmental, Health and Safety Guidelines for Mining](#).

Dewatering tailings to reduce waste volumes and risks

Tailings dewatering techniques offer several benefits, including less land use, lower risk of dam failure and reduced scope for acid drainage. Thickened or dried tailings can be disposed of as a paste or through dry-stacking, both of which create more stable disposal structures and allow water recovery. Many methods exist to dewater tailings, including pressure filtering and thickening agents, but until recently, these methods had been used primarily at high-grade, low-throughput operations due to technical limitations and high capital costs. However, a recent pilot project in the Escondida copper mine in Chile demonstrated their feasibility at higher-throughput projects, indicating that the economics of these technologies are improving. Furthermore, increasing water scarcity and safety requirements created in the wake of the Brumadinho disaster may provide the push needed to scale up tailings dewatering (Leonida, 2020).

Thickened tailings can also facilitate tailings reprocessing and support a more recovery-focused management strategy. This enables waste reduction while also increasing mineral supply. Most types of waste generated by mining can be used by other sectors, for example, in cement production. Moreover, metals contained in products that reach their end of life can generally be recycled, even if this potential is still widely underexplored (see Chapter 3).

Box 4.4. Managing tailings: Challenges for a Global Industry Standard

An analysis of tailings incidents showed that about 80% of the root causes of dam failures are related to controllable factors (e.g. slope stability), while only the remaining 20% result from uncontrollable failures, such as earthquakes (Accenture, 2019). The most common cause identified was overtopping (i.e. when water flows over the dam) as a result of overfilling. This suggests that improving tailings management can mitigate associated risks. Best practice benchmarks are a step towards better management, even if companies' actions often face shortcomings. In the Brumadinho case, the German TÜV SÜD had certified the dam as safe months prior to the collapse, and Vale's automated monitoring equipment had displayed worrying signs days before the event (BBC, 2019).

The [Global Industry Standard on Tailings Management](#) aims to provide global best practices for tailings storage facilities and enable zero harm to people and the environment. It is the result of a joint effort of the International Council on Mining and Metals, the United Nations Environment Programme, and the Principles for Responsible Investment. Underpinned by an integrated approach to tailings management, the standard's goal is to prevent catastrophic failure and enhance the safety of mine tailings facilities worldwide. It is directed at operators and will be supported by implementation protocols that provide detailed guidance for certification.

The standard comprises six key topics and related principles:

1. Respect the rights of project-affected people and meaningfully engage them at all phases of the tailings facility life cycle.
2. Develop and maintain an interdisciplinary knowledge base with associated technical, environmental and social information.
3. Design plans and criteria for the tailings facility to minimise risk for all project phases – including closure and post-closure – and implement a related monitoring system.
4. Establish systems and accountabilities to support the safety and integrity of the tailings facility.
5. Prepare for emergency response to accidents and long-term recovery in the event of catastrophic failure.
6. Publicly disclose and provide access to information about the tailings facility to support public accountability.

As is often the case, managing impacts can help mitigate related risks and vice versa. The use of tailings for backfilling, for example, can lower water consumption and minimise land use impacts, as well as reduce subsidence or dam failure risks.

Air quality: Tailored solutions for tackling air pollution

Sources of air pollution are concentrated in mine exploration and development, but also present further down the value chain during smelting, refining and distribution. The main sources of air pollution include (ELAW, 2010):

- Particulate matter mobilised due to excavations, blasting, ore crushing, transport of materials and wind erosion. It is also present in fugitive dust from tailings facilities, stockpiles, waste dumps and haul roads – as well as in exhaust emissions from mobile sources (e.g. trucks).
- Gaseous emissions from fuel combustion in stationary sources (e.g. drying and smelting operations) and mobile sources, explosions and mineral processing.

Particle emissions contribute to the majority of air quality problems at mines, whereas gaseous emissions can affect a broader area and be more problematic in smelting and refining. Gaseous emissions include sulfur, nitrogen and carbon oxides; photochemical oxidants; volatile organic compounds and hydrocarbons. These pollutants have detrimental health effects and cause environmental impacts, such as those associated with acid rain. Of note, some pollutants present in mineral deposits are released into the air during mining activities, such as heavy metals and radioactive emissions in REE extraction, posing occupational hazards.

Typically, each source of emissions requires a different control technology. Dust control can be addressed during mine planning with the aid of air dispersion modelling and the development of wind barriers. During operations, dust management may involve the use of containment measures, including soil stabilisation and vegetation growth, as well as moisture control (e.g. by spraying water onto stockpiles and roads).

Stationary sources can reduce emissions by using filters, wet scrubbers, electrostatic precipitators and other treatment technologies. Meanwhile, mobile sources can benefit from increased electrification and the use of clean fuels (e.g. low-carbon hydrogen), which enable both lower gaseous emissions and a reduced overall carbon footprint.

Air pollution can be tackled by many of the same policy instruments presented earlier in this section. For example, ESIA's and EMPs can affect project design and ensure the implementation of measures to control particulates and stationary sources. Additionally, jurisdictions often set requirements for pollutant emissions, define overall air quality standards and monitor pollution levels. In this context, the Initiative for Responsible Mining Assurance outlines requirements related to the management of air contaminants in its [Standard for Responsible Mining](#) and references the [European Union's Air Quality Standards](#).

Responsible minerals development

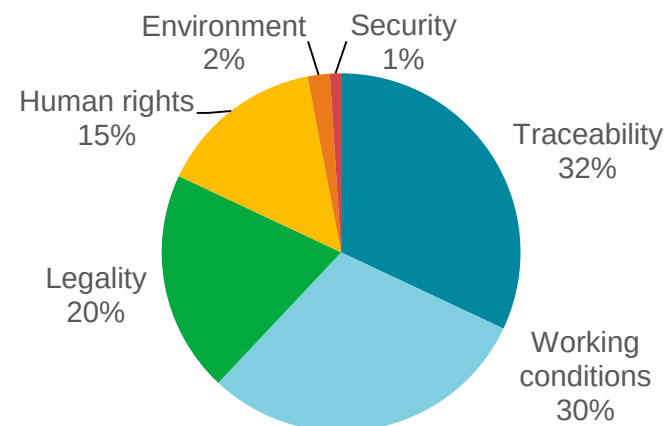
Mineral wealth has great potential to bring social and economic benefits to the local population, but many challenges remain to ensure responsible development of energy transition minerals

In most countries, mineral deposits are public resources and the government is charged with managing them in a manner that brings a public benefit. As demand grows for energy transition minerals, so does the potential for these public resources to contribute to economic growth and deliver just outcomes for national governments, companies and communities. Unfortunately, there are myriad examples where development of resources has not led to sustainable economic growth or has caused corresponding social harm.

There are many causes for this so-called “resource curse”. In many cases, public officials may act to subvert entrusted power over public resources into private gain – i.e. corruption. These problems may be particularly problematic in countries where mineral extraction contributes a large share of fiscal revenues. In addition to corruption, mining operations may have negative impacts on people and communities due to environmental damage, inadequate safety and health protections and human rights violations. Downstream consumers also contribute to these problems.

Some forms of harm are more attention grabbing than others, particularly child labour concerns. However, other impacts may ultimately be more widespread than child labour. Governments and companies increasingly cannot afford to ignore any of these impacts.

Incidents at mine sites in the Democratic Republic of the Congo categorised by type of risk



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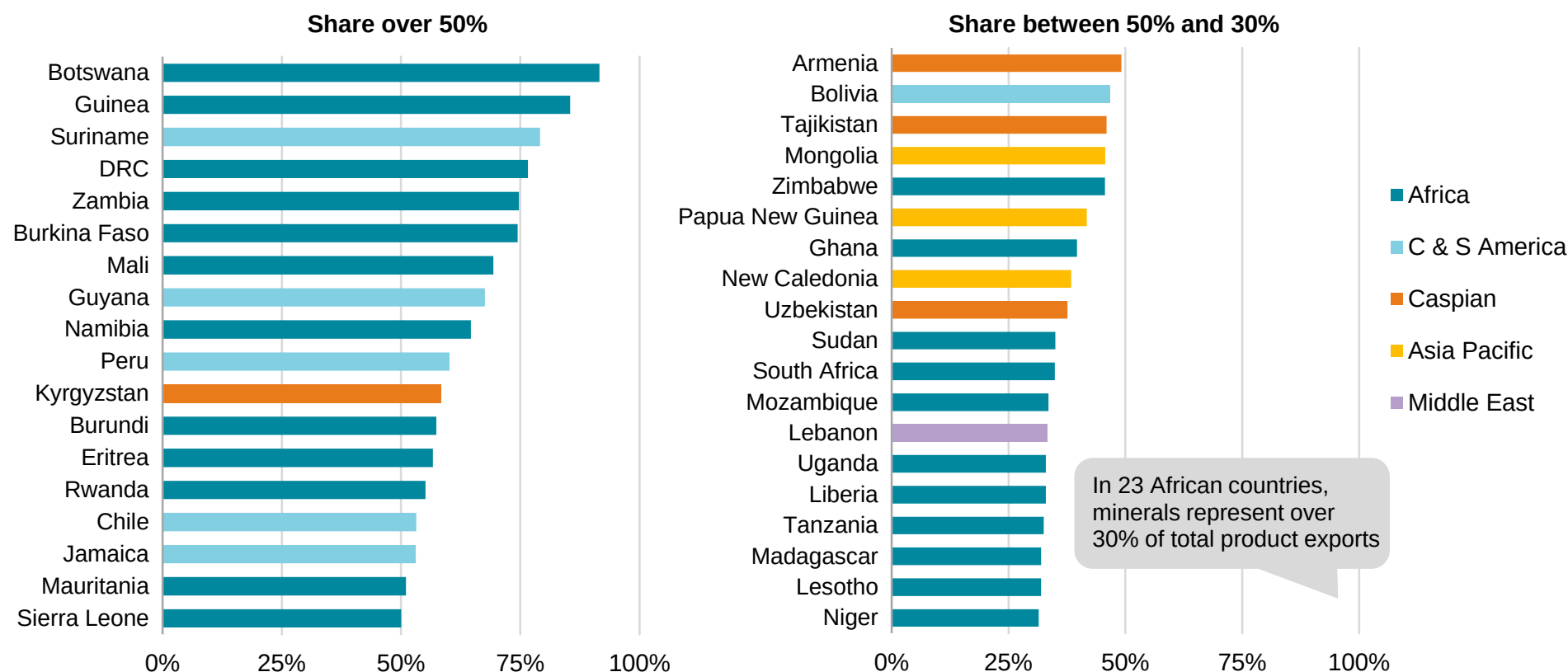
Notes: The data reflects the proportion of registered incidents fitting the risk category at artisanal and small-scale mine sites.

Source: RCS Global Group (2019).

This section begins with a discussion of the potential for mineral development to contribute to economic growth and create sustainable jobs. Then, it turns to the primary forms of social harm associated with energy transition minerals, including public corruption, risks to public safety and health, child labour and gender discrimination, with a focus on policy and regulatory strategies to mitigate these risks.

Many mineral-producing countries rely heavily on revenue from mineral extraction, underscoring the need for transparent management of mineral wealth

Share of minerals and metals in total product exports for mineral producing countries, 2019



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Notes: The chart shows countries whose share (based on monetary value) is above 30%. Standard international trade classification codes 27, 28, 68, 667 and 971 were included in the minerals and metals category. C & S America = Central and South America.

Source: IEA analysis based on UNCTAD (2021).

The economic benefits of mining must be managed with carefully designed legal frameworks

Although mineral production contributes to economic development in many ways, the most direct contribution is through tax and royalty revenue. In many countries this revenue source can be significant. In Chile, for example, revenue from copper production averaged around 10% of the fiscal revenue between 2010 and 2019 (Cochilco, 2020). However, without careful management, translating mining revenue into economic prosperity can be a daunting task. Volatile commodity prices often lead to procyclical public spending, which undermines the effectiveness of government expenditure in promoting economic growth. In addition, a high reliance on export revenue from minerals could lead to underinvestment in other sectors, making the economy more vulnerable to changes in global commodity prices. This underscores how fiscal revenues from mining must be used wisely to support diversification of the national economy.

The relationship between companies and communities

While mining brings in large amounts of revenue, the contribution to labour demand may be relatively small and may vary throughout the project life cycle. Governments have used various strategies to define expectations for the relationship between companies and communities and to foster “links” to other aspects of the domestic economy, such as the development of a local supplier industry to support mine operators (GIZ, 2016) (see Box 4.5).

Clear expectations for each phase of the project will help to ensure a sustainable relationship between the project developer and the local community and to enable the community to prepare for expected shifts in economic activity. Further, if the economic contribution is stable throughout these phases, it is likely to contribute to the project developing a social license to operate.

Mine operators often contribute to local communities by developing local infrastructure, providing training opportunities or making direct financial payments to community institutions. Given these contributions, companies and governments often negotiate “community development agreements” either voluntarily or pursuant to legislative requirements (Otto, 2018). In Canada, for example, there is a well-developed practice of developing impact and benefit agreements between companies and indigenous communities (NRCan, 2020). Provided that community development agreements are implemented in an inclusive and transparent fashion, they can create a structured framework for stakeholder engagement and define expectations for community investment.

Separately, governments may require companies to assess socio-economic impacts of mining projects and develop appropriate mitigation plans prior to obtaining approval. This can take place alongside assessment of environmental impacts where already required.

Box 4.5. Fostering local “linkages” in Chile

Resource-rich countries often adopt policies designed to facilitate inter-sectoral “linkages” that create jobs, transfer technology, encourage entrepreneurship and increase local equity (Ramdoo, 2016). In many cases, the role of local suppliers is difficult to assess due to inconsistent or limited data. Initiatives like the [Local Procurement Reporting Mechanism](#) aim to provide better data for governments and companies to manage the economic impacts and benefits of local procurement.

Rule-based numerical local content requirements, although common, can be difficult to implement if not clearly defined – in Zambia, for example, an earlier law had no definition for “local” (IGF, 2018b) – and may give rise to trade disputes (Korinek and Ramdoo, 2017). As an alternative, countries may pursue horizontal policies targeted at fostering industrial development, innovation and skills training (OECD, 2019b). Chile, for example, directs revenues from mining to support innovative projects through a government-funded partnership, Fundación Chile, which operates like a venture capital firm. This funding is not limited to the mining sector and has helped to develop the salmon and wine industries. Chile has also established royalty-supported funds to support science and technology R&D and to provide local entrepreneurs with seed capital and technical support (IGF, 2018c).

Chile also supports local suppliers directly through programmes such as the World Class Suppliers Programme, which identifies and funds innovative local suppliers to address specific operational challenges. Suppliers are supported throughout the implementation phase to allow testing of ideas within real-time operations, and eventually to scale up to international markets (Navarro, 2017).

Despite some successes, Chile has not yet developed a competitive cluster of mining services suppliers. Critics have noted that the scale of supplier support programmes is too small to have the desired impact, and that a comprehensive industrial policy is needed to support the transition of the sector towards higher-value products and services (Lebdioui et al., 2020).

Although intended to foster the development of a local industry that can support economic livelihoods and drive economic development, it is clear from these examples that policies designed to increase local linkages can stumble without robust policy co-ordination. As there are many drivers of local industrial development, including access to capital, innovation funding and skilled labour, policy makers must develop a comprehensive approach that addresses the barriers to local industry without creating unintentional market distortions.

Corruption and bribery pose major liability risks for companies, but can be managed with supply chain due diligence policies

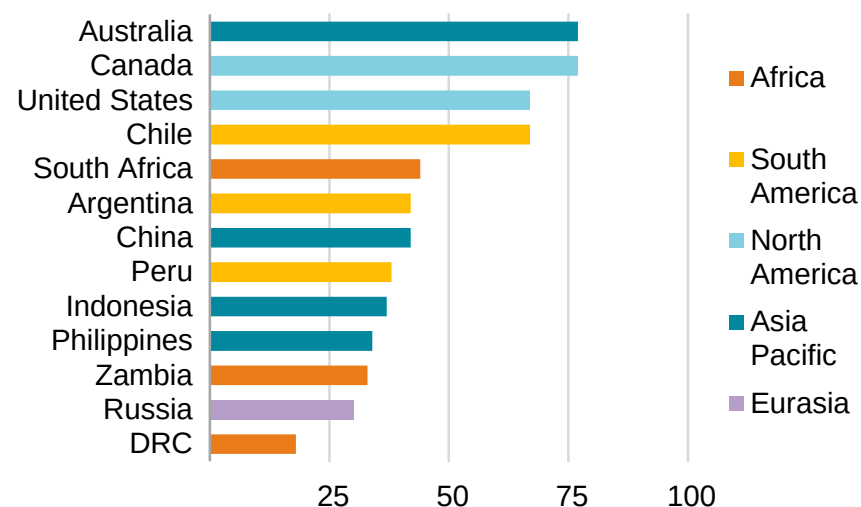
Mining operations are exposed to higher risks in locations with political instability, weak institutions and weak rule of law. The risk that mineral revenues may be used to finance armed conflict has received particular attention recently, with regulations coming into force requiring mandatory supply chain due diligence (see Box 4.8).

Although conflict-related risks are currently low for energy transition minerals, corruption and bribery risks remain high. A survey of foreign bribery enforcement actions by the Organisation for Economic Co-operation and Development (OECD) found that almost 20% of cases occurred in the extractive sector, a category that includes oil and gas production as well as mining (OECD, 2014). Further, energy transition minerals are often produced in countries that score below average in measures of perceived corruption risk.

Companies cannot afford to ignore the risk that their employees and business partners may engage in bribery. In many countries, corporations can be prosecuted for failing to prevent bribery within their overseas operations. The potential liability can be enormous, with fines reaching hundreds of millions of dollars and potential imprisonment for executives. Even short of prosecution, responding to an investigation can be extremely costly. The average investigation under the US Foreign Corrupt Practices Act lasts 38 months and costs USD 1.8 million per month (Stanford Law School, 2020).

Most major mining companies prohibit bribery among their employees, but in order to be effective, such policies must be backed up with additional measures, including risk assessments, training for employees and investigation mechanisms (RMF, 2020a). Critically, given the risks involved, companies should implement processes to identify, prevent and mitigate risks across their full supply chains, including risk-based due diligence (OECD, 2021a).

Corruption Perceptions Index for selected countries, 2020



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Note. The index ranks perceived levels of public corruption where 100 is “very clean” and zero is “highly corrupt”.

Source: Transparency International (2021).

Governments in both producing and consuming countries can do more to mitigate corruption by increasing transparency and supporting development of institutions and the rule of law

Corruption leads to numerous pernicious effects, including decreased fiscal revenue, reduced economic growth and erosion of the rule of law (OECD, 2021a). Policy makers in both producing and consuming countries are increasingly recognising these impacts as negative social externalities that must be addressed through expanded support for legal institutions, transparency and the rule of law.

Transparency is often presented as a critical tool for addressing corruption. If governments publicly disclose contracts and payment and expenditure data, the argument goes, the public will be able to hold governments accountable for their actions, which can reduce corruption and ensure that mineral wealth actually translates into public benefit.

To support development of transparency practices, a coalition of supporting governments, companies and civil society organisations established the Extractive Industries Transparency Initiative (EITI) to help countries improve governance in the sector. In order to receive support, countries must apply to become an “implementing country”, and in turn must agree to international oversight, including regular assessment of progress and adherence to specific reporting requirements. EITI has developed a [global standard](#) setting out transparency principles for governments with respect to licensing and

contracting, managing extraction operations, collection of revenue and government expenditure.

EITI reports that most implementing countries are making at least “meaningful progress” against key metrics (EITI, 2020a). For example, following EITI recommendations, Madagascar changed its practices regarding publication of data about mining revenues owed to local governments (EY, 2019). This has led to constructive dialogue between the government and local officials, and EITI has rated Madagascar’s progress on the issue as “meaningful” (EITI, 2020b).

EITI has been particularly successful in calling attention to vulnerabilities that increase the risk of corruption and in increasing the availability of data (Sahla et al., 2021). However, scholars have noted that simply adopting transparency processes may not necessarily reduce corruption. In order to have a meaningful impact on corruption, this type of information must actually reach the public and the public must be able to sanction corrupt conduct (Lindstedt and Naurin, 2010). Thus, further effort is needed to support the distribution of information in a format and language the public can understand, and to further develop local institutions to reduce corruption risks and ensure that corrupt officials are held to account.

Minerals workers and the public face various health and safety risks, including accidents and exposure to toxic chemicals

Although it is difficult to compare countries, existing evidence indicates that mineworkers are subject to significant health and safety risks. In the United States, for example, the extractive sector has among the highest fatality rates – 14.6 per 100 000 workers, compared to 9.7 for the construction sector (US BLS, 2020).

Types of risk to the health and safety of mine workers

Category	Examples
Safety	Accidents involving machinery, vehicles or rockfalls in underground mines
Chemical	Exposure to acids, carbon monoxide or particulate matter such as silica dust
Biological	Insect bites or contact with animals
Physical	Loud noise, radiation or heat
Ergonomic	Frequent weight lifting or exposure to vibration
Psychological	Sexual harassment or workplace violence

Practices vary among companies

According to the Responsible Mining Foundation, most companies show a commitment to ensuring safe and healthy working conditions (RMF, 2020a). However, only two-thirds of these back this commitment with resources, including staff or financial capital. Furthermore, only a few engage with workers’ representatives on the identification of occupational health and safety risks or have systems in place to ensure their operations provide gender-appropriate safety equipment. Even fewer have systems in place to protect women workers from sexual harassment and violence.

Adopting clear risk management policies can help companies to reduce potential harm, both to workers and to the public at large. Risk is a function of the frequency of an event and the magnitude of its potential consequences, and policies can act on both inputs to this equation. Prevention policies include work permit systems, which assess and set requirements to ensure the safety of work procedures, and the installation of monitoring equipment (e.g. flammable gas detectors). In parallel, policies can help to mitigate the consequences should an incident occur by requiring personal protective equipment (e.g. helmets and gloves) and developing and exercising emergency response plans.

Box 4.6. Tailings dam collapses at Brumadinho (Brazil)

On 25 January 2019 a dam failure at an iron ore mine operated by Vale S.A. near the city of Brumadinho, Brazil, released an enormous wave of mud that flowed for nearly 10 km, killing over 270 people (Watson, 2020). This disaster has led to major pressure on mine operators across all minerals from regulators and investors alike, especially as it came on the heels of high-profile dam failures in the same state in Brazil in 2015, which killed 19 and caused vast environmental damage, and at the Mount Polley copper mine in Canada in 2014 (Cornwall, 2020).

Much of the commentary following the Brumadinho failure has centred on the method of construction – known as upstream construction. Some evidence suggests that liquefaction (when the solids in the tailings pond act as a fluid, allowing material to flow downstream as the dam collapses) is more likely with upstream construction (Kossof et al., 2014). However, commenters have also noted that poor management and operational practices are more likely to blame (Santamarina et al., 2019).

Within days of the Brumadinho disaster, the government announced a ban on new “upstream” dams and ordered existing dams to be decommissioned by 2021 (Reuters, 2019b). This prohibition was subsequently enshrined into legislation. It is not yet clear whether these laws will lead to safety improvements given the history of

weak enforcement and relaxation of environmental laws (Fernandes et al., 2016). Despite having been established in 2017 with the aim of increasing regulatory autonomy and budgets, the National Mining Agency has had continued budgetary difficulties and limited resources for inspections, with just 34 inspectors responsible for nearly 800 dams (Jucá, 2019).

There are signs that these high-profile disasters have been a wake-up call for the industry. Faced with potentially enormous liability, Vale has created a new safety executive board, updated emergency plans and begun de-characterising nine dams built using the upstream method (Vale, 2020). A number of other companies have adjusted their safety practices as well, including Glencore, which has committed to upgrade 17 dams that could pose stability concerns under certain conditions (Glencore, 2019). As discussed above, the industry pushed for the development of a new [Global Industry Standard on Tailings Management](#) in August 2020, designed to enhance safety at tailings facilities. Though these actions are promising, the response has not been uniform. Since 2019 the Church of England Pensions Board, a major institutional investor, has requested information about tailings dams from 726 companies. Of these companies, only about 50% responded (Church of England, 2020).

Health and safety protections are not uniform between large and small-scale mines

Operators of large-scale mines, smelters and refineries are typically subject to occupational and public health and safety regulations, and evidence indicates that effective regulation can lead to a reduction in risks to workers from accidents and other adverse working conditions (Holland, 2019). The International Labour Organization has developed many [international labour standards and voluntary codes of practice](#) that can reduce the risks to workers in these operations.

To a certain extent, companies can be expected to address safety risks through voluntary action to avoid accidents that may incur costs from lost productivity, civil liability and damage to public relations. As companies pay increasing attention to maintaining a social licence to operate, they may take greater effort to adhere to such voluntary safety standards. Many international standards on safety already exist, such as the Mining Association of Canada's [Towards Sustainable Mining](#) safety and health protocol and framework.

However, industry may not be capable of self-regulating for all types of safety risk – particularly where large-scale risks are involved or where there is a lack of investor pressure. In these contexts, effective enforcement or regulatory standards will be critical. For example, weak enforcement may have played a role in the Mariana and Brumadinho dam collapses (see Box 4.6).

Artisanal and small-scale mining risks remain high

Conditions are usually worse where regulatory protections are unenforced or non-existent. The problem is particularly acute for ASM, where workers are typically paid only for what they produce and lack access to health care or compensation in the event of an accident (OECD, 2019b). A 2019 survey of cobalt ASM workers in the Democratic Republic of the Congo (DRC) found that the working conditions of most miners were “unacceptable”. Conditions in ventilation shafts and underground mines tended to be hazardous and all workers used protective equipment at only 2 of 58 mine sites. The survey also found that the preceding year had seen more than 60 fatal accidents and over 100 accidents involving injury (BGR, 2019).

Efforts to “formalise” ASM activities may improve health and safety conditions to the extent that formalisation allows the application of safety practices. A study of one such site in the DRC showed that the co-operative responsible for the site removed overburden to allow workers to access deposits safely, provided personal protective equipment for workers, and carried out weekly briefings on safety and other aspects (WEF, 2020). However, the long-term viability of this model remains in question as the site closed down in 2020 (Reuters, 2020a).

Artisanal and small-scale mining of cobalt gives rise to child labour concerns

The International Labour Organization has estimated that over a million children work in mines and quarries (ILO, 2019). Child labour primarily occurs in ASM activities and is associated most closely with the mining of gold and cobalt. The problem is particularly acute in the DRC, where 10-20% of supply comes from ASM (Roskill, 2021). Although there is no reliable data on the prevalence of child labour, surveys have found children present in about 30% of the visited ASM sites in the DRC (BGR, 2019).⁴ Studies have shown that children working outside the home in the DRC is directly linked to poverty, as children take on work to earn additional income (Faber et al., 2017).

The DRC has signed international conventions prohibiting child labour, including ILO Conventions No. 138 on the Minimum Age of Employment and No. 182 on the Worst Forms of Child Labour, and its labour and mining codes generally meet international standards in prohibiting child labour, forced labour and child trafficking (US DOL, 2019). However, child labour persists where ASM activities take place outside the legal structure.

Following the publication of a major report by Amnesty International calling attention to this issue (Amnesty International, 2016), some companies initially committed to sourcing ASM-free cobalt in order to

mitigate child labour practices. However, in the years since, companies have evolved their thinking in recognition of the fact that ASM provides a critical source of income for many people. Removing that source of income could paradoxically exacerbate the problem (OECD, 2019b). This evolution is represented by the LME's decision to adopt a policy of non-discrimination between large-scale mining and ASM (LME, 2019). Current industry initiatives such as the Fair Cobalt Alliance and the Responsible Minerals Initiative now emphasise formalisation of ASM sites to ensure that standards are upheld and actions taken to address the root causes of child labour.

There is some evidence that ASM formalisation can be successful at reducing child labour concerns (WEF 2020; OECD, 2019b). However, successes have so far been limited in scale (BGR, 2019), and the DRC's efforts in particular have been limited by regulatory ambiguity in the mining code (OECD, 2019b). Continued multi-stakeholder engagement is needed, bringing together governments, companies and civil society to improve the situation. In this regard, the recent announcement that the [DRC Minister of Mines is joining the Cobalt Action Partnership](#) is a positive step.

⁴ The simple presence of children at a mine site does not necessarily indicate a human rights violation. The ILO Convention on the Worst Forms of Child

Labour applies to work that is by its nature "likely to harm the health, safety or morals of children".

Inclusive legal frameworks and voluntary industry action can reduce the prevalence of the worst forms of child labour

Existing legal and regulatory frameworks do not always differentiate between large-scale mining and ASM, essentially applying the same requirements and limitations to all mines. This generally means that ASM activities will be “informal” or “illegal”, as individuals will not be able to obtain an exploitation permit via a system designed for large companies. Even where there are special provisions for ASM, there may still be obstacles that discourage workers from working at formalised ASM sites. If enforcement is lax, or if the legal regime is burdensome, workers may continue to work at unregulated sites (IGF, 2017; IMPACT, 2018).

To be effective, policy and regulatory measures must address the root cause – i.e. poverty – and create an alternative to mining for poor children and families. While investment and technical support to develop new formalised mine sites is needed, community development and support for education and other social programmes will be important complementary strategies. The IGF has developed [guidance on establishing a comprehensive ASM strategy](#) to aid policy makers in improving the legal framework.

Industry initiatives can be scaled up

For their part, companies can do more to address the worst forms of child labour in the mineral supply chain. It is not necessarily a good

solution for companies to adopt blanket “ASM-free” policies as a mitigation strategy because complete disengagement may exacerbate the causes of child labour. As an alternative, companies can seek to engage with formalised ASM and to work together with multi-stakeholder groups to promote formalisation (OECD, 2019b).

Separately, companies should seek to apply enhanced due diligence measures to their operations. Although supply chain due diligence remains voluntary for energy transition minerals, they are being increasingly adopted into regulations and market rules, and a mandatory due diligence requirement for all companies is currently under discussion at the European Parliament (European Parliament, 2021). The OECD has developed a set of [practical actions that companies can take to address child labour](#) based on the existing OECD Due Diligence Guidance, discussed in the next section.

Several industry initiatives already exist that combine several of these elements, including the Responsible Cobalt Initiative, launched by the Chinese Chamber of Commerce for Metals, Minerals and Chemicals and the Fair Cobalt Alliance. While promising, the proliferation of initiatives may cause some concern as they are not necessarily co-ordinated and risk overlapping. Thus, continued engagement throughout the value chain is needed, particularly to ensure consistency and interoperability of standards.

Box 4.7. Formalising artisanal and small-scale mining in the DRC

Despite longstanding recognition of the potential for formalisation, as of 2019 the DRC had no more than five active formalised (or semi-formalised) ASM cobalt sites (OECD, 2019b). The government has promised reforms that may support formalisation. In November 2019 the government mandated that all ASM cobalt be sold to the newly formed Entreprise Générale du Cobalt, a subsidiary of the state mining company. In March 2021 it released a responsible sourcing standard designed to support establishing new ASM sites in the DRC (EGC, 2021), although the impact of the standard remains to be seen.

There are currently two models for formalisation of projects in the DRC. In the first model, a registered co-operative can establish an ASM site within an area designated by the government for ASM – known as a Zone d'Exploration Artisanal (ZEA). The DRC currently has 92 ZEAs in the cobalt producing region. However, these are mostly in geologically underexplored areas with less developed mining infrastructure, and a 2019 study found only two producing sites within these zones (BGR, 2019).

In the second model, the concession holder enters into an agreement with a registered co-operative to operate the site, with the concession holder setting standards for production and purchasing all material (OECD, 2019b). It is unclear how many such

agreements exist, but there have been at least two documented projects so far – both initiated by buyers. A 2020 study found mixed results. While both sites had eliminated child labour and made improvements in safety practices, workers did not routinely use protective equipment and critics have noted that the sites have not led to economic or social benefits for workers (WEF, 2020). Since that study, one of the two sites has shut down (Reuters, 2020a), while for the other, the buyer announced that it would suspend purchases until it could confirm that it was free of human rights abuses (Reuters, 2020b).

From these examples, it is clear that long-term engagement with the buyer is critical to ensure that the mines are economically viable. Even with buyer support, structural barriers remain to scaling up this approach. Significant up-front investment is needed for geological analysis and to purchase the necessary infrastructure, including fences, machinery and protective equipment. In parallel, there is a need for community development to provide alternative options for children (WEF, 2020). While formalisation has the potential to improve conditions for ASM workers, a long-term commitment from buyers and mining companies alike will be necessary to ensure that it actually leads to the expansion of opportunities for ASM workers.

Government and industry can do more to address persistent, unequal impacts on women

Historically, women have been largely excluded from large-scale mining. In the United States, women make up only about 14% of the mining workforce (US BLS, 2021). IEA analysis shows that this figure is similar in the European Union (IEA, 2020d). Although data is poor, there is little reason to think the situation is different in developing countries.

Women's participation may be greater at ASM sites, as some estimates place women at around 30% of the workforce (IGF, 2018d). However, women are most often employed in less lucrative “auxiliary activities” at these sites due to cultural barriers and gendered assumptions that mining is “man’s work” (OECD, 2019b; IGF, 2018d). Women also may lack access to finance to invest in equipment and often remain fully responsible for domestic responsibilities, which limits the time and energy they have available for work. Worse, they are subject to increased risk of sexual and gender-based violence (GIZ, 2020) and can be driven to engage in sex work by financial exploitation (IGF, 2018c).

Changes in the community associated with mining may also have a disparate impact on women, even if they do not engage directly in mining activities. For example, women may be marginalised from community outreach by companies (RMF, 2020b), and the move from a subsistence to a cash economy may also give rise to family disputes and increased risk of domestic violence (GIZ, 2020).

Industry responses have so far been lacking. The Responsible Mining Foundation found that the mining sector ranked low in respect of Sustainable Development Goal 5 on gender equality (RMF & CCSI, 2020). Similarly, the foundation found in 2020 that among the 38 companies it surveyed, none had a system to regularly assess the company's impact on women (RMF, 2020b).

Creating an inclusive environment for women

The industry can do more to create an inclusive environment for women, both in their operations and in stakeholder consultations concerning community impacts and working conditions. As a first step, companies can conduct dedicated assessments of the impact of their activities on women and seek to improve gender-disaggregated data.

Governments can also play a role in promoting the inclusion of women miners and community members in multi-stakeholder consultations, as recommended by EITI (EITI, 2018). Regulatory authorities can also implement training for government and law enforcement personnel to ensure that they are prepared to intervene and address rights violations. Governments may also fund programmes designed to reduce the barriers for women to work, including providing reliable access to finance and social services to assist with childcare and domestic responsibilities.

International co-ordination

International co-ordination on sustainable and responsible extraction already exists

Selected initiatives categorised by activity area

Name	Climate	Sustainability	Responsible sourcing	Rights of workers	Fairness and inclusivity	Governance	Security of supply
World Bank Climate Smart Mining Initiative	●	●				●	●
European Battery Alliance							●
European Raw Materials Alliance							●
Extractive Industries Transparency Initiative						●	
Global Battery Alliance	●	●	●				
Energy Resource Governance Initiative		●	●	●		●	
Fair Cobalt Alliance				●	●		
International Council on Mining & Metals	●	●	●	●	●	●	
Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development		●	●	●	●	●	
Initiative for Responsible Mining Assurance	●	●	●	●	●	●	
Towards Sustainable Mining	●	●	●	●	●		
OECD Responsible Business Conduct			●	●	●	●	
Responsible Minerals Initiative			●	●			
Responsible Minerals Foundation	●	●	●	●	●	●	
Women's Rights and Mining			●		●		

Note: Primary activity type: ● = Technical assistance. ● = Industry standardisation. ● = Investment/funding. ● = Research and analysis.

International co-ordination continues to play a critical role in encouraging companies to identify and address risks across their entire supply chains

Growing demand for energy transition minerals entails the expansion of supply chains and an increase in associated environmental and social risks for upstream and downstream companies alike. Identifying and addressing risks across jurisdictions with a patchwork of legal frameworks and local contexts is indeed technically challenging and resource-intensive. But ignoring supply chain risks is increasingly costly in light of pressure from consumers, investors and regulators. For instance, mining companies and traders have faced criminal probes and financial sanctions due to corrupt practices in their supply chains in the DRC (OECD, 2019c).

A prime strategy to mitigate risks is enhancing traceability, accountability, audits and other measures that allow companies to assess their supply chains. These efforts are supported by international frameworks for due diligence, such as the OECD Guidance (see Box 4.8). The operationalisation of these frameworks can be tailored to specific supply chains through industry standards. The growth of an entire industry catering to the needs of companies looking to implement these frameworks speaks to their broad uptake. Certain industry initiatives are calling attention to a broader set of risks beyond conflict financing, serious violations of human rights and economic crime, with increasing attention paid to environmental concerns. For example, the Responsible Minerals Initiative, the

Cobalt Industry Responsible Assessment Framework and the Copper Mark adhere to the principles set out in the OECD Guidance, but go beyond the risks explicitly covered by its Annex II. The expanding coverage of due diligence frameworks and legislation reflects a broader trend of investors, consumers and civil society increasingly calling on companies to look more closely at their supply chains and reduce environmental and social harms through proactive engagement, rather than “de-risking” by exiting fraught supply chains altogether.

Innovation and due diligence

Innovation can also play a role in enhancing supply chain transparency. For example, shifting internal management systems from paper-based to digital documentation facilitates traceability and public access. The European Union, the Global Battery Alliance and the LME are all looking at increasing traceability through digital “passports” attached to individual batteries or metals. Market players are also considering distributed ledger technologies (blockchain) to ensure integrity of mineral supply chain data. While technological solutions alone cannot replace a company’s due diligence obligations, they can play an important role in streamlining these efforts.

Box 4.8. OECD due diligence guidance for responsible supply chains

The [OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas](#) (OECD Guidance) aims to help companies achieve responsible sourcing of minerals and avoid contributing to conflicts, human rights violations and economic crime. It serves as a global reference for public and private stakeholders. Although it initially focused on minerals from conflict-affected and high-risk areas, e.g. tin, tantalum, tungsten and gold, the scope is much broader: it can be applied to all minerals and all types of upstream and downstream risks. It covers both ASM and large-scale mining and is applicable globally, making it increasingly difficult for companies to “opt out”. The OECD is working on a complementary tool addressing environmental risks to enhance coverage of supply chain issues.

The OECD Guidance facilitates the prevention and mitigation of human rights abuses, support to armed forces, and other risks such as tax evasion, fraud and bribery. This is achieved through a five-step framework involving establishing internal management systems, identifying and assessing risks, developing a mitigation strategy, carrying out independent audits and annual reporting. Supply chain stakeholders must establish traceability or a chain of custody system to track minerals and undertake on-the-ground assessments for “red-flagged” supply chains. Critically, companies

are instructed to remedy shortcomings in supply chains rather than disengage. In energy transition mineral supply chains, the OECD Guidance has *de facto* become a core component of countries’ legal frameworks for responsible sourcing. Responsible sourcing requirements based on the OECD Guidance are incorporated into the EU Regulation on Conflict Minerals (currently only applicable to tin, tantalum, tungsten and gold) and the proposed Batteries Regulation. Similar requirements were implemented through the U.S. Dodd-Frank Act and in several African countries (OECD, 2021b). The shift from a voluntary approach to mandatory legal frameworks or market rules reflects broad global consensus regarding enhanced supply chain due diligence.

In 2016 the OECD launched an Alignment Assessment project aimed at measuring the extent to which recommendations had been incorporated into industry standards and effectively implemented. This first exercise revealed significant gaps between the standards under review and OECD Guidance, which were subsequently largely remedied (OECD, 2018). Uptake studies are now underway to evaluate implementation at a company level. While these exercises alone cannot drive full compliance, they ensure a measure of accountability in the rapidly expanding world of industry initiatives, and highlight implementation gaps for policy makers.

The international trade and investment regime is key to maintaining reliable mineral supplies, but policy support is needed to improve application of environmental and social regulations

The global trade and investment regime has helped to reduce tariffs, subsidies and other barriers to trade, enabling companies to weave global supply chains to meet the market's needs. At the same time, this regime can be seen as limiting the policy options available to governments to address environmental and social issues. Although the trade system recognises governments' authority in these areas, for example through exceptions to Article XX of the General Agreement on Tariffs and Trade, progress on incorporating sustainability norms into the international trade regime has been limited and debate continues about including enforceable standards in free-trade agreements (Bronckers and Gruni, 2021).

Governments are therefore looking to update their trade policies in line with civil society's expectations and to balance this goal with stability of supply and national security considerations. Export controls, subsidies to state-owned enterprises in the mining and processing sectors, or carbon border taxes could also lead to distortions in free trade. Such measures reflect the potential tension between international trade disciplines and the mainstreaming of environmental and social concerns.

Further, the international trade regime remains largely deadlocked at the World Trade Organization level, notably in respect of industrial subsidies reform. Due to the lack of impetus for global trade

agreements, countries are increasingly shifting to bilateral or regional agreements to secure supplies of raw materials. EU trade policy strongly favours including environmental and social standards in such agreements. For example, agreements under negotiation with Chile, Australia and China, and the completed Comprehensive Economic and Trade Agreement with Canada, all include commitments to multilateral labour and environmental agreements and responsible business conduct. Apart from the draft agreement with China, they all include specific language on supporting uptake of the OECD Due Diligence Guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. They reflect the important role of international trade to promote consistency in standards. However, these commitments remain largely unenforceable as they are not subject to the agreements' dispute settlement chapter.

Although international trade undoubtedly plays a role in ensuring the stability of energy transition mineral supplies, governments must achieve both security aims and a just transition. Encouragingly, responsible and sustainable sourcing of energy transition minerals is increasingly perceived as a pillar of security of supply, and not as a necessary trade-off. As such, trade policies should reflect these standards rather than rely on them to erect new trade barriers.

Enhancing capacity building and knowledge sharing can address critical resource gaps between countries...

Capacity building and knowledge transfer can be a particularly fruitful area of co-operation, as experience and capacity varies greatly between countries. Australia, Canada and the United States, all of which have well-developed regulatory systems addressing environmental and social concerns, are increasingly offering technical assistance to countries with nascent regulatory regimes.

Role of multilateral initiatives

At a government-to-government level, countries work together through institutions like the World Bank and the OECD to support sustainable mining and supply chain practices. Separately, governments have set up extraction-specific initiatives such as the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) and the Energy Resource Governance Initiative (ERGI) to provide technical assistance.

The IGF provides a platform for more than 75 member countries to discuss issues related to mineral resource governance and promote sustainable mining practices. In particular, it provides technical capacity building and shares best practices through its [Mining Policy Framework](#). Similarly, ERGI shares best practices on mining governance through its [ERGI Toolkit](#), which is primarily designed for mineral-producing economies and focuses on responsible and

sustainable mining. In particular, these high-level initiatives can help ensure consistent communications with all relevant ministries in resource-rich countries, and more generally ensure issues receive appropriate levels of attention. To harness this potential, synergies between initiatives could be better exploited, and new areas for knowledge sharing could be explored beyond mining frameworks.

Public-private collaboration

Some companies have achieved high levels of sustainability performance, and governments can facilitate sharing of these experiences and good practices. For example, the Mining Association of Canada's TSM standard covers issues such as tailings management, worker safety, child labour and relationships with indigenous communities. The Canadian government actively promotes the TSM standard and supports uptake by other countries (Government of Canada, 2021b). The World Bank's [Climate Smart Mining initiative](#) also brings together public and private actors across the mineral sector to facilitate collaboration. Industry and governments have thus stepped in to facilitate knowledge sharing on a significant scale, but more is needed to achieve a comprehensive minerals governance framework.

...but there is scope for better alignment and co-ordination

To be sure, the proliferation of international initiatives has led to encouraging success stories, including the global adoption and implementation of the OECD Due Diligence Guidance, the LME's responsible sourcing criteria and sustainability initiative, and continued improvement of transparency standards in producer economies via the EITI. However, uncoordinated efforts can lead to potential duplication – where multiple initiatives form around the same issue with different membership – or discontinuity when competing standards follow different approaches. Even where a harmonised approach emerges, to the extent that initiatives are voluntary, some important players may opt out.

As discussed in Chapter 3, a high-level forum for co-ordination could be pivotal in standardising environmental and social standards and co-ordinating activity on security of supply. There has been some success at co-ordinating competing efforts, but only on certain issues, for instance due diligence practices through the OECD Guidance. Generalised organisations like the G7 and G20 have also played this role in the past. For example, the Brisbane 2014 [G20 Principles of Energy Collaboration](#) reflected the need to make minerals governance an integral part of countries' energy security policies. New or long-standing fora such as the Climate Smart Mining Initiative or the IGF can also play an important role in channelling discussion and co-operation on energy transition minerals.

An international governance framework

Despite increasing levels of global adherence to environmental and social standards, they generally offer few avenues for collective action among governments. Policy integration through the European Union or other regional blocs alone is also insufficient to ensure consistency on a global scale. Therefore, a systemic approach is needed to ensure countries take action not only in certain notoriously fraught supply chains or in specific regions, but also for all minerals that underpin the energy transition and across jurisdictions.

A governance framework for minerals should provide countries with the tools they need to address GHG emissions, local and regional environmental impacts and social and human rights risks. It could ultimately contribute to maintaining a reliable supply of minerals necessary for the energy transition. As such, the UN Environment Programme's International Resource Panel has underlined that “[t]here is a need for an international body with a similar role to that of the International Energy Agency in the energy sector” (IRP, 2020, 131). The IEA's energy security framework could thus serve as a template for international minerals governance, underpinned by data sharing, co-ordination mechanisms and collective actions, fostering sustainable and responsible supply chains that contribute to a low-carbon economy.

Annexes

Scope

This report assesses the mineral requirements for the following clean energy technologies:

- **Solar PV** (utility-scale and distributed)
- **Wind** (onshore and offshore)
- **Concentrating solar power** (parabolic troughs and central tower)
- **Hydropower**
- **Geothermal**
- **Bioenergy for power**
- **Nuclear power**
- **Electricity networks** (transmission, distribution, and transformer)
- **Electric vehicles** (battery electric and plug-in hybrid electric vehicles)
- **Battery storage** (utility-scale and residential)
- **Hydrogen** (electrolysers and fuel cells).

All of these energy technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this report covers the entire mineral and metal value chain from mining to processing operations, we use “minerals” as a representative term for the sake of simplicity.

Minerals are not only used in the clean energy sector, but are also used widely across the entire energy system, in technologies that improve efficiency and reduce emissions. For example, the most efficient coal-fired power plants require a lot more nickel than the least efficient ones in order to allow for higher combustion temperatures. However, here we focus specifically on the use of minerals in clean energy technologies, given that they generally require considerably more minerals than fossil fuel counterparts. Our analysis also focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our report considers a wide range of minerals used in clean energy technologies listed in the table below. They include chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others.

Steel is widely used across a broad range of technologies, but we have excluded it from the scope given that it does not have substantial security implications and the energy sector is not a major driver of growth in steel demand. Steel and aluminium are widely used across many clean energy technologies, but we have excluded it from the scope of this analysis. Steel does not have substantial security implications and the energy sector is not a major driver of

growth in steel demand. Aluminium demand is assessed for electricity networks only as the outlook for copper is inherently linked with aluminium use in grid lines, but is not included in the aggregate demand projections. Overall aluminium demand projections are regularly assessed as part of the *WEO* and *Energy Technology Perspectives* series.

Projection results are available for download from the report webpage: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>.

Minerals in scope

Focus minerals	Other minerals	
Cobalt	Arsenic	Niobium
Copper	Boron	Platinum
Lithium	Cadmium	Selenium
Nickel	Chromium	Silicon
Rare earth elements (Neodymium, Dysprosium, Praseodymium, Terbium, others)	Gallium	Silver
	Germanium	Tantalum
	Graphite	Tellurium
	Hafnium	Tin
	Indium	Titanium
	Iridium	Tungsten
	Lead	Vanadium
	Magnesium	Zinc
	Manganese	Zirconium
	Molybdenum	

Methodology

Demand

For each of the clean energy technologies, we estimate overall mineral demand using four main variables:

- clean energy deployment trends under different scenarios;
- sub-technology shares within each technology area;
- mineral intensity of each sub-technology; and
- mineral intensity improvements.

Clean energy deployment trends under the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS) are taken from the projections in the *World Energy Outlook 2020*, complemented by the results in the *Energy Technology Perspectives 2020*.

Sub-technology shares within each technology area (e.g. solar PV module types; EV battery chemistries) are also taken from the *World Energy Outlook 2020*, complemented by the *Energy Technology Perspectives 2020* and other sources.

Mineral intensity assumptions were developed through extensive literature review (see Table) and expert and industry consultations, including with IEA [Technology Collaboration Programmes](#).

The pace of mineral intensity improvements varies by scenario, with the STEPS generally seeing minimal improvement over time as compared to modest improvement (around 10% in the longer term) assumed in the SDS. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar PV, platinum loading in fuel cells, REE use in wind turbines), we applied specific improvement rates based on the review of underlying drivers.

The report assesses demand from other sectors for the five focus minerals using historical consumption by end-use applications, relevant activity drivers (e.g. GDP, industry value added, vehicle activities, steel production) and material intensities.

Supply

Annual mineral production estimates are based on the analysis of the individual project data provided by S&P Global (2021) and BloombergNEF (2020), and supplemented with public data sources.

Operating projects are defined as mines of which development stage is operating, expansion or limited production due to some reasons. Under-construction projects are taken to be mines of which development stage is commissioning, construction planned, construction started or preproduction.

Secondary production is estimated with two parameters: the average recycling rate and the lifetime of each end-use sector. The recycling rate is the combination of the end-of-life collection rate (the amount of a certain product being collected for recycling) and the yield rate (the amount of material a recycling process can actually recover). For existing waste streams (e.g. industrial applications), we assume only marginal improvement in collection rates, while for emerging technologies such as lithium-ion batteries, we assume collection rates increase at a faster pace. For batteries, the collection rates gradually increase from around 45% in the early-2020s to 80% by 2040. For batteries, the yield rate is assumed to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries faces many technical and regulatory obstacles.

Sources for mineral intensity assumptions

Technology	Sources
Solar PV	<p>Candelise, C. et al. (2011), Materials availability for thin film (TF) PV technologies development: a real concern? <i>Renewable and Sustainable Energy Reviews</i>, 15(9), 4972-4981, https://doi.org/10.1016/j.rser.2011.06.012</p> <p>Carrara S. et al. (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, European Commission Joint Research Centre (JRC), http://dx.doi.org/10.2760/160859%20</p> <p>Elshkaki, A., and Graedel, T. E. (2013), Dynamic analysis of the global metals flows and stocks in electricity generation</p>

Technology	Sources
	<p>technologies, <i>Journal of Cleaner Production</i>, 59, 260-273, https://doi.org/10.1016/j.jclepro.2013.07.003</p> <p>Fizaine, F. and Court, V., (2015), Renewable electricity producing technologies and metal depletion: a sensitivity analysis using the EROI, <i>Ecological Economics</i>, 110, 106–118, https://doi.org/10.1016/j.ecolecon.2014.12.001</p> <p>Frischknecht, R. et al. (2020), Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, <i>IEA PVPS Task 12</i>, Report T12-19:2020. https://iea-pvps.org/key-topics/life-cycle-inventories-and-life-cycle-assessments-of-photovoltaic-systems</p> <p>Giurco, D. et al. (2019). Requirements for minerals and metals for 100% renewable scenarios, In: Teske S. (eds) Achieving the Paris Climate Agreement Goals, https://doi.org/10.1007/978-3-030-05843-2_11</p> <p>IRENA (International Renewable Energy Agency) (2017), Renewable Energy Benefits Leveraging Local Capacity for Solar PV, https://www.irena.org/publications/2017/Jun/Renewable-Energy-Benefits-Leveraging-Local-Capacity-for-Solar-PV</p> <p>World Bank (2017), The Growing Role of Minerals and Metals for a Low Carbon Future, https://doi.org/10.1596/28312</p> <p>Private communication with researchers of early-stage technologies</p>
Wind	<p>Carrara S. et al. (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, European Commission Joint Research Centre (JRC), http://dx.doi.org/10.2760/160859%20</p> <p>Månberger, A. and Stenqvist, B. (2018), Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development, <i>Energy Policy</i>, 119, 226-241, https://doi.org/10.1016/j.enpol.2018.04.056</p> <p>Private communication with companies</p>

Technology	Sources
CSP	<p>Watari, T. et al. (2019), Total material requirement for the global energy transition to 2050: A focus on transport and electricity, <i>Resources, Conservation and Recycling</i>, 148, 91-103, https://doi.org/10.1016/j.resconrec.2019.05.015</p> <p>Pihl, E. et al. (2012), Material constraints for concentrating solar thermal power. <i>Energy</i>, 44(1), 944-954, https://doi.org/10.1016/j.energy.2012.04.057</p>
Hydro	<p>Ashby, M. F. (2013), Materials for low-carbon power, In <i>Materials and the Environment</i> (2nd ed., pp. 349–413), https://doi.org/10.1016/b978-0-12-385971-6.00012-9</p> <p>Moss, R. L. et al. (2013), The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. <i>Energy Policy</i>, 55, 556-564, https://doi.org/10.1016/j.enpol.2012.12.053</p>
Geothermal	<p>Ashby, M. F. (2013), Materials for low-carbon power, In <i>Materials and the Environment</i> (2nd ed., pp. 349–413), https://doi.org/10.1016/b978-0-12-385971-6.00012-9</p> <p>Saner, D. et al. (2010), Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. <i>Renewable and Sustainable Energy Reviews</i>, 14(7), 1798-1813, https://doi.org/10.1016/j.rser.2010.04.002</p> <p>European Geothermal Energy Council (private communications)</p> <p>Moss, R. L. et al. (2013), The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. <i>Energy Policy</i>, 55, 556-564, https://doi.org/10.1016/j.enpol.2012.12.053</p> <p>Watari, T. et al. (2019), Total material requirement for the global energy transition to 2050: A focus on transport and electricity, <i>Resources, Conservation and Recycling</i>, 148, 91-103, https://doi.org/10.1016/j.resconrec.2019.05.015</p> <p>Private communication with researchers</p>

Technology	Sources
Biomass	<p>Ashby, M. F. (2013), Materials for low-carbon power, In <i>Materials and the Environment</i> (2nd ed., pp. 349–413), https://doi.org/10.1016/b978-0-12-385971-6.00012-9</p> <p>Moss et al. (2011), <i>Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies</i>, EC JRC (Joint Research Center), https://doi.org/10.2790/35716</p>
Nuclear	<p>Anigstein et al (2001), <i>Potential recycling of scrap metal from nuclear facilities</i>, https://nepis.epa.gov/Exe/ZyPDF.cgi/P100NQVK.PDF?Dockey=P100NQVK.PDF</p> <p>Ashby, M. F. (2013), Materials for low-carbon power, In <i>Materials and the Environment</i> (2nd ed., pp. 349–413), https://doi.org/10.1016/b978-0-12-385971-6.00012-9</p> <p>Fizaine, F. and Court, V., (2015), Renewable electricity producing technologies and metal depletion: a sensitivity analysis using the EROI, <i>Ecological Economics</i>, 110, 106–118, https://doi.org/10.1016/j.ecolecon.2014.12.001</p> <p>Moss et al. (2011), <i>Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies</i>, EC JRC (Joint Research Center), https://doi.org/10.2790/35716</p> <p>NEA (Nuclear Energy Agency) provided valuable inputs on mineral intensities for nuclear</p> <p>Valero, A. et al. (2018), Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways, <i>Energy</i>, 159, 1175-1184, https://doi.org/10.1016/j.energy.2018.06.149</p> <p>Vidal, O., Goffé, B., and Arndt, N. (2013), Metals for a low-carbon society, <i>Nature Geoscience</i>, 6(11), 894-896, https://doi.org/10.1038/ngeo1993</p>

Technology	Sources
Electricity networks	<p>BloombergNEF (2020), <i>Copper and Aluminum Compete to Build the Future Power Grid</i>.</p> <p>Private communication with companies</p>
EV batteries	<p>Argonne National Laboratory (2020), BatPaC Model Software Version 4.0, https://www.anl.gov/cse/batpac-model-softwareBatPac 2020</p> <p>Argonne National Laboratory (2020), GREET 2020, https://greet.es.anl.gov/</p> <p>Keshavarzmohammadian, A. (2018), <i>Impact of Breakthrough Battery Technology on Energy Use and Emissions from the US Transportation Sector</i>, https://scholar.colorado.edu/downloads/44558d438.</p> <p>Troy, S. et al. (2016), Life Cycle Assessment and resource analysis of all-solid-state batteries. <i>Applied Energy</i>, 169, 757-767, https://doi.org/10.1016/j.apenergy.2016.02.064.</p> <p>Wu, Z., and Kong, D. (2018), Comparative life cycle assessment of lithium-ion batteries with lithium metal, silicon nanowire, and graphite anodes, <i>Clean Technologies and Environmental Policy</i>, 20(6), 1233-1244, https://doi.org/10.1007/s10098-018-1548-9</p> <p>Private communication with researchers of early-stage technologies</p>
EV motors	<p>Argonne National Laboratory (2020), GREET 2020, https://greet.es.anl.gov/</p> <p>Ballinger, B. et al. (2019), The vulnerability of electric vehicle deployment to critical mineral supply, <i>Applied Energy</i>, 255, 113844, https://doi.org/10.1016/j.apenergy.2019.113844</p> <p>Fishman, T. et al. (2018), Implications of emerging vehicle technologies on rare earth supply and demand in the US, <i>Resources</i>, 7(1), 1–15. https://doi.org/10.3390/resources7010009</p> <p>Nordelöf, A. et al. (2019), Life cycle assessment of permanent magnet electric traction motors, <i>Transportation Research Part</i></p>

Technology	Sources
	<p><i>D: Transport and Environment</i>, 67, 263–274, https://doi.org/10.1016/j.trd.2018.11.004</p> <p>Pavel, C. C. et al. (2017), Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications, <i>Sustainable Materials and Technologies</i>, 12, 62–72, https://doi.org/10.1016/j.susmat.2017.01.003</p> <p>Weiss, M. et al. (2015), On the electrification of road transportation—a review of the environmental, economic, and social performance of electric two-wheelers, <i>Transportation Research Part D: Transport and Environment</i>, 41, 348-366, https://doi.org/10.1016/j.trd.2015.09.007</p>
Battery storage	<p>Argonne National Laboratory (2020), BatPaC Model Software Version 4.0, https://www.anl.gov/cse/batpac-model-softwareBatPac 2020</p> <p>Bushveld Minerals, (2018), <i>Energy Storage & Vanadium Redox Flow Batteries 101</i>, http://www.bushveldminerals.com/wp-content/uploads/2018/11/Energy-Storage-Vanadium-Redox-Flow-Batteries-101.pdf.</p> <p>Fernandez-Marchante, C. M. et al. (2020), Environmental and preliminary cost assessments of redox flow batteries for renewable energy storage, <i>Energy Technology</i>, 8(11), 1900914, https://doi.org/10.1002/ente.201900914</p> <p>Le Varlet, T. et al. (2020), Comparative life cycle assessment of lithium-ion battery chemistries for residential storage, <i>Journal of Energy Storage</i>, 28, 101230, https://doi.org/10.1016/j.est.2020.101230</p> <p>Zhang, X. et al. (2016), Optimal sizing of vanadium redox flow battery systems for residential applications based on battery electrochemical characteristics, <i>Energies</i>, 9(10), 857, https://doi.org/10.3390/en9100857</p>

Technology	Sources
Hydrogen	<p>Bareiß, K. et al. (2019), Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, <i>Applied Energy</i>, 237, 862–872, https://doi.org/10.1016/j.apenergy.2019.01.001</p> <p>Fuel Cells and Hydrogen Joint Undertaking (2018), <i>Addendum to the Multi-Annual Work Plan 2014-2020</i>, https://www.fch.europa.eu/sites/default/files/MAWP%20final%20Version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf</p> <p>James, B. D. et al. (2018), <i>Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update</i>, https://www.energy.gov/sites/prod/files/2019/12/f70/fcto-sa-2018-transportation-fuel-cell-cost-analysis.pdf</p> <p>Kiemel, S. et al. (2021), Critical materials for water electrolyzers at the example of the energy transition in Germany, <i>International Journal of Energy Research</i>, January, 1–22, https://doi.org/10.1002/er.6487</p> <p>Koj, J. C. et al. (2017), Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis, <i>Energies</i>, 10(7), https://doi.org/10.3390/en10070860</p> <p>Lundberg, S. (2019), <i>Comparative LCA of Electrolyzers for Hydrogen Gas Production</i>, http://www.diva-portal.org/smash/get/diva2:1331089/FULLTEXT01.pdf</p> <p>NEDO (2008), 水素製造コスト削減のための技術開発, https://www.nedo.go.jp/content/100105282.pdf</p> <p>Smolinka, T. et al. (2018), <i>Industrialisierung der Wasser elektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme</i>, https://www.now-gmbh.de/content/service/3-publikationen/1-nip-wasserstoff-und-brennstoffzellentechnologie/indwede-studie_v04.1.pdf</p> <p>US Department of Energy (2014), <i>Manufacturing Cost Analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) for Auxilliary Power Applications</i>,</p>

Technology	Sources
	<p>https://www.energy.gov/sites/default/files/2014/06/f16/fcto_battelle_cost_analysis_apu_feb2014.pdf</p> <p>US Department of Energy (2015), <i>DOE Technical Targets for Polymer Electrolyte Membrane Fuel Cell Components</i>, https://www.energy.gov/eere/fuelcells/doe-technical-targets-polymer-electrolyte-membrane-fuel-cell-components</p> <p>Private communication with companies</p>

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References

Introduction

IEA (International Energy Agency) (2021), How global electric car sales defied Covid-19 in 2020, <https://www.iea.org/commentaries/how-global-electric-car-sales-defied-covid-19-in-2020>

IEA (2020), *Renewables 2021*, <https://www.iea.org/reports/renewables-2020>

Key findings

Adamas Intelligence (2020), Rare earth magnet market outlook to 2030, Adamas Intelligence, Ontario, Canada.

Argonne National Laboratory (2020), *GREET 2020*, <https://greet.es.anl.gov/>

Argonne National Laboratory (2019), *GREET 2019*, <https://greet.es.anl.gov/>

IEA (International Energy Agency) (2020a), *World Energy Outlook 2020*, <https://www.iea.org/reports/world-energy-outlook-2020>

IEA (2020b), *Global Electric Vehicle Outlook 2020*, <https://www.iea.org/reports/global-ev-outlook-2020>

Kelly, J.C., Dai, Q. and Wang, M. (2020) Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries, *Mitigation and Adaptation Strategies for Global Change* 25, 371–396, <https://doi.org/10.1007/s11027-019-09869-2>

Marx, J. et al. (2018), Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits, *ACS Sustainable Chemistry and Engineering*, 6(5), 5858–5867, <https://doi.org/10.1021/acssuschemeng.7b04165>

Rio Tinto (2020), *Our approach to climate change 2019*, London, United Kingdom.

S&P Global (2021), New lithium supply chains could slash sector emissions by nearly a third, <https://www.spglobal.com/platts/en/market-insights/latest-news/coal/121120-new-lithium-supply-chains-could-slash-sector-emissions-by-nearly-a-third-roskill>

USGS (United States Geological Survey) (2021), *Mineral Commodity Summaries 2021*, USGS, Boulder, Colorado.

World Bureau of Metal Statistics (2020), *World Metal Statistics Yearbook 2020*, Herts, United Kingdom.

Chapter 1: The state of play

Adamas Intelligence (2020), Rare earth magnet market outlook to 2030, Adamas Intelligence, Ontario, Canada.

Eurometaux (2019), *Metals for a Climate Neutral Europe: A 2050 Blueprint*, <https://eurometaux.eu/media/2005/full-report-8-56-17.pdf>

Hastings-Simon and Bazilian (2020), *Critical Minerals Don't Burn Up: Why The Energy Security Playbook Needs A Re-Write*, <https://www.globalpolicyjournal.com/blog/23/07/2020/critical-minerals-dont-burn-why-energy-security-playbook-needs-re-write>

Henckens (2021), Scarce mineral resources: Extraction, consumption and limits of sustainability, *Resources, Conservation and Recycling*, Volume 169, <https://doi.org/10.1016/j.resconrec.2021.105511>

IEA (International Energy Agency) (2021a), *Global EV Outlook 2021*, <https://www.iea.org/reports/global-ev-outlook-2021>

IEA (2021b), *Global Energy Review: CO2 Emissions in 2020*, <https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020>

IEA (2020a), *World Energy Outlook 2020*, <https://www.iea.org/reports/world-energy-outlook-2020>

IEA (2020b), Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals,

<https://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-critical-minerals>

OECD (Organisation for Economic Co-operation and Development) (2019), *Global material resources outlook to 2060*, OECD, Paris, <https://www.oecd.org/environment/global-material-resources-outlook-to-2060-9789264307452-en.htm>

Sverdrup and Ragnarsdottir (2016), A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use, *Resources, Conservation and Recycling*, Volume 114, <https://doi.org/10.1016/j.resconrec.2016.07.011>

S&P Global (2021), *S&P Global Market Intelligence Platform (database)*, accessed multiple times in November 2020 - March 2021.

UNEP (United Nations Environment Programme). (2011). *Recycling rates of metals: a status report*, UNEP, Nairobi.

USGS (United States Geological Survey) (2021), *Mineral Commodity Summaries 2021*, USGS, Boulder, Colorado.

World Bank (2020), *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*, World Bank, Washington, DC, <https://pubdocs.worldbank.org/en/961711588875536384/Minerals->

[for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition](#)

World Bureau of Metal Statistics (2020), *World Metal Statistics Yearbook 2020*, Herts, United Kingdom.

Chapter 2: Mineral requirements for clean energy transitions

Adamas Intelligence (2021a), *EV Battery Capacity and Battery Metals Tracker*, Adamas Intelligence, Ontario, Canada.

Adamas Intelligence (2021b), *EV Motor Materials Monthly*, Adamas Intelligence, Ontario, Canada.

Agamloh, E., von Jouanne, A., and Yokochi, A. (2020), An overview of electric machine trends in modern electric vehicles, *Machines*, 8(2), <https://doi.org/10.3390/MACHINES8020020>

Argonne National Laboratory (2020a), *BatPaC Model Software*, <https://www.anl.gov/cse/batpac-model-software>

Argonne National Laboratory (2020b), *GREET 2020*, <https://greet.es.anl.gov/>

Ashby, M. F. (2013), Materials for low-carbon power, In *Materials and the Environment* (2nd ed., pp. 349–413), <https://doi.org/10.1016/b978-0-12-385971-6.00012-9>

Ballinger, B. et al. (2019), The vulnerability of electric vehicle deployment to critical mineral supply, *Applied Energy*, 255, 113844, <https://doi.org/10.1016/j.apenergy.2019.113844>

BareiB, K. et al. (2019), Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, *Applied Energy*, 237, 862–872, <https://doi.org/10.1016/j.apenergy.2019.01.001>

Bellini, E. (2020), Vanadium redox flow battery goes online in Spain. *PV Magazine*, <https://www.pv-magazine.com/2020/12/17/vanadium-redox-flow-battery-goes-online-in-spain/>

Bleicher, A. (2010), Thin-Film Trick Makes Gallium Arsenide Devices Cheap, *IEEE Spectrum*, <https://spectrum.ieee.org/semiconductors/materials/thinfilm-trick-makes-gallium-arsenide-devices-cheap>

BloombergNEF (2020), 2020 Lithium-Ion Battery Price Survey.

BloombergNEF (2021), 1H 2021 Energy Storage Market Outlook.

Campbell, P. (2021), GM aims to end petrol and diesel sales by 2035, *Financial Times*, <https://www.ft.com/content/ea49d8cc-0e40-4dcd-ab60-0decc7146f5a>

Cui, H., Hall, D. and Lutsey, N. (2020), Update on the global transition to electric vehicles through 2019, *International Council on*

Clean Transportation, <https://theicct.org/publications/update-global-ev-transition-2019>

Ding, Y. et al. (2019), Automotive Li-Ion Batteries: Current Status and Future Perspectives, *Electrochemical Energy Reviews*, 2(1), 1-28, <https://doi.org/10.1007/s41918-018-0022-z>

EC JRC (Joint Research Center), (2011), *Critical Metals in Strategic Energy Technologies*, <https://doi.org/10.2790/35716>

Elia, A. et al. (2020), Wind turbine cost reduction: A detailed bottom-up analysis of innovation drivers, *Energy Policy*, 147 (October), <https://doi.org/10.1016/j.enpol.2020.111912>

EV-Volumes. (2021), *EV Data Center*, <https://www.ev-volumes.com/datacenter/>

Fishman, T. et al. (2018), Implications of emerging vehicle technologies on rare earth supply and demand in the US, *Resources*, 7(1), 1–15. <https://doi.org/10.3390/resources7010009>

Fraunhofer ISE (2020), *Photovoltaics Report*, <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

Fuel Cells and Hydrogen Joint Undertaking (2018), *Addendum to the Multi-Annual Work Plan 2014-2020*, <https://www.fch.europa.eu/sites/default/files/MAWP%20final%20ver>

[sion_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf](https://www.fch.europa.eu/sites/default/files/MAWP%20final%20ver)

General Office of the State Council of the People's Republic of China (2020), *New Energy Automobile Industry Development Plan 2020-2035*, http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm

Hall, D. et al. (2020), Electric vehicle capitals: Cities aim for all-electric mobility, *International Council on Clean Transportation*, September, <https://theicct.org/publications/update-global-ev-transition-2019>

Hendricks, C. et al. (2015), A failure modes, mechanisms, and effects analysis (FMMEA) of lithium-ion batteries, *Journal of Power Sources*, 297, 113–120, <https://doi.org/10.1016/j.jpowsour.2015.07.100>

Hess, S., Wohlfahrt-Mehrens, M., and Wachtler, M. (2015), Flammability of Li-Ion Battery Electrolytes: Flash Point and Self-Extinguishing Time Measurements, *Journal of The Electrochemical Society*, 162(2), A3084–A3097, <https://doi.org/10.1149/2.0121502jes>

Horowitz, K. et al. (2018), *A Techno-Economic Analysis and Cost Reduction Roadmap for III-V Solar Cells*, <https://www.nrel.gov/docs/fy19osti/72103.pdf>

IEA (2021), *Global EV Outlook 2021*,
<https://www.iea.org/reports/global-ev-outlook-2021>

IEA (2020a), *Energy Storage*, Tracking Clean Energy Progress,
<https://www.iea.org/reports/energy-storage>

IEA (2020b), *Global EV Outlook 2020*,
<https://www.iea.org/reports/global-ev-outlook-2020>

IEA (2020c), *World Energy Outlook 2020*,
<https://www.iea.org/reports/world-energy-outlook-2020>

IRENA (International Renewable Energy Agency) (2019),
Renewable Power Generation Costs in 2018,
<https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018>

IRENA (2016), *End of Life Management Solar PV Panels*,
<https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels>

Irvine, M. and Rinaldo, M. (2020), *Tesla's Battery Day and the Energy Transition*, DNV, <https://www.dnv.com/feature/tesla-battery-day-energy-transition.html>

ITRPV (2020), Results 2019 including maturity report 2020,
<http://itrpv.vdma.org/documents/27094228/29066965/Readiness01TRPV02020/2a8588fd-3ac2-d21d-2f83-b8f96be03e51>

James, B. D. et al. (2018), *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update*,
<https://www.energy.gov/sites/prod/files/2019/12/f70/fcto-sa-2018-transportation-fuel-cell-cost-analysis.pdf>

Janek, J. and Zeier, W. G. (2016), A solid future for battery development. *Nature Energy*, 1(9), 1–4,
<https://doi.org/10.1038/nenergy.2016.141>

Kane, M. (2021), SVOLT's Cobalt-free NMx Cell Are Now Available For Order, *InsideEVs*, <https://insideevs.com/news/483181/svolt-cobalt-free-nmx-cell-available-order/>

Kiemel, S. et al. (2021), Critical materials for water electrolyzers at the example of the energy transition in Germany, *International Journal of Energy Research*, January, 1–22,
<https://doi.org/10.1002/er.6487>

Kim, H. S. et al. (2012), Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9%, *Scientific Reports*, 2(1), 1–7,
<https://doi.org/10.1038/srep00591>

Koj, J. C. et al. (2017), Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis, *Energies*, 10(7), <https://doi.org/10.3390/en10070860>

Lee, Y. G. et al. (2020), High-energy long-cycling all-solid-state lithium metal batteries enabled by silver–carbon composite anodes, *Nature Energy*, 5(4), 299–308, <https://doi.org/10.1038/s41560-020-0575-z>

Lundberg, S. (2019), *Comparative LCA of Electrolyzers for Hydrogen Gas Production*, <http://www.diva-portal.org/smash/get/diva2:1331089/FULLTEXT01.pdf>

McKinsey (2020), *McKinsey Electric Vehicle Index: Electric Vehicle Trends*, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/mckinsey-electric-vehicle-index-europe-cushions-a-global-plunge-in-ev-sales>

Nature Energy (2020), Perovskites take steps to industrialization, *Nature Energy*, 5(1), 1–1, <https://doi.org/10.1038/s41560-020-0552-6>

NEDO (2008), 燃料電池用白金代替触媒の研究開発動向 (R&D trends in platinum alternative catalysts for fuel cells), <https://www.nedo.go.jp/content/100105282.pdf>

Nishiyama, A. (2020), China to ban new gas-powered car sales by 2035 to meet 2060 pledge, *Asahi Shinbun*, <http://www.asahi.com/ajw/articles/13878544>

Nordelöf, A. et al. (2019), Life cycle assessment of permanent magnet electric traction motors, *Transportation Research Part D:*

Transport and Environment, 67, 263–274, <https://doi.org/10.1016/j.trd.2018.11.004>

NREL (National Renewable Energy Laboratory) (2019), *Best Research-Cell Efficiency Chart*, <https://www.nrel.gov/pv/cell-efficiency.html>

Nunez, C. (2020), Researchers eye manganese as key to safer, cheaper lithium-ion batteries, *Argonne National Laboratory*, <https://www.anl.gov/article/researchers-eye-manganese-as-key-to-safer-cheaper-lithiumion-batteries>

Pavel, C. C. et al. (2017), Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications, *Sustainable Materials and Technologies*, 12, 62–72, <https://doi.org/10.1016/j.susmat.2017.01.003>

Pillot, C. (2019), *The Rechargeable Battery Market and Main Trends 2018-2030*, https://www.bpifrance.fr/content/download/76854/831358/file/02_-_Presentation_Avicenne_-_Christophe_Pillot_-_28_Mai_2019.pdf

Pillot, C. (2017), *The Rechargeable Battery Market and Main Trends 2015-2025*, http://www.avicenne.com/pdf/The%20Rechargeable%20Battery%20Market%20and%20Main%20Trends%202016-2025_C%20Pillot_M%20Sanders_September%202017.pdf

Placke, T. et al. (2017), Lithium ion, lithium metal, and alternative rechargeable battery technologies: The odyssey for high energy density, *Journal of Solid State Electrochemistry*, 21(7), 1939–1964, <https://doi.org/10.1007/s10008-017-3610-7>

S&P Global (2021), Volkswagen's plan on LFP use shifts hydroxide dominance narrative in EV sector, <https://www.spglobal.com/platts/en/market-insights/latest-news/metals/031721-volkswagens-plan-on-lfp-use-shifts-hydroxide-dominance-narrative-in-ev-sector>

Saliba, M. et al. (2018), Perovskite Solar Cells: From the Atomic Level to Film Quality and Device Performance, *Angewandte Chemie - International Edition*, 57(10), 2554–2569, <https://doi.org/10.1002/anie.201703226>

Shirayama, M. et al. (2016), Degradation mechanism of CH₃NH₃PbI₃ perovskite materials upon exposure to humid air, *Journal of Applied Physics*, 119(11), 115501, <https://doi.org/10.1063/1.4943638>

Smolinka, T. et al. (2018), Industrialisierung der Wasser elektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme (Industrialization of water electrolysis in Germany: opportunities and challenges for sustainable hydrogen for transport, electricity and heat), [https://www.now-gmbh.de/content/service/3-publikationen/1-nip-](https://www.now-gmbh.de/content/service/3-publikationen/1-nip-wasserstoff-und-brennstoffzellentechnologie/indwede-studie_v04.1.pdf)

[wasserstoff-und-brennstoffzellentechnologie/indwede-studie_v04.1.pdf](https://www.now-gmbh.de/content/service/3-publikationen/1-nip-wasserstoff-und-brennstoffzellentechnologie/indwede-studie_v04.1.pdf)

Sprecher, B. et al. (2014), Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets, *Environmental Science and Technology*, 48(7), 3951–3958, <https://doi.org/10.1021/es404596g>

Times of India (2021), Switch-hit: Mass campaign to popularise electric vehicles in Delhi, <https://timesofindia.indiatimes.com/city/delhi/switch-hit-mass-campaign-to-popularise-e-vehicles/articleshow/80695293.cms>

US Department of Energy (2014), Manufacturing Cost Analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) for Auxilliary Power Applications, https://www.energy.gov/sites/default/files/2014/06/f16/fcto_battelle_cost_analysis_apu_feb2014.pdf

US Department of Energy (2015), *DOE Technical Targets for Polymer Electrolyte Membrane Fuel Cell Components*, <https://www.energy.gov/eere/fuelcells/doe-technical-targets-polymer-electrolyte-membrane-fuel-cell-components>

USGS (2021), *Mineral Commodity Summaries 2021*, <https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf>

Varzi, A. et al. (2016), Challenges and prospects of the role of solid electrolytes in the revitalization of lithium metal batteries, *Journal of*

Materials Chemistry A, 4(44), 17251–17259,
<https://doi.org/10.1039/c6ta07384k>

Wappelhorst, S. and Cui, H. (2020), Growing momentum: Global overview of government targets for phasing out sales of new internal combustion engine vehicles, ICCT,
<https://theicct.org/blog/staff/global-ice-phaseout-nov2020>

Watari, T. et al. (2019), Total material requirement for the global energy transition to 2050: A focus on transport and electricity, *Resources, Conservation and Recycling*, 148, 91–103,
<https://doi.org/10.1016/j.resconrec.2019.05.015>

Widmer, J. D., Martin, R., and Kimiabeigi, M. (2015), Electric vehicle traction motors without rare earth magnets, *Sustainable Materials and Technologies*, 3, 7–13,
<https://doi.org/10.1016/j.susmat.2015.02.001>

Willuhn, M. (2020), Not just for outer space: NREL has a path to cheaper GaAs solar cells, *PV Magazine*, <https://pv-magazine-usa.com/2020/01/13/solar-cells-from-space-are-on-the-way/>

Wood, D. L., Li, J., and Daniel, C. (2015), Prospects for reducing the processing cost of lithium ion batteries, *Journal of Power Sources*, 275, 234–242,
<https://doi.org/10.1016/j.jpowsour.2014.11.019>

Zhao, Z. et al. (2017), Mixed-Organic-Cation Tin Iodide for Lead-Free Perovskite Solar Cells with an Efficiency of 8.12%, *Advanced Science*, 4(11), 1700204, <https://doi.org/10.1002/advs.201700204>

Chapter 3: Reliable supply of minerals

Adamas Intelligence (2020), Rare earth magnet market outlook to 2030, Adamas Intelligence, Ontario, Canada.

Africa Oil & Power (2021), DRC announces extension on export ban moratorium for key minerals,
<https://www.africaoilandpower.com/2020/08/27/drc-announces-extension-on-export-ban-moratorium-for-key-minerals/>

Argonne National Laboratory (2020), *BatPaC Model Software*,
<https://www.anl.gov/cse/batpac-model-software>

Balaram, V. (2019), Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact, *Geoscience Frontiers*, 10,
<https://doi.org/10.1016/j.gsf.2018.12.005>

BHP (2011), *BHP Billiton Site Tour Presentation*, BHP, Melbourne, Australia.

Bio by Deloitte (2014), *Development of Guidance on Extended Producer Responsibility (EPR)*, European Commission,
https://ec.europa.eu/environment/archives/waste/eu_guidance/pdf/report.pdf

BloombergNEF (2020a), *Global Nickel Outlook 2020-2030*.

BloombergNEF (2020b), *Critical Minerals Primer: Rare Earths*.

BloombergNEF (2019), *Lithium-Ion Battery Recycling_ 2 Million Tons by 2030*.

China Briefing (2021), *China Tightens Control Over Management of Rare Earths*, <https://www.china-briefing.com/news/china-tightens-control-over-management-of-rare-earths/>

CSIS (Center for Strategic and International Studies) (2021), *The Geopolitics of Critical Minerals Supply Chains*, <https://www.csis.org/analysis/geopolitics-critical-minerals-supply-chains>

COCHILCO (Comisión Chilena del Cobre / Chilean Copper Commission) (2020), *YEARBOOK: COPPER AND OTHER MINERAL STATISTICS 2000-2019*, https://www.cochilco.cl/_layouts/download.aspx?SourceUrl=/Lists/Anuario/Attachments/23/Anuario%20Final%202019%20-%202014ago2020.xlsx

COCHILCO (2018), *Regulations and Social Receptivity about Impurities in Copper Raw Material Chilean situation at 2018*, <http://www.iogmec.go.jp/content/300358431.pdf>

CRU (2020a), *Water - a major disrupter to copper supply*, <https://www.crugroup.com/knowledge-and-insights/insights/2020/water-a-major-disrupter-to-copper-supply>

CRU (2020b), *The Rare Earths “Basket Problem” is Intensifying*, The 2020 Tech Metals Edition of The Assay, The Assay, Hong Kong.

DG Trade (Directorate General for Trade of the European Commission) (2021), *EU files WTO panel request against illegal export restrictions by Indonesia on raw materials for stainless steel*, https://ec.europa.eu/commission/presscorner/detail/en/IP_21_105

DISER (Department of Industry, Science, Energy and Resources, Australian Government) (2021), *Resources Technology and Critical Minerals Processing National Manufacturing Priority road map*, <https://www.industry.gov.au/data-and-publications/resources-technology-and-critical-minerals-processing-national-manufacturing-priority-road-map>

EURACTIV (2020), *EU to push new standards for ‘greenest’ car batteries on earth*, <https://www.euractiv.com/section/energy-environment/news/eu-to-push-new-standards-for-greenest-car-batteries-on-earth/>

Eurometaux (2019), *Metals for a Climate Neutral Europe: A 2050 Blueprint*, <https://eurometaux.eu/media/2005/full-report-8-56-17.pdf>

European Commission (2020a), *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, <https://ec.europa.eu/docsroom/documents/42849>

European Commission (2020b), Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798>

EUROSTAT (2020), Waste statistics – recycling of batteries and accumulators, https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_recycling_of_batteries_and_accumulators#Recycling_of_batteries_and_accumulators

Foreign Policy (2019), *Mining The Future: How China is set to Dominate the Next Industrial Revolution*, <https://foreignpolicy.com/2019/05/01/mining-the-future-china-critical-minerals-metals/>

Forsén, O. et al. (2017), Primary Copper Smelter and Refinery as a Recycling Plant: A System Integrated Approach to Estimate Secondary Raw Material Tolerance, *Recycling*, 2(4), 19, <https://doi.org/10.3390/recycling2040019>

Gaines, L. et al. (2018), Key issues for Li-ion battery recycling, *MRS Energy & Sustainability*, 5, E14, <https://doi.org/10.1557/mre.2018.13>.

Grant (2019), *Lithium (Extraction Technology) in 2025*, <https://static1.squarespace.com/static/5c9aa323c46f6d499a2ac1c5/t/5e4548755e51623210e6da82/1581598838742/Lithium+%28Extraction+Technology%29+in+2025.pdf>

Harper, G. et al. (2019), Recycling lithium-ion batteries from electric vehicles, *Nature*, 575, <https://doi.org/10.1038/s41586-019-1682-5>

Hatayama, H. and Tahara, K. (2018), Adopting an objective approach to criticality assessment: Learning from the past, *Resources Policy*, 55, <https://doi.org/10.1016/j.resourpol.2017.11.002>

Hawker, W. et al. (2014), A synergistic hydro- and pyro-metallurgical process for low-energy copper production, https://www.researchgate.net/publication/290998079_A_synergistic_hydro-_and_pyro-metallurgical_process_for_low-energy_copper_production

Heffernan, O. (2019), Deep-sea dilemma: Mining the ocean floor could solve mineral shortages – and lead to epic extinctions in some of the most remote ecosystems on Earth, *Nature*, 571, <https://media.nature.com/original/magazine-assets/d41586-019-02242-y/d41586-019-02242-y.pdf>

Henckens, M. L. and E. Worrell (2020), Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates, *Journal of Cleaner Production*, 264, 121460, <https://doi.org/10.1016/j.jclepro.2020.121460>

Henckens (2021), Scarce mineral resources: Extraction, consumption and limits of sustainability, *Resources, Conservation and Recycling*, Volume 169, <https://doi.org/10.1016/j.resconrec.2021.105511>

IAI (International Aluminium Institute) (2020), *Aluminium Recycling*, https://www.world-aluminium.org/media/filer_public/2020/10/20/wa_factsheet_final.pdf

IEA (International Energy Agency) (2020), *CO₂ Emissions from Fuel Combustion: Overview*, <https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview>

IRENA (International Renewable Energy Agency) (2019), *A New World: The Geopolitics of the Energy Transformation*, <https://www.irena.org/publications/2019/Jan/A-New-World-The-Geopolitics-of-the-Energy-Transformation>

IRP (International Resource Panel) (2020), *Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development*, United Nations Environment Programme, <https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century>

IUPAC (International Union of Pure and Applied Chemistry) (2005), *Nomenclature of Inorganic Chemistry, IUPAC Recommendations 2005*, https://iupac.org/wp-content/uploads/2016/07/Red_Book_2005.pdf

JOGMEC (Japan Oil, Gas and Metals National Corporation) (2020), *Final Report of Analysis on Rare Earth Supply Chains in North America*, http://mric.jogmec.go.jp/wp-content/uploads/2020/05/ree_supply_northamerica20200228.pdf

JOGMEC (2019a), Summary of lithium production technology – current situation and future outlook, *JOGMEC Mineral Resource Report*, 19-03 (48), http://mric.jogmec.go.jp/wp-content/uploads/2019/03/mr201903_03.pdf.

JOGMEC (2019b), Trends of cobalt production technology, *JOGMEC Mineral Resource Report*, 19-05 (49), http://mric.jogmec.go.jp/wp-content/uploads/2019/04/mr201904_05.pdf

Kumar, A. et al. (2019), Lithium Recovery from Oil and Gas Produced Water: A Need for a Growing Energy Industry, *ACS Energy Lett.* 2019, 4, 6, <https://doi.org/10.1021/acsenergylett.9b00779>

Lee, J. et al. (2020), Reviewing the material and metal security of low-carbon energy transitions, *Renewable and Sustainable Energy Reviews*, Volume 124, <https://doi.org/10.1016/j.rser.2020.109789>

Liu, W. et al. (2019), Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile, *International Journal of Applied Earth Observation and Geoinformation*, 80, <https://doi.org/10.1016/j.jag.2019.04.016>

Lutsey, N. and D. Hall (2018), Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions, https://www.researchgate.net/publication/323118874_Effects_of_battery_manufacturing_on_electric_vehicle_life-cycle_greenhouse_gas_emissions

Manuel (2017), Taconite dreams: The Struggle to Sustain Mining on Minnesota's Iron Range, 1915-2000, *Environmental History*, Volume 22, Issue 1, January 2017,

Messner (2002), Material substitution and path dependence: Empirical evidence on the substitution of copper for aluminium, *Ecological Economics*, Volume 42, Issues 1–2, August 2002,

METI (Ministry of Economy, Trade and Industry, Japan) (2017), World's First Success in Continuous Ore Lifting test for Seafloor Polymetallic Sulphides, METI, Tokyo, https://www.meti.go.jp/english/press/2017/0926_004.html

Mining Technology (2020), Trafigura announces end of artisanal cobalt formalisation project in Congo, <https://www.mining-technology.com/news/trafigura-announces-end-of-artisanal-cobalt-formalisation-project>

Ministry of Industry and Information Technology et al. (2018), *Provisional Regulation on the Recycling and Reuse of Traction Batteries from New Energy Vehicles (NEVs)*, http://www.xinhuanet.com/english/2018-02/27/c_137001646.htm

Nicolli, F., Johnstone, F. and Söderholm, P. (2012), Resolving failures in recycling markets: The role of technological innovation. *Environmental Economics and Policy Studies*, 14, <https://doi.org/10.1007/s10018-012-0031-9>

Northvolt (2019), Revolt: The technologies paving the way for Li-ion battery recycling, <https://northvolt.com/stories/RevoltTechnologies>

NRCAN (Natural Resources Canada) (2020), Rare earth elements facts, <https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/rare-earth-elements-facts/20522>

OECD (2014), *Creating Incentives for Greener Products Policy Manual for the Eastern Partnership Countries*, <https://www.oecd.org/environment/outreach/Creating%20Incentives%20for%20Greener%20Products.pdf>

Peelman, S. et al. (2016), Hydrometallurgical Extraction of Rare Earth Elements from Low Grade Mine Tailings, *Rare Metal Technology 2016*, Springer, Cham, https://doi.org/10.1007/978-3-319-48135-7_2

Reuters (2021a), China rare earths extend surge on worries over Myanmar supply, inspection threat,

<https://www.reuters.com/article/us-china-rare-earths-myanmar-idUSKBN2BI1HR>

Reuters (2021b), Indonesia stays China's second-biggest nickel ore supplier despite export ban, <https://www.reuters.com/article/china-economy-trade-nickel-idUSL4N2JP36N>

Roskill (2021a), Nickel: Tsingshan to disrupt the nickel market again? <https://roskill.com/news/nickel-tsingshan-to-disrupt-the-nickel-market-again>

Roskill (2021b), Cobalt, sustainability: DRC launches monopoly over cobalt ASM to improve ESG credentials, <https://roskill.com/news/cobalt-sustainability-drc-launches-monopoly-over-cobalt-asm-to-improve-esg-credentials>

Rötzer, N. and Schmidt, M. (2018), Decreasing Metal Ore Grades: Is the Fear of Resource Depletion Justified? *Resources*, 7, 88.

Rüttinger et al. (2020), *Impacts of climate change on mining, related environmental risks and raw material supply*, <https://www.umweltbundesamt.de/en/publikationen/impacts-of-climate-change-on-mining-related>

S&P Global (2021), *S&P Global Market Intelligence Platform* (database), accessed multiple times in November 2020 - March 2021.

S&P Global (2020), Top mines average time from discovery to production: 16.9 years, S&P Global, New York.

S&P Global (2019a), Lithium supply is set to triple by 2025. Will it be enough? <https://www.spglobal.com/en/research-insights/articles/lithium-supply-is-set-to-triple-by-2025-will-it-be-enough>

S&P Global (2019b), ESG industry report card: Metals and mining, https://www.spglobal.com/_media/documents/spglobalratings_esgin_dustryreportcardmetalsandmining_jun_03_2019-003-.pdf

SAE International (2016), Automotive Battery Recycling Identification and Cross-Contamination Prevention, J3071_201604.

Schippers A. et al. (2014), Biomining: Metal recovery from ores with microorganisms. *Adv Biochem Eng Biotechnol.*, 141:1-47, https://doi.org/10.1007/10_2013_216

Schodde, R. (2017), Time delay between discovery and development – is it getting more difficult?, <https://minexconsulting.com/wp-content/uploads/2019/04/China-Mining-R-Schodde-Sept-2017.pdf>

Seabra, D. and Caldeira-Pires, A. (2020), Destruction mitigation of thermodynamic rarity by metal recycling. *Ecological Indicators*, 119, <https://doi.org/10.1016/j.ecolind.2020.106824>

Söderholm, P. and Ekvall, T., (2020), Metal markets and recycling policies: Impacts and challenges, *Mineral Economics*, 33, <https://doi.org/10.1007/s13563-019-00184-5>

Spooren, J. et al. (2020), Near-zero-waste processing of low-grade, complex primary ores and secondary raw materials in Europe: Technology development trends, *Resources, Conservation and Recycling*, 160, <https://doi.org/10.1016/j.resconrec.2020.104919>

STRADE (Strategic Dialogue on Sustainable Raw Materials for Europe) (2018), *Non-European Country Engagement with Resource-Rich Developing Countries*, http://stradeproject.eu/fileadmin/user_upload/pdf/STRADE_Report_01_2018_Third_Country_Approaches_Min_Dev_Res_Rich.pdf

Swedish Energy Agency (2019), State-of-the-art in reuse and recycling of lithium-ion batteries – A research review, <http://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf>

The West Australian (2021), Rio Tinto reveals \$14.5m pilot plan to tap US waste rock for lithium riches, <https://thewest.com.au/business/mining/rio-tinto-reveals-145m-pilot-plan-to-tap-us-waste-rock-for-lithium-riches-ng-b881359859z>

Umicore (2018), BMW Group, Northvolt and Umicore join forces to develop sustainable life cycle loop for batteries, [https://www.umicore.com/en/newsroom/news/bmw-group-northvolt-](https://www.umicore.com/en/newsroom/news/bmw-group-northvolt-and-umicore-join-forces-to-develop-sustainable-life-cycle-loop-for-batteries/)

[and-umicore-join-forces-to-develop-sustainable-life-cycle-loop-for-batteries/](https://www.umicore.com/en/newsroom/news/bmw-group-northvolt-and-umicore-join-forces-to-develop-sustainable-life-cycle-loop-for-batteries/)

UNCTAD (United Nations Conference on Trade and Development) (2017), Using trade policy to drive value addition: Lessons from Indonesia's ban on nickel exports, https://unctad.org/system/files/non-official-document/suc2017d8_en.pdf

UNEP (United Nations Environment Programme) (2011), *Recycling Rates of Metals – A Status Report*, <https://www.resourcepanel.org/reports/recycling-rates-metals>

UNEP (2013), Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel, <https://www.resourcepanel.org/reports/metal-recycling>

USABC (US Advanced Battery Consortium) (2014), Recommended practice for recycling of xEV electrochemical energy storage systems, <http://www.uscar.org/guest/teams/12/U-S-Advanced-Battery-Consortium-LLC>.

USGS (United States Geological Survey) (2021), *Mineral Commodity Summaries 2021*, USGS, Boulder, Colorado.

USGS (2020), *Mineral Commodity Summaries 2020*, USGS, Boulder, Colorado.

USGS (2013), *Metal Prices in the United States Through 2010*, USGS, Boulder, Colorado, <https://pubs.usgs.gov/sir/2012/5188>

WEF (World Economic Forum) (2020), The Global Battery Alliance Battery Passport: Giving an identity to the EV's most important component, http://www3.weforum.org/docs/WEF_GBA_Battery_Passport_Overview_2021.pdf

World Bank (2020), *Worldwide Governance Indicators*, accessed in April 2021, <https://info.worldbank.org/governance/wgi>

World Bureau of Metal Statistics (2020), *World Metal Statistics Yearbook 2020*, Herts, United Kingdom.

WRI (World Resources Institute) (2019), *Aqueduct 3.0 dataset*, accessed in March 2021, <https://www.wri.org/publication/aqueduct-30>

WTO (World Trade Organization) (2015), *DS431: China — Measures Related to the Exportation of Rare Earths, Tungsten and Molybdenum*, https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds431_e.htm

WWF (World Wide Fund for Nature) (2021), Brands Back Call for Moratorium on Deep Seabed Mining, https://www.panda.org/wwf_news/press_releases/?1909966/Brands-Back-Call-for-Moratorium-on-Deep-Seabed-Mining

Zhang, R. et al. (2020), Bioleaching of cobalt from Cu/Co-rich sulfidic mine tailings from the polymetallic Rammelsberg mine, Germany, *Hydrometallurgy*, 197, <https://doi.org/10.1016/j.hydromet.2020.105443>

Chapter 4: Sustainable and responsible development of minerals

Accenture (2019), *Intelligent Technologies for Tailings Management* (web page), <https://www.accenture.com/us-en/blogs/chemicals-and-natural-resources-blog/intelligent-technologies-for-tailings-management>

Amnesty International (2016), *This is what we die for: Human Rights Abuses in the Democratic Republic of the Congo Power the Global Trade in Cobalt*, <https://www.amnesty.org/en/documents/afr62/3183/2016/en/>

Anglo American (2019), *Anglo American Partners ENGIE to Develop World's Largest Hydrogen-powered Mine Truck* (web page), <https://www.angloamerican.com/media/press-releases/2019/10-10-2019>

Argonne National Laboratory (2020), *GREET 2020*, <https://greet.es.anl.gov/>

Argonne National Laboratory (2019), *GREET 2019*, <https://greet.es.anl.gov/>

Australia Minerals (2021), *Mineral Resources Information*,
<http://www.australiaminerals.gov.au/mineral-resources-information>

Azadi, M. et al. (2020), Transparency on greenhouse gas emissions from mining to enable climate change mitigation, *Nature Geoscience*, 13(2), 100–104, <https://doi.org/10.1038/s41561-020-0531-3>

BBC (2019), Brazil's dam disaster: Looking for bodies, looking for answers, https://www.bbc.co.uk/news/resources/idx-sh/brazil_dam_disaster

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe / Federal Institute for Geosciences and Natural Resources) (2019), Mapping of the Artisanal Copper-Cobalt Mining Sector in the Provinces of Haut-Katanga and Lualaba in the Democratic Republic of the Congo,
http://congominer.org/system/attachments/assets/000/001/659/original/BGR_%282019%29_Mapping_of_the_DRC_artisanal_copper-cobalt_sector_engl-min.pdf?1570629800

BHP (2020), *Climate Change 2020: Carbon Disclosure Project*, p. 51. https://www.bhp.com/-/media/documents/environment/2020/200928_bhpcdpresponsecclimatechange2020.pdf?la=en

BloombergNEF (2020), *Defining Sustainable Nickel for an EV Future*.

Bronckers M., Gruni G. (2021), Retooling the sustainability standards in EU free trade agreements, *Journal of International Economic Law*,
<https://academic.oup.com/jiel/article/24/1/25/6146679>

Campbell, R. et al. (2017), *Dark Side of the Boom: What we Do and Don't Know about Mines, Closures and Rehabilitation*, Australia Institute, Canberra, <https://australiainstitute.org.au/wp-content/uploads/2020/12/P192-Dark-side-of-the-boom-web.pdf>

Carmo, F. F. do et al. (2017), Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context, *Perspectives in Ecology and Conservation*, <https://doi.org/10.1016/j.pecon.2017.06.002>

CCSI (Columbia Center on Sustainable Investment) (2018), *The Renewable Power of the Mine – Accelerating Renewable Energy Intergration*, <http://ccsi.columbia.edu/files/2018/12/3418-CCSI-RE-and-mining-report-09-lr-reduced-optimized-07-no-links.pdf>

Church of England (2020), *Investor Mining and Tailings Safety Initiative* (web page),
<https://www.churchofengland.org/about/leadership-and-governance/church-england-pensions-board/old-pensions-board-investments-0>

Cochilco (Comisión Chilena del Cobre / Chilean Copper Commission) (2020), *Yearbook: Copper and Other Mineral Statistics 2000-2019*,

<https://www.cochilco.cl/layouts/download.aspx?SourceUrl=/Lists/Anuario/Attachments/23/Anuario%20Final%202019%20-%202014ago2020.xlsx>

Copper Alliance (2021), *Best Practices: Copper Mining, Water and the United Nations' SDGs*, <https://sustainablecopper.org/best-practices/copper-mining-water-and-the-united-nations-sdgs>

Cornwall, W. (2020), Catastrophic failures raise alarm about dams containing muddy mine wastes, *Science*, <http://doi:10.1126/science.abe3917>

Davies, R. et al. (2020), Lessons in climate risk reporting on the path to mandatory disclosure: A marathon, not a sprint (blog post), <https://www.dlapiper.com/fr/france/insights/publications/2020/12/lessons-climate-risk-mandatory-disclosure/>

Dong, D. et al. (2020), Assessing the future environmental impacts of copper production in China: Implications of the energy transition *Journal of Cleaner Production*, 274 (November 2020), 1–24, <https://doi.org/10.1016/j.jclepro.2020.122825>

Donoso, G. (2018), Overall assessment of Chile's water policy and its challenges, *Water Policy in Chile* (pp. 209-219), Springer, Cham.

Donoso, G., E. Lictevout and J. D. Rinaudo (2020), Groundwater management lessons from Chile, *Sustainable Groundwater Management* (pp. 481-509), Springer, Cham.

EC JRC (Joint Research Center) (2018), Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries in accordance with Directive 2006/21/EC, <http://doi:10.2760/35297>

EGC (Entreprise Générale du Cobalt / General Cobalt Company) (2021), *EGC Responsible Sourcing Standard*, https://www.trafigura.com/media/3098/2021_trafigura_egc_responsible_sourcing_standards_english.pdf

EITI (Extractives Industries Transparency Initiative) (2020a), *Progress Report*, https://eiti.org/files/documents/eiti_progress_report_2020_english.pdf

EITI (2020b), *Board Decision on the Second Validation of Madagascar*, [https://eiti.org/scorecard-pdf?filter\[country\]=33&filter\[year\]=2019](https://eiti.org/scorecard-pdf?filter[country]=33&filter[year]=2019)

EITI (2018), *Establishment and Governance of Multi-stakeholder Groups: Guidance Note 14 – Requirement 1.4*, https://eiti.org/files/documents/guidance_note_14_on_establishment_and_governance_of_msgs.pdf

Energy Storage News (2020), European partnership targets 'zero carbon lithium' extraction in Germany, Energy Storage News, <https://www.energy-storage.news/news/european-partnership-targets-zero-carbon-lithium-extraction-in-germany>

Eurometaux (2019), *Metals for a Climate Neutral Europe: A 2050 Blueprint*, <https://eurometaux.eu/media/2005/full-report-8-56-17.pdf>

European Commission (2020), *Sustainable Development* (web page), <https://ec.europa.eu/trade/policy/policy-making/sustainable-development/>

European Parliament (2021), *Corporate Due Diligence and Corporate Accountability*, P9_TA(2021)0073, https://www.europarl.europa.eu/doceo/document/TA-9-2021-0073_EN.html

Eurostat (2021), *Generation of Waste by Waste Category, Hazardousness and NACE Rev. 2 Activity [ENV_WASGEN]* (database), https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN/default/table, (accessed 23 February 2021).

EY (Ernst & Young) (2019), *Rapport de Reconciliation 2018: EITI-Madagascar (Reconciliation Report 2018: EITI-Madagascar)*, https://eiti.org/files/documents/eiti_2018_-_rapport_final_du_13122019.pdf

Faber, B. et al. (2017), *Artisanal Mining, Livelihoods, and Child Labor in the Cobalt Supply Chain of the Democratic Republic of Congo*, Center for Effective Global Action, https://cega.berkeley.edu/assets/cega_research_projects/179/CEG A_Report_v2.pdf

Farjana, S. H., N. Huda and M. A. P. Mahmud (2019), Life cycle assessment of cobalt extraction process, *Journal of Sustainable Mining*, 18(3), 150–161, <https://doi.org/10.1016/j.jsm.2019.03.002>

Fernandes, G. W. et al. (2016), Deep into the mud: Ecological and socio-economic impacts of the dam breach in Mariana, Brazil, *Natureza & Conservação*, No 14, 35-45, <https://doi.org/10.1016/j.ncon.2016.10.003>

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH / German Corporation for International Cooperation) (2020), *Sexual and Gender-Based Violence in the Mining Sector in Africa*, <https://www.kit.nl/wp-content/uploads/2020/09/SGBV-in-the-Mining-Sector-in-Africa.pdf>

GIZ (2016), *Assessing the Effectiveness and Impact of the Extractive Industries Transparency Initiative*, https://eiti.org/files/documents/eiti_impact_study_giz_2016.pdf

Glencore (2019), *Sustainability Report 2019*, <https://www.glencore.com/dam/jcr:31236b6f-34a4-432a-b4b3-6fe133488bb8/2019-Glencore-Sustainability-Report-.pdf>

Government of Canada (2021a), *A Healthy Environment and a Healthy Economy, Annex: Pricing Carbon Pollution*, <https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/healthy-environment-healthy-economy/annex-pricing-carbon-pollution.html>

Government of Canada (2021b), *Canada Sets a World Standard for Sustainable Mining* (web page),

<https://www.tradecommissioner.gc.ca/canadexport/0003604.aspx?lang=eng>

Government of Canada (2020), *Regulatory Impact Analysis Statement*, Canada Gazette, Part I, Volume 154, Number 51: Clean Fuel Regulations, <https://canadagazette.gc.ca/rp-pr/p1/2020/2020-12-19/html/reg2-eng.html>

Government of Canada (2019), *Output-Based Pricing System Regulations: SOR/2019-266*, Canada Gazette, Part II, Volume 153, Number 14, <https://canadagazette.gc.ca/rp-pr/p2/2019/2019-07-10/html/sor-dors266-eng.html>

Gunson, A. et al. (2012), Reducing mine water requirements, *Journal of Cleaner Production* 21, 71–82, <https://doi.org/10.1016/j.jclepro.2011.08.020>

Gutierrez, M. (2020), Editorial for Special Issue “Sustainable use of abandoned mines”, *Minerals* 10, no. 11: 1015. <https://doi.org/10.3390/min10111015>

Holland, M. (2019), *Reducing the Health Risks of Copper, Rare Earth and Cobalt Industries: The Transition to a Low-carbon Economy*, OECD 2019 GGSD Forum: Greening heavy and extractive industries, [https://www.oecd.org/greengrowth/Reducing%20the%20health%20r](https://www.oecd.org/greengrowth/Reducing%20the%20health%20risks%20of%20the%20copper,%20rare%20earth%20and%20cobalt%20industries.pdf)

[isks%20of%20the%20copper,%20rare%20earth%20and%20cobalt%20industries.pdf](https://www.oecd.org/greengrowth/Reducing%20the%20health%20risks%20of%20the%20copper,%20rare%20earth%20and%20cobalt%20industries.pdf)

Hong, J. et al. (2018), Life cycle assessment of copper production: a case study in China, *International Journal of Life Cycle Assessment*, 23(9), 1814–1824. <https://doi.org/10.1007/s11367-017-1405-9>

IEA (International Energy Agency) (2020a), *Global Electric Vehicle Outlook 2020*, <https://www.iea.org/reports/global-ev-outlook-2020>

IEA (2020b), *World Energy Outlook 2020*, <https://www.iea.org/reports/world-energy-outlook-2020>

IEA (2020c), *Iron and Steel Technology Roadmap*, <https://www.iea.org/reports/iron-and-steel-technology-roadmap>

IEA (2020d), *Gender Diversity in Energy: What We Know and What We Don't Know*, <https://www.iea.org/commentaries/gender-diversity-in-energy-what-we-know-and-what-we-dont-know>

IAEA (International Atomic Energy Agency) (2005), *Naturally Occurring Radioactive Materials (NORM IV)*, Proceedings of an international conference held in Szczyrk, Poland, 17-21 May 2004, IAEA, VIENNA, <https://www.iaea.org/publications/7384/naturally-occurring-radioactive-materials-norm-iv-proceedings-of-an-international-conference-held-in-szczyrk-poland-17-21-may-2004>

IBAMA (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis / Brazilian Institute of the Environment and

Renewable Natural Resources) (2016), *Projeto Carajás S11D, no Pará, recebe Licença de Operação (Carajás S11D Project, in Pará, receives License to Operate)* (web page), <http://www.ibama.gov.br/noticias/58-2016/768-projeto-carajas-s11d-no-para-recebe-licenca-de-operacao-do-ibama>

ICAP (International Carbon Action Partnership) (2021), *Chile, ETS Detailed Information*, [https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems\[\]=54#:~:text=In%20this%20content%2C%20a%20carbon,to%20combustion%20processes%20per%20year.](https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems[]=54#:~:text=In%20this%20content%2C%20a%20carbon,to%20combustion%20processes%20per%20year.)

IGF (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development) (2019), *Background Document: Legal Framework of Environmental and Social Impact Assessment in the Mining*, International Institute for Sustainable Development, <https://www.iisd.org/system/files/publications/igf-esia-background-en.pdf?q=sites/default/files/publications/igf-esia-background-en.pdf>

IGF (2018a), *State of Sustainability Initiatives, Standards and the Extractive Economy*, International Institute for Sustainable Development, <https://www.iisd.org/system/files/publications/igf-ssi-review-extractive-economy.pdf>

IGF (2018b). *Zambia: Upstream Linkages*, International Institute for Sustainable Development,

<https://www.iisd.org/sites/default/files/publications/case-study-zambia-upstream-linkages.pdf>

IGF (2018c), *Chile: Horizontal Linkages*, International Institute for Sustainable Development, <https://www.iisd.org/sites/default/files/publications/case-study-chile-horizontal-linkages.pdf>

IGF (2018d), *Women in Artisanal and Small-Scale Mining: Challenges and Opportunities for Greater Participation*, International Institute for Sustainable Development, <https://www.iisd.org/system/files/publications/igf-women-asm-challenges-opportunities-participation.pdf>

IGF (2017), *Guidance for Governments: Managing Artisanal and Small-scale Mining*, International Institute for Sustainable Development, https://www.iisd.org/system/files/publications/igf-guidance-for-governments-asm_0.pdf

ILO (International Labour Organization) (2019), *Child Labour in Mining and Global Supply Chains*, https://www.ilo.org/manila/publications/WCMS_720743/lang-en/index.htm

IMPACT (2018), *Best Practices: Formalization and Due Diligence in Artisanal and Small-scale Mining*, https://media.africaportal.org/documents/IMPACT_ASM-Best-Practices_May-2018-EN-web.pdf

IRP (International Resource Panel) (2020). *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development*, United Nations Environment Programme, p.131, <https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century>

Jiang, S. et al. (2020), Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment, *Journal of Environmental Management*, 262 (January), 110253, <https://doi.org/10.1016/j.jenvman.2020.110253>

Jucá, B. (2019), Responsável por fiscalizar barragens, anm já admitiu falta de verba para vistorias ‘in loco’ (Responsible for dams’ inspections, anm has already admitted lack of funds for ‘in loco’ verifications), https://brasil.elpais.com/brasil/2019/02/07/politica/1549559820_961591.html

Kelly, J.C., Dai, Q. and Wang, M. (2020) Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change* 25, 371–396. <https://doi.org/10.1007/s11027-019-09869-2>

Kobayashi, H., H. Watando and M. Kakimoto (2014), A global extent site-level analysis of land cover and protected area overlap with mining activities as an indicator of biodiversity pressure, *Journal of Cleaner Production*, 84(1), 459–468, <https://doi.org/10.1016/j.jclepro.2014.04.049>

Kossof, D. et al. (2014), Mine tailings dams: Characteristics, failure, environmental impacts, and remediation, 51 *Applied Geochemistry* 229-245, <https://doi.org/10.1016/j.apgeochem.2014.09.010>

Korinek, J. and Ramdoo, I. (2017), Local content policies in mineral-exporting countries, *OECD Trade Policy Papers*, No. 209, OECD Publishing, Paris, <https://doi.org/10.1787/18166873>

Lebdioui, A. et al. (2020), Local-foreign technology interface, resource-based development and industrial policy: how Chile and Malaysia are escaping the middle-income trap, *Journal of Technology Transfer*, <https://doi.org/10.1007/s10961-020-09808-3>

Lèbre, É. and G. Corder, (2015), Integrating industrial ecology thinking into the management of mining waste, *Resources*, 4(4), 765–786, <https://doi.org/10.3390/resources4040765>

Lee et al. (2020), Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains, *Environmental Research Letters*, 15 103009, <https://iopscience.iop.org/article/10.1088/1748-9326/ab9f8c/pdf>

Leonida C. (2020), How to make filtered tailings feasible, *Engineering and Mining Journal*, <https://www.emj.com/features/how-to-make-filtered-tailings-feasible/>

Lindstedt, C., and D. Naurin (2010), Transparency is not enough: Making transparency effective in reducing corruption, *International Political Science Review*, no. 31, 301-322.

LME (London Metal Exchange) (2020), *General Updates 20/194, Discussion Paper on LME Passport*, <https://www.lme.com/-/media/Files/News/Notices/2020/08/GENERAL-UPDATES-20-194-Discussion-Paper-on-LMEpassport.pdf>

LME (2019), *LME Responsible Sourcing Requirements – Summary, Fact Sheet*, <https://www.lme.com/-/media/Files/About/Responsibility/Responsible-Sourcing/LME-responsible-sourcing-factsheet.pdf>

Lutter S. and S. Giljum (2019), *FINEPRINT Brief No. 9, December 2019, Copper Production in Chile Requires 500 Million Cubic Metres of Water*, <https://www.fineprint.global/publications/briefs/chile-copper-water/>

Marx, J. et al. (2018), Comparative life cycle assessment of NdFeB permanent magnet production from different rare earth deposits, *ACS Sustainable Chemistry and Engineering*, 6(5), 5858–5867, <https://doi.org/10.1021/acssuschemeng.7b04165>

McKinsey (2020), *Climate risk and decarbonization: What every mining ceo needs to know*, <https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know>

Memary, R. et al. (2012), Life cycle assessment: A time-series analysis of copper, *Journal of Cleaner Production*, 33, 97–108, <https://doi.org/10.1016/j.jclepro.2012.04.025>

Miller, K. A. et al. (2018), An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps, *Frontiers in Marine Science*, 4 (JAN), <https://doi.org/10.3389/fmars.2017.00418>

Mudd, G. M. and Jowitt S. M. (2016), *From Mineral Resources to Sustainable Mining – the Key Trends to Unlock the Holy Grail?*, Proceedings of the 3rd AusIMM International Geometallurgy Conference, Australasian Institute of Mining and Metallurgy, Perth, Australia, 15-16 June 2016, p. 18.

Murakami, S. et al. (2020), Ecological footprint and total material requirement as environmental indicators of mining activities: Case studies of copper mines, *Environmental and Sustainability Indicators*, 8 (October), 100082, <https://doi.org/10.1016/j.indic.2020.100082>

Navarro, L. (2017), The World Class Supplier Program for mining in Chile: Assessment and perspectives, *Resources Policy* 58, 49-61, <https://doi.org/10.1016/j.resourpol.2017.10.008>

Northey, S. A. et al. (2014), Evaluating the application of water footprint methods to primary metal production systems, *Minerals Engineering*, 69, 65–80, <http://doi:10.1016/j.mineng.2014.07.006>

NRCAN (Natural Resources Canada) (2021), *Glencore RAGLAN Mine Renewable Electricity Smart-Grid Pilot Demonstration* (web page), <https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/glencore->

[raglan-mine-renewable-electricity-smart-grid-pilot-demonstration/16662](#)

NRCan (2020), *Lands and Minerals Sector – Indigenous Mining Agreements* (interactive map and database), <https://atlas.gc.ca/imaema/en/index.html>, (accessed 12 April 2021).

NRCan (2016), *CanmetMINING Research Plan 2016–2021: Green Mining Initiative*, https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/mining-materials/PDF/CanmetMINING_research_plan_document_access_e.pdf

Nuss, P. and M. J. Eckelman (2014), Life cycle assessment of metals: A scientific synthesis, *PLoS ONE*, 9(7), 1–12, <https://doi.org/10.1371/journal.pone.0101298>

OECD (Organisation for Economic Co-operation and Development) (2021a), *How to Address Bribery and Corruption Risks in Mineral supply chains*, <https://mneguidelines.oecd.org/faq-how-to-address-bribery-and-corruption-risks-in-mineral-supply-chains.pdf>.

OECD (2021b), *An International Standard: OECD Due Diligence Guidance for Responsible Mineral Supply Chains*, <http://mneguidelines.oecd.org/an-international-standard-oecd-due-diligence-guidance-for-responsible-mineral-supply-chains.htm>

OECD (2019a), *Mining and Green Growth in the EECCA Region*, <https://doi.org/10.1787/1926a45a-en>

OECD (2019b), *Trade Policy Brief: Local Content Requirements*, https://issuu.com/oecd.publishing/docs/local_content_requirements

OECD (2019c), *Interconnected Supply Chains: A Comprehensive Look at Due Diligence Challenges and Opportunities Sourcing Cobalt and Copper from the Democratic Republic of the Congo*, <https://mneguidelines.oecd.org/Interconnected-supply-chains-a-comprehensive-look-at-due-diligence-challenges-and-opportunities-sourcing-cobalt-and-copper-from-the-DRC.pdf>

OECD (2018), *Alignment Assessment of Industry Programmes with the OECD Minerals Guidance*, <http://mneguidelines.oecd.org/Alignment-assessment-of-industry-programmes-with-the-OECD-minerals-guidance.pdf>

OECD (2016), *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas: Third Edition*. <http://dx.doi.org/10.1787/9789264252479-en>

OECD (2014), *Foreign Bribery Report: An Analysis of the Crime of Bribery of Foreign Public Officials*, <https://www.oecd-ilibrary.org/docserver/9789264226616-en.pdf>

Opitz, J. and W. Timms (2016), *Mine water discharge quality – a review of classification frameworks*, Proceedings of the International Mine Water Association, IMWA 2016, Iied 2002, 17–26, https://www.imwa.info/docs/imwa_2016/IMWA2016_Opitz_58.pdf

Otto, J. (2018), How do we legislate for improved community development in extractive industries, *The management of resources as a driver of sustainable development*, Oxford University Press, <https://oxford.universitypressscholarship.com/view/10.1093/oso/9780198817369.001.0001/oso-9780198817369-chapter-32>

Pan, Y. and H. Li (2016), Investigating heavy metal pollution in mining brownfield and its policy implications: A case study of the bayan obo rare earth mine, Inner Mongolia, China, *Environmental Management*, 57(4), 879–893. <http://doi:10.1007/s00267-016-0658-6>

Ramdoo, I. (2016), Local content, trade and investment: Is there policy space left for linkages development in resource-rich countries? (Discussion Paper. No. 205), ECDPM, <http://ecdpm.org/publications/local-content-trade-investment/>

RCS Global Group (2019), *Saving the EV revolution: better mining*, <https://www.rcsglobal.com/pdfs/20191810%20RCS%20Global%20Group%20Better%20Mining%20Saving%20EVs%20Report%20Public.pdf>

RMF (Responsible Mining Foundation) and CCSI (Columbia Center on Sustainable Investment) (2020), *Mining and the SDGs: a 2020 status update*, https://www.responsibleminingfoundation.org/app/uploads/RMF_CCSI_Mining_and_SDGs_EN_Sept2020.pdf

RMF (2020a), *RMI Report 2020*, <https://2020.responsibleminingindex.org/en>

RMF (2020b), *Gender Inequality Runs Deep in Mining*, <https://www.responsibleminingfoundation.org/research/gender2020/>

Reuters (2020a), Trafigura's Congo artisanal cobalt project to end, replaced by industrial mining, <https://www.reuters.com/article/us-congo-mining-idUSKBN28R348>

Reuters (2020b), Huayou temporarily suspends purchases of cobalt from two Congo mines, <https://www.reuters.com/article/congo-mining-huayou-cobalt/huayou-temporarily-suspends-purchases-of-cobalt-from-two-congo-mines-idINL8N2FE5MZ>

Reuters (2019a), BHP switches to green power for chilean copper starting 2021, <https://www.reuters.com/article/us-bhp-chile-renewables-idUSKBN1X0019>

Reuters (2019b), Brazil bans upstream mining dams after deadly vale disaster, <https://www.reuters.com/article/us-vale-sa-disaster-idUSKCN1Q718C>

Rio Tinto (2020), *Our Approach to Climate Change 2019*, London, United Kingdom.

Roskill (2021), Cobalt, sustainability: DRC launches monopoly over cobalt ASM to improve ESG credentials,

<https://roskill.com/news/cobalt-sustainability-drc-launches-monopoly-over-cobalt-asm-to-improve-esg-credentials>

Roskill (2020), Roskill: CO2 emissions from lithium production set to triple by 2025, <https://www.globenewswire.com/news-release/2020/10/05/2103285/0/en/Roskill-CO2-emissions-from-lithium-production-set-to-triple-by-2025.html>

Sahla et al. (2021), *How can Anticorruption Actors use EITI Disclosures?*, Natural Resource Governance Institute, https://resourcegovernance.org/sites/default/files/documents/how_c_an_anticorruption_actors_use_eiti_disclosures.pdf

Santamarina, J. et al. (2019), Why coal ash and tailings dam disasters occur, 364 *Science* 526-528, <https://www.doi.org/10.1126/science.aax1927>

Sonter, L. J. et al. (2014), Processes of land use change in mining regions, *Journal of Cleaner Production*, 84(1), 494–501, <https://doi.org/10.1016/j.jclepro.2014.03.084>

Stanford Law School (2020), *Foreign Corrupt Practices Act Clearinghouse, Key Statistics from 1977 to Present* (database), <http://fcpa.stanford.edu/statistics-keys.html>, (accessed 16 February 2021).

S&P Global (2021), New lithium supply chains could slash sector emissions by nearly a third, <https://www.spglobal.com/platts/en/market-insights/latest->

[news/coal/121120-new-lithium-supply-chains-could-slash-sector-emissions-by-nearly-a-third-roskill](https://www.spglobal.com/platts/en/market-insights/latest-news/coal/121120-new-lithium-supply-chains-could-slash-sector-emissions-by-nearly-a-third-roskill)

Tost, M. et al. (2018), Metal mining's environmental pressures: A review and updated estimates on CO2 emissions, water use, and land requirements, *Sustainability* (Switzerland), 10(8), <https://doi.org/10.3390/su10082881>

Transparency International (2021), *Corruption Perceptions Index 2020* (database), <https://www.transparency.org/en/cpi/2020/index/nz>, (accessed 12 April 2021).

UNCTAD (United Nations Conference on Trade and Development) (2021), *UNCTAD Statistics – International merchandise trade datasets* (database), <https://unctadstat.unctad.org/EN/BulkDownload.html>, (accessed 26 February 2021).

US BLS (US Bureau of Labor Statistics) (2021), Labor Force Statistics from the Current Population Survey: 18. Employed Persons by Detailed Industry, Sex, Race, and Hispanic or Latino Ethnicity, <https://www.bls.gov/cps/cpsaat18.htm>

US BLS (2020), Number and rate of fatal work injuries, by industry sector, <https://www.bls.gov/charts/census-of-fatal-occupational-injuries/number-and-rate-of-fatal-work-injuries-by-industry.htm>, (accessed 3 March 2021).

US DOL (US Department of Labor) (2019), *Findings on the Worst Forms of Child Labor: Democratic Republic of the Congo*, <https://www.dol.gov/agencies/ilab/resources/reports/child-labor/congo-democratic-republic-drc>

Vale (2020), *Sustainability Report 2019*, [http://www.vale.com/EN/investors/information-market/annual-reports/sustainability-reports/Sustainability%20Reports/Relatorio sustentabilidade vale 2019 alta en.pdf](http://www.vale.com/EN/investors/information-market/annual-reports/sustainability-reports/Sustainability%20Reports/Relatorio_sustentabilidade_vale_2019_alta_en.pdf)

Vulcan Energy (2020), Zero Carbon Lithium®, <https://v-er.com/wp-content/uploads/2020/11/2020AGMPresentation.pdf>

Watson, K. (2020), 'Vale ended our lives': Broken Brumadinho a year after dam collapse, BBC, <https://www.bbc.com/news/world-latin-america-51220373>

WEF (World Economic Forum) (2020), *Making Mining Safe and Fair: Artisanal Cobalt Extraction in the Democratic Republic of the Congo*, [http://www3.weforum.org/docs/WEF Making Mining Safe 2020.pdf](http://www3.weforum.org/docs/WEF_Making_Mining_Safe_2020.pdf)

World Mine Tailings (2020), *World Mine Tailings Failures – From 2015, State of Worldmine Tailings 2020* (web page), <https://worldminetailingsfailures.org/>

WRI (World Resources Institute) (2021), *Aqueduct Country Rankings* (database), <https://www.wri.org/applications/aqueduct/country-rankings/>, (accessed 30 April 2021).

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Environmental impacts, pollution sources and pathways of spent lithium-ion batteries

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There is a growing demand for lithium-ion batteries (LIBs) for electric transportation and to support the application of renewable energies by auxiliary energy storage systems. This surge in demand requires a concomitant increase in production and, down the line, leads to large numbers of spent LIBs. The ever-increasing battery waste needs to be managed accordingly. Currently, there are no universal or unified standards for waste disposal of LIBs around the globe. Each country uses one or a combination of practices such as landfilling, incineration and full or partial recycling depending on the number of batteries leaving the market, current legislation and infrastructures. Informal disposal or reprocessing is not a rare activity. This review records, identifies and categorises the environmental impacts, sources and pollution pathways of spent LIBs. The drawbacks of the disposal practices are highlighted and the threats associated with them are discussed. The evidence presented here is taken from real-life incidents and it shows that improper or careless processing and disposal of spent batteries leads to contamination of the soil, water and air. The toxicity of the battery material is a direct threat to organisms on various trophic levels as well as direct threats to human health. Identified pollution pathways are via leaching, disintegration and degradation of the batteries, however violent incidents such as fires and explosions are also significant. Finally, the paper discusses some of the main knowledge gaps for future assessments. The current study offers a comprehensive overview of the threats and hazards that need to be managed in order to ensure the design and implementation of safe disposal and processing options for spent LIBs.

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Broader context

Lithium-ion batteries (LIBs) are permeating ever deeper into our lives – from portable devices and electric cars to grid-scale battery energy storage systems, which raises concerns over the safety and risk associated with their disposal. Spent LIBs are currently landfilled, incinerated, partially/fully recycled, or a combination of these, depending on the existing infrastructure, legislation *etc.* of the country concerned. Spent LIBs are considered hazardous wastes (especially those from EVs) due to the potential environmental and human health risks. This study provides an up-to-date overview of the environmental impacts and hazards of spent batteries. It categorises the environmental impacts, sources and pollution pathways of spent LIBs. Identified hazards include fire and explosion, toxic gas release (*e.g.* HF and HCN), leaching of toxic metal nanooxides and the formation of dangerous degradation products from the electrolyte. Ultimately, pollutants can contaminate the soil, water and air and pose a threat to human life and health. In this work, we discuss some of the main knowledge gaps and probe questions on the environmental impacts of spent LIBs that might help to manage these better in the future to design and implement safe disposal and processing options for spent LIBs.

1. Introduction

Lithium-ion batteries (LIBs) are found in all aspects of our lives – from small portable electronic devices through electric vehicles

(EVs) to battery energy storage systems (BESS). LIBs are perceived as crucial to support the wide adoption of renewable energy sources as these do require BESS to manage the intermittency in their power supply for a reliable operation of the electricity grid. The application of LIBs in electric traction has initiated a revolution in the automotive industry that is motivated to decarbonise the transport sector and reduce local air pollution. In 2009, there were nearly 25.6 GW h (about 134 000 tons) of LIB energy storage capacity placed on the global market, in 2019 it was about 218 GW h (over 1.2 million tons), and it has been

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estimated that in 2030 more than 2500 GW h (over 12.7 million tons) will be placed on the market, which subsequently results in a vast amount of waste from the spent LIBs.¹

Various international and domestic initiatives like the European Green Deal in the EU,² the UK Government pledge to ban new ICE cars by 2030 (hybrids by 2035)³ or the need to establish zero-emission mobility as an urgent priority,⁴ require a very large increase in the production of new LIBs. Moreover, transitioning to a low carbon economy⁵ requires building new, more powerful BESS all around the world. These installations will be used as storage of intermittent solar, wind, or wave electricity, grid support, frequency stabilisation and behind-the-meter-storage, replacing conventional technologies. On one

hand, the increased number of LIBs has created concerns over the availability of some critical metals, and their wild short-term price volatility which could affect the sustainable supply of such energy storage devices.⁶ There are also some ethical and environmental concerns with the extraction of some metals for LIBs.⁷ On the other hand, this surge in demand for batteries will require a concomitant increase in production and, down the line, large numbers of LIBs reaching end-of-life (EoL). Hence, that will cause an ever-increasing battery waste that needs to be managed accordingly.⁸ However, many types of batteries currently do end up in landfills or are incinerated, primarily due to the lack of adequate standards; enforcement of regulatory controls, inefficient, or absence of, national battery



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Fig. 1 Disposal routes of LIBs.

collection and recycling schemes.⁹ As a result, human health and environmental quality could be placed at risk as a wide range of pollutants could be released like heavy metals or hydrofluoric acid (HF) when batteries are disposed of inappropriately.

The main aim of this study is to provide an up-to-date overview of the environmental impact and hazards of spent batteries. This paper reports and discusses the fate, disposal routes and potential pollution sources and pathways from spent LIBs. Despite the clear importance of this area, the data on the environmental impact of EoL LIBs is extremely limited, thus, this study identifies the possible environmental impacts associated with battery EoL. There is an urgent need from manufacturers, waste handling companies, recycling firms and public stakeholders to understand this matter as wrong disposal practices, lack of data or improper identification of hazards will drastically increase the number of incidents, fires and potentially fatal accidents. The possible emission routes and pollution pathways *e.g.* air, water and land, are also evaluated through the course of this study. We have also recognised possible hazards to human health and ecosystem quality due to different battery treatment and disposal practices. Finally, the knowledge gaps are identified that need to be covered if the right disposal practices and management systems are to be implemented.

2. Disposal of spent batteries

The management of spent LIBs incorporates reuse, recycling, landfilling, processing or (unfortunately) illegal disposal (Fig. 1). The local disposal routes depend on national legislation and regulations, recycling capacities, collection systems, consumer behaviours and the battery retail markets.¹⁰ Clearly, different approaches are required for small batteries compared to large ones.

Small LIBs are returned by the customer either through battery drop-off points (LIBs that can be easily detached from the device) or given to waste electrical and electronic equipment sites (WEEEs) if the user cannot remove them from the

electrical device. From these collection points, they are transported to sorting facilities and later to be recycled or landfilled. Through ignorance of the collection system or idleness, small spent LIBs may be put into general waste or into recycle bins by customers, which led to damaging fires during transportation or in material recovery facilities (MRFs). Veolia, one of the global waste handling companies, has noted a 38% increase of incidents since 2017,¹¹ due to the presence of the LIBs in the waste stream. At MRFs, LIBs will be crushed or penetrated during the standard processing, which can also lead to fires or even explosions. The Environmental Services Association estimates that¹² there were *ca.* 250 fires in the UK waste treatment facilities caused by small LIBs between April 2019 and March 2020, compared to *ca.* 130 in the year to March 2020, a rise of 25% of all fires in these facilities.^{13,14} The German steel recyclers confederation (BDSV) has claimed that 90% of fires at their associated sites in the last years were caused by LIBs.¹⁵ Some specific examples of such fires are the incident at the Great Blakenham scrapyards, UK (15th Sep 2017) where 100 tonnes of metal and a crane were caught up in fire;¹⁶ multiple incidents at Tokyo's Musashino Clean Center garbage disposal facility, Japan, in 2017 and 2018;¹⁷ and some other regular incidents in the UK, USA, Scotland, and Germany.¹⁸

Large LIBs are typically transported by professional services once removed from EVs,¹⁹ however, their health status is usually unknown. If internally damaged, they are in slow thermal runaway and hence remain unnoticed for a long time, after which they may either burst into flames or they release gases and droplets of solvent, the "white vapour", composed of toxic and explosive gases.^{7,20–24} These events may take place during transportation, storage, recycling or landfilling.

2.1 Recycling

2.1.1 Low recovery rates. Material recovery from the EoL batteries is the preferred option over the other disposal routes^{10,25,26} since LIBs are now considered a strategically valuable waste stream containing relatively valuable metals such as cobalt,



nickel or lithium.^{27,28} These are of significant value, especially in light of the shrinking global supply of critical materials.^{29–32} Material recovery is also the way to be less dependent on raw mining elsewhere or to protect the country's own small reserves. For instance, the lithium demand for LIBs produced in China by 2050 could meet up 60% by recycling.³³ Currently, China is the largest consumer and producer of LIBs and recycling of spent LIBs has only started recently.³⁴ Although some 14 pieces of legislation try to manage the emission pathways of all types of batteries waste, effective regulation of controlling spent LIB is still in its infancy.³⁴ In the USA the management and regulation of LIBs is also fragmented, due to its Federal States, with some federal policies guiding battery disposal, specifically the 1996 Mercury-Containing and Rechargeable Battery Management Act to manage certifications and standards of batteries.³⁵ However, overall, it is patchwork of state by state regulations with different levels of maturity and control.³⁶ In the EU, new legislation is coming into force in 2022 to manage and control the raw material sourcing, disposal and recycling of LIBs.¹

Clearly, material recovery should avert the environmental burden from ore mining and beneficiation of metals used in LIBs by replacing the recycled ones in the production chain,³⁷ and could also avoid the environmental burdens from the other harmful disposal routes. In 2018, it is estimated that 97 000 tonnes of LIBs were recycled globally,¹⁹ including LIBs from portable electronics as well as LIBs from EVs and BESS applications. Small LIBs currently dominate recycling (*i.e.* more than 80% of the recycled batteries) as the number of batteries reaching actual EoL from EVs is relatively low.³⁸ This is due to the relatively nascent application of LIBs in EVs, and the fact that when EV LIBs have reached EoL they still have potential use in other applications, such as supporting the Grid or renewable energy generation, as they typically retain up to 80% of their original capacity.³⁹ Thus, LIBs from EVs may be finally discarded up to 10 years after their first life.⁴⁰

A closer look at the recovery of LIBs reveals that compared to the amount of LIBs placed on the global market, the actual recovery rates are quite low. For example, the average collection rate in the EU, one of the well-regulated markets, is nearly 40% while only 12% belongs to LIBs.⁴¹ The average recovery rates are also lower for some other less-regulated markets such as Australia and the US.^{29,42} However, there are still few markets that perform better than the EU. More specifically, South Korea and China together showed better recovery rates. Actually, these countries are the destination of most of the exported batteries (either in a separate battery form or as part of electronic devices) from many parts of the world especially Europe and North America. This is also reflected in the total quantity of LIBs recycled: from 97 000 tonnes treated globally in 2018, 67 000 were processed in China and 18 000 in South Korea.¹⁹ However, it is estimated that less than 40% of the total battery materials actually can be recycled under the current materials flow scheme.⁴³ For instance, in 2016, only around 30% of nickel, 33% of cobalt, 23% of lithium and 5% of graphite were recovered in China.⁴⁴ Such poor management resulted in

economic loss due to the free discharge of valuable materials, as well as damage to the environment and human health.^{45,46} Various national and international initiatives have been implemented to tackle this low recovery problem such as the 2006 EU battery directive⁴⁷ and the proposed new EU regulation which concerns batteries and waste batteries.⁴⁸ The key challenge, however, is the lack of recycling infrastructure around the world, there are only a few full-scale recycling facilities (Table 1).^{49,50} Illustration of this problem is the UK situation. Prior to exiting the EU on the 31st December 2020, the regular practice was to ship batteries to mainland Europe for recycling, *e.g.* to Umicore in Belgium. However, with the restricted access to the EU market and strict regulations treating large LIBs as hazardous materials, the UK, without proper recycling infrastructure, may either have to landfill its batteries⁵¹ or temporarily store them in dedicated facilities until suitable facilities are built or until an appropriate trade deal with the EU is agreed.

Both landfilling and stockpiling will have a potentially negative effect on the surrounding environment as they can release pollutants, contaminants and cause accidental fires, which are discussed below.

2.1.2 Recycling methods. Material recovery from the EoL LIBs is currently carried out by one of three major processes: pyrometallurgy, hydrometallurgy, and direct recycling.^{25,40} Pyrometallurgy employs smelting in a high-temperature process, which usually involves burning and subsequent separation to produce a mixed metal alloy of Co, Cu, Fe and Ni.⁵² That is an established technology commonly applied to small and large LIBs, especially to cobalt-rich batteries. Usually this method does not require pre-sorting of battery types, however, the resulting alloy requires further processing. Hydrometallurgy recovers the desired metals from cathode material *via* leaching in an acidic or basic aqueous solution. Additional steps such as subsequent concentration and purification are later required. This process allows the recovery of almost all LIBs components with high purity.⁵³ However, the separation of the metals from each other requires additional purification steps: in addition, unlike pyrometallurgy, sorting is required. Finally, direct recycling involves the direct re-use of the cathode and/or anode material from the electrodes of spent LIBs after reconditioning. Although promising in principle, as it allows the simple recovery and re-use (without further processing) of most of the battery constituents,^{25,54,55} it is still not fully matured as a technology. There are also alternative technologies under investigation such as plasma smelting technology,³⁷ bioleaching,⁵⁶ redox targeting-based material recycling,⁵⁷ *etc.*

Each of the listed technologies has its own limitations in recovering LIB's materials. Therefore, the final process should involve a combination of various techniques with a well-defined material flow chart to assure the highest efficiency of recycling.⁵⁸ The enormous research and development effort should tackle this issue, however, the gradual but constant change in battery chemistry will require the facilities to shift their operational mode in just a few years. Is the process safe to operate with new chemistry? Are there any hazardous by- and end-products that need to be treated accordingly? These and



Table 1 Current recycling facilities around the world adopted from ref. 49 and 50

Company name	Location	Process ^a	Capacity (tonne of battery per year)
Accurec Recycling	Germany	P, M	4000
Akkuser	Finland	M	1000
Aubermacher Redux	Germany	M	1000
Bangpu Ni\& Co High Tech	China	H	3600
Batrec	Switzerland, Wimmis	P	200
Dowa Eco-System Co. Ltd	Japan	P, H	1000
Duesenfeld	Germany	M	3000
Envirostream	Australia	P	3000
Euro Dieuze	France	M, H	6000
GEM	China	H	100 000
Glencore	USA, Canada, Norway	P	7000 (Norway)
High Power International	China	P, H	10 000
Huayou Cobalt	China	H	60 000
Hunan Brunp Recycling Tech	China	H	30 000
Inmetco	USA	P	6000
Jiangxi Ganfeng Lithium	China	H	5000
JX Nippon Mining & Metals Corp	Japan, Tsuraga	P, H	600
KOBAR	South Korea	H	1000
LiCycle	Canada	H	2500
Nickelhütte Aue	Germany	P, H	1000
Nippon Recycle Center Corp	Japan	P	2000
Recupyl	France/Singapore	H	110/1200
SNAM	France	P, M, H	1500
SungEel Hitech	South Korea	H	8000
Sungeel Hi-tech	Hungary	M, H in South Korea	3000
Taisen Recycling	China & South Korea	H	6000
Tele Recycle	China	H	2000
TES (Recupyl)	France	M, H in Singapore	1000
Umicore	Belgium	P, H	7000
Ute Vilomara	Spain	H	> 53.32

^a P – pyrometallurgy, H – hydrometallurgy, M – physical separation.

other questions must be answered to ensure the safety of the workers and mitigate the environmental impact of the process.

2.1.3 Pollution specific to recycling and the potential environmental impacts. Materials recovery is not a pollution-free activity. For example, pyrometallurgy is a highly energy-demanding process, resulting in GHG emissions and the generation of toxic gases or hazardous slag that may need to be landfilled.³¹ Moreover, the intermittent product, so-called “black mass” (a sludgy mixture of lithium, manganese and cobalt), may also contain other hazardous substances such as alkylfluorophosphates that are a serious health concern.⁵⁹ Pyrometallurgical recycling process could impose environmental risks in global warming, photochemical ozone creation, carcinogenic and non-carcinogenic effect, ozone layer depletion and eutrophication impact categories.¹⁸ A recent study on plasma smelting recycling showed that the employed energy source (for the smelter), recycling efficiency, the quality of the recycled materials, aluminium recovery and adopting a battery waste improvement process could significantly affect the overall environmental impacts of pyrometallurgy.³⁷

In contrast, hydrometallurgy produces far less GHG emissions but requires supplementary wastewater treatment to ensure that receiving waters do not suffer additional pollution, *e.g.* from acids. Hydrometallurgical recycling processes were reported to impose environmental risks on freshwater and terrestrial acidification.¹⁸ Mohr *et al.* (2020) compared the environmental impacts of recycling of different battery chemistries (*i.e.* NMC, NCA, LFP

and solid-state) using a conventional pyrometallurgical, a conventional hydrometallurgical process and an advanced hydrometallurgical process (that recovers graphite and electrolyte).⁶⁰ The results indicated that the advanced hydrometallurgical processes could perform the best (in terms of global warming impact) due to additional recovery of graphite and electrolyte, while the pyrometallurgical process performs the worst due to high energy consumption and lack of Li recovery. The authors also suggested that a cell chemistry specific approach for recycling should be taken into consideration since some recycling processes could lead to unfavourable impact on the environment when treating some specific chemistries, for example, hydrometallurgical recycling of LFP and sodium-ion batteries (SIB) could add more burden in abiotic resource depletion potential; or pyrometallurgical recycling of LFP cells could increase the global warming impact.

As direct recycling is still in its very early stages of development, there are no real-world data on potential pollution. According to Dunn *et al.* (2015), using a direct recycling process for NMC, LCO, LFP and LMO batteries could significantly reduce the emissions of GHGs and SO_x (from the production of batteries) and thus mitigate global warming and acidification potential of the whole battery life cycle.⁶¹ It should be noted that when talking about the environmental impacts of a specific recycling process, the net impact on the environment is usually considered which is calculated by subtracting the released emissions from the avoided emissions (recycling benefits). Thus, a recycling process itself may have a



negative impact on the environment in a specific environmental impact category while the credits from the recycled materials (environmental impacts avoided due to returning the recovered material to the market) might compensate those negative impacts and make the net environmental impact favourable. Overall, it should be noted that the environmental impacts of different recycling processes could vary based on the processed cell chemistry, the employed emission reduction technology, recycling efficiency and the quality of the materials recovered.

2.1.4 Comparison to non-lithium ion battery recycling methods. Finally, there is a lesson to be learnt from the already established recycling processes for other battery types. For example, the processing of lead-acid batteries is of major concern especially in developing countries⁶² as, in such locations, recycling is often performed without controlling lead emissions.⁶³ In addition, there is also often a lack of appropriate regulation and the consequent existence of informal and polluting recycling industries. Thus, in the absence of adequate standards and/or lack of enforcement of regulatory controls, the lead recycled from batteries results in significant environmental contamination and human exposure even in established, industrial-scale recycling facilities.⁶⁴ It has been estimated that over 495 000 deaths and more than 9 million disability-adjusted life years (DALYs) occur as a result of the long-term impact of lead exposure on health. Reports also show that low- and middle-income countries have the highest death rates associated with lead exposure.⁶⁵ Comparative analysis reveals that current environmental and social influence such as consumption of raw material/metal, energy demand, scrap emissions, recycling or disposal cost; of the lead-acid battery system is greater than that of the LIB system.⁶⁶ However, it should be highlighted that such studies are performed on retrospective data (*i.e.* for China in 2016) and do not fully reflect the future with much higher numbers of production and recycling/disposal of LIBs. Therefore, it is essential to assess in detail all the gaps in knowledge and technology, as well as socio-economic issues, and apply these to the future LIB recycling industry. This is important not only for developed countries but even more for emerging economies that usually have lax or weak environmental legislation.⁶⁷

2.2 Landfill

Landfilling is the main method of disposing of solid waste⁶⁸ – with the rates of deposition of municipal waste ranging from 53% in the USA,⁶⁹ 79% in China⁷⁰ to 94% in Malaysia.⁷¹ Of these, around 4% includes electronic wastes (e-waste), often containing batteries.⁷² Given the low global recovery rates, it is clear that most e-wastes containing small LIBs are discarded into the landfill sites rather than recovered.^{73–76} This is the case not only for many emerging economies but also in developed ones due to (as stated above) lax or weak regulations as well as the lack of recycling infrastructure. Therefore, in the short-term at least, it is certain that LIBs (especially those from small portable devices) will be buried. Currently, due to the relatively small number of EVs, large LIBs are usually recovered.⁴⁴ However, with the rapid growth in volume and still inadequate

infrastructure, even high-powered batteries may be either land-filled or temporarily stored. Yet, in the long-term, it is more likely they will follow the recovery route rather than landfilling, as it would be a waste of a significant resource of valuable materials.⁶⁷

The landfill itself can be both a sink or source of pollution that can have negative impacts on surrounding communities.⁶⁸ The main sources of emissions from landfills are surface dust, landfill gases (*e.g.* biogas), leachate and fires.^{77,78} The extent of pollution from a site depends upon location, waste composition and age, and geo-climatic conditions.^{51,79–81} However, in the future it's possible that landfills may be a place of valuable resources for urban mining – the sink of the rare and needed metals that can be extracted without actual mining.

2.2.1 Landfill fires. Landfill fires are clearly undesirable but unfortunately quite frequent.^{82–86} There are two types of fire, surface and subsurface (cavity); and in most cases, they are due to the spontaneous auto-ignition of methane.⁸⁷ Surface fire spreads outside the landfill area but is relatively easy to extinguish. Cavity fires are a form of combustion (pyrolysis) where the thermal reaction takes place under anoxic conditions deep below the landfill surface.^{77,88} These are difficult to detect and may create large voids in the landfill, which can cause the landfill surface to cave in. Buried LIBs, which may be holding a charge and contain flammable electrolytes, may trigger, amplify and prolong landfill fires.

Landfill fires caused by (usually small) LIBs are a major emerging problem. The Environmental Services Association (ESA), the trade body representing the UK's resource and waste management industry, reported that 25% of total landfill fires (>500) in the UK in the period 2017–18, were attributed to LIBs: a significant 20% increase in comparison to the previous year.⁸⁹ Examples of such fires include that at the Dunbar landfill site on 22nd January 2019, where around 300 tonnes of waste burst into flames in waste sorting building.⁹⁰ Fires in pre-landfilling facilities may be illustrated by Shoreway MRF, USA. At least 25 fires at this facility were caused by LIBs between April 2013 and September 2017. The most severe fire, on the 9th September 2017, required over 100 firefighters to extinguish it, and the fire shut the facility for 3 months and cost over \$8.5M in restoration.⁹¹

Accurate prediction of the ignition potential of LIBs is challenging, as spent batteries will have various compositions, States of Health (SoH) and charge (SoC); besides, it is likely that cells, modules and packs will be dumped and landfilled. In landfills, batteries may be damaged during compacting and hence ignite either immediately or after burial: in the latter case, serious fires could result due to surrounding flammable materials and existing methane in the landfill environment. Even if damaged batteries do not ignite, the pyrolysis that accompanies thermal runaway will generate significant heat and toxic and potentially explosive gases.⁹² It should be noted that fires caused by batteries may occur months or even years after they were buried.

The hazards of damaged LIBs are in addition to conventional landfill fires, which produce a mixture of toxic gases and



smoke^{77,93} consisting of polycyclic aromatic hydrocarbons (PAHs),^{94–96} dioxins/furans,^{97–101} volatile organic compounds (VOCs),^{102,103} heavy metals^{104,105} polychlorinated biphenyls or organochlorine pesticides¹⁰⁴ and finally, particulate matter (PM) with an aerodynamic diameter smaller than 2.5 μm .^{106,107} Subsurface fires favour the generation of harmful gases such as CO, SO₂ or H₂S⁷⁷ – some of these gases are also generated within burning batteries.^{7,20–24} Landfill fires do not only affect the air around the site as the smoke can carry particulate matter and chemicals to further distances: for example, it has been shown that there may be a short term rise in the concentrations of heavy metals and Chemical Oxygen Demand (COD) or PAHs⁸⁶ in water bodies next to burning sites. Therefore, avoiding battery landfilling or at least neutralization/immobilization of hazardous content must be seriously considered. That could be for instance (i) complete discharging-no excess of the energy, immobilization of copper on aluminium foil; (ii) removal of the flammable electrolyte from the battery – reduced fire risk, formation of hazardous gasses and vapour cloud explosion; (iii) using additional liners (bentonite clay *etc.*) capable of binding heavy metals – no transport through landfill layers.

2.3 Illegal disposal and processing

Wherever there is a potential of making profit there are attempts to bypass official routes of making business. As the recycling of LIBs will be profitable at least to some degree, there is a big chance that some illegal processing will occur, as it happened for waste electronic equipment. Such activity will result in pollution surrounding the processing site, poor working conditions of workers and thus worsening their health and quality of life. Illegal disposal will occur if the recycling or official landfilling will be to “too expensive” for some “business”. The dumpsites will be located in very random places, completely not fit for purpose and that will result in severe pollution, unexpected fires and huge additional costs to local residents/councils – utilization and remediation of the area. Unexpected incidents (*e.g.* fires) may even occur months after the disposal making the process of finding responsible/guilty person very tricky.

It is certain that LIBs will be illegally recycled and disposed of.^{67,108} Moreover, the burden of illegal processing will be mostly put on emerging economies due to the high costs of labour, lack of recycling facilities and strict environmental laws in developed countries.⁶ A good example of this exploitation is the export of e-waste facilitated by rich and developed nations to poor and developing ones.^{109,110} This is also reflected in the statistics: for instance, two-thirds of global e-waste collected in 2014 were exported, but more importantly, half of it was through illegal routes.¹¹¹ This resulted in over 3 million tonnes of e-waste exported outside of regulated schemes. Data for 2019 show that 82.6% of global e-waste flows were neither formally collected, properly managed nor documented.⁷² The EU generates *ca.* 44.3 Mt of e-waste annually, however only 0.6 Mt is known to reach landfills whilst the rest is dumped, traded, informally exported or recycled in a non-environmentally appropriate way.¹¹² Hence there is no guarantee that exported

EoL LIBs will be recycled or processed in regulated, safe and environmentally friendly ways.⁴⁴

2.3.1 E-Waste problem. Interestingly, even now with a relatively low number of EoL EVs, it is possible to buy used LIB cells, modules on the popular, online, auction portals. This means that they are sold outside official collection/recycling schemes, even though they have reached their first EoL. With the growing demand from individuals, *e.g.* for behind-the-meter energy storage, some of the batteries may be illegally sold, especially in countries with weak or no regulations, and the obvious question arises: what happens to such self-made systems when they reach real EoL? Will they be passed to accredited recycling centres or dumped? In addition, what would be the impact of the illegal processing of LIBs on human health and the natural environment? These issues can be illustrated by current informal WEEE operations – often the recycling is carried out without any environmental and health protection, and this results in the contamination of soil, air and water and a serious impact on human health.^{108,113–121} The findings include the fact that heavy metals (*i.e.* lead or cadmium) and polycyclic aromatic hydrocarbons in the soils or watercourses surrounding such centres are significantly above national safety limits. Cobalt, copper and nickel are also heavy metals included in LIBs that might cause hazards if LIBs are inappropriately treated. Lead-acid battery informal processing can highlight potential issues for LIBs in the future. For instance, estimates have shown that there could be between 10 000 and 30 000 informal lead-acid battery recyclers in 90 low- and middle-income countries that pose a major threat to up to 16 million people.¹²² Such sites elevate levels of lead in soils and plants¹²³ and have caused higher concentrations of the metal in children's blood in Serbia,¹²⁴ Australia,¹²⁵ China¹²⁶ and India.^{127,128} Informal sites rarely control their harmful emissions, are subject to weak or no regulation, and are often located within residential areas.^{124,129,130}

2.4 Incidents involving LIBs

Incidents involving LIBs are mostly focused on fires and the release of toxic gases. In addition to the risk of these hazards to first responders and spectators at, for example, a road traffic accident, there is also the broader spectrum of the environmental impact of such fires. Fig. 2^{131,132} shows typical emission pathways from a burning LIB to the surroundings. In addition to heat, fire or a toxic and potentially explosive vapour cloud there is also a possibility of air transportation of substances and with time, their deposition in other, distant places. The close surroundings are also affected by the fire debris, transportation of pollutants by fire extinguishing agents and release of remaining contamination from burnt carcasses – depending on the type and place of the disposal.

The sometimes explosive failure of LIBs is always due to some form of abuse which can be from heat, penetration, blunt trauma or overcharging, and examples of the results of these can be found in the literature citing examples on the land, sea and in the air.^{133,134} Spontaneous ignition of LIBs has also been reported, particularly concerning electric vehicles;¹³⁵ the events leading to this remain essentially unknown, but contamination





Fig. 2 Emission pathways from fires (adapted from ISO, 2011; Stec et al., 2019).

during production or poor design is often quoted. An increasing and slightly worrying phenomenon is the incidence of fires and explosions in large LIB energy storage systems (LIBESS). The first such incident occurred in Arizona in 2012 in a new 1.5 MW LIBESS owned by Arizona Public Services.¹³⁶ Several design flaws were identified following the incident including a lack of proper ventilation and inadequate monitoring all of which were supposed to have been addressed¹³⁷ when a second LIBESS owned by APS exploded in April 2019 injuring four first responders, two of whom badly. The incident is now believed to have been a vapour cloud explosion.^{138,139} We listed some other examples of LIBESS incidents in Table 2 to illustrate the rising problem.

In essence, LIBs in thermal runaway produce gases that are a mixture including hydrogen, carbon monoxide, carbon dioxide, HF, short-chain alkanes and alkenes, HCN, NO_x and droplets of solvent,^{21,23,138,140–142} the last giving the mixture the appearance of a white cloud.¹⁴³ In broad terms, the composition of the white vapour varies little as a function of cell chemistry, form factor or manufacturer.¹³⁸ The gas mixture will be vented either when safety valves/blast caps activate or when a pouch cell bursts: at high SOC and in the presence of sufficient oxygen, the white vapour ignites to produce flare-like flames. At low SOC or in the absence of sufficient air (*e.g.* the air is displaced by the vapour or by fire suppressant) the white vapour does not ignite,¹⁴⁴ in which case, in a confined space, there could be a possibility of a flash fire, fireballs developing, or in extreme cases, even a vapour cloud explosion.

LIBs are also more and more used in marine transportation. They can work as a propulsion system, powering ferries or even submarines,¹⁴⁵ energy recapture systems or hybrid systems. The advantage is usually lower weight and better efficiency in comparison to *i.e.* lead-acid systems.¹⁴⁶ As in the case of the EVs and BESS, there is a possibility of faults, incidents, fires and thus pollution of water ecosystems. An example of such an incident is a fire and subsequent gas explosion on board a diesel-electric ferry in Norway on the 10th of October 2019¹⁴⁷ – the

fire was spotted during the crossing, but the ferry returned to the harbour under its power where everyone was safely evacuated. Overnight, however, a serious gas explosion rocked the battery room causing significant damage. It was reported that twelve firefighters were hospitalized due to exposure to hazardous gases associated with the burning batteries. Table 2 also shows some other known up-to-date incidents.

Fire extinguishing agents (water, foam *etc.*) used to mitigate the incidents will be a carrier to all pollutants released from LIBs. That can broaden the area of the impact. For instance, HF released during a fire may form a solution with the fire extinguishing agent and thus, at concentrations as low as 0.01%, could cause injury to the more sensitive areas of human skin following exposures as short as 5 min.¹⁴⁸ If we add that between 20 and 200 mg of HF could be released per W h of an EV battery pack,²² such solution or even higher concentrations may be of no surprise. This reaction should be also taken into account when designing and using any extinguishing systems in places dealing with larger amounts of LIBs. The first responders must also be aware of the additional hazards, thus proper personal protective equipment (PPE) and operating procedures should be in place.

When the fire is gone there are left carcasses of burnt batteries. Except probably some steel parts (pack cover, module case *etc.*) they would not represent any value for recycling thus probably discarded/landfilled. These carcasses may be treated as fire debris according to Fig. 2. Currently, there are no data directly revealing what kind of pollutants may be released from such waste. Given the typical post-fire analysis^{132,149} and the composition of LIBs, we can suspect these may be remains of nanooxides, metals, PAHs and VOCs.

3. Sources and pollution pathways

Spent LIBs are considered hazardous wastes (especially those from EVs) due to the potential environmental and human



Table 2 List of some major involving LIBESS and Maritime incidents

Major LIBESS incidents		
Place	Date	Comments
APS Arizona, USA	February 2012	Testing a new 1.5 MW BESS linked to a solar energy system when it was destroyed by fire. Subsequent investigation concluded that lack of ventilation and inadequate monitoring were the major causes of the incident and recommended improved ventilation, 24/7 monitoring and the ability to send remote alarms. ^a
Wisconsin, USA	August 2016	The damage is estimated up to \$4M. The fire started in the DC power and control system rather than the lithium ion batteries. ^b
Drogenbos, Belgium	November 2017	Fire badly damaged the container of a 1 MW BESS after the fire detection and control system failed to control the blaze. ^c
Various places across South Korea	2018–2019	Up to 30 fires involving LG Chem lithium ion BESS. The causes of these fires have not been made public as yet, but defective lithium ion cells were not believed to be a major contributing factor. The concatenation of multiple factors have been postulated. ^d
Surprise Arizona	April 2019	Vapour cloud explosion. Four first responders were injured, 2 very badly. 9 first responders contaminated with hydrogen cyanide. ^e
Nathan campus of Griffiths University, Brisbane, Australia	March 2020	LFP BESS exploded causing major damage to buildings. The cause of the fire and explosion has been stated as having been an internal short circuit. ^f
Carnegie Road, Merseyside, UK	September 2020	One of three containers exploded in the early hours of 15 September, followed by a fire. The ventilation units were blown off the roof of the container by the blast, with debris (including one of the doors) scattered across a wide area. The cause of the explosion remains under investigation. ^g
Perles-et-Castelet, Ariège France	December 2020	A BESS containing 60 “batteries” ignited. The container was situated on top of a second container and presented some difficulties to the fire service, which had to pull the burning container down. The cause of the fire is under investigation. ^h
SBG-2 OVHcloud data centre in Strasbourg, France	March 2021	One data centre was completely destroyed and 4 of the 12 rooms of a second centre were also destroyed. Unconfirmed reports that fire started in BESS. ⁱ
Hongseong, South Chungcheong Province, China	April 2021	Fire in the BESS supporting a solar energy facility, supplied by LG Energy Solution (LGES). The fire destroyed the facility causing ca. 440 M Won damage. ^k
Shopping mall in Beijing, China	April 2021	Explosion and fire in a 25 MW h LFP BESS situated on the roof of a shopping mall. The BESS supported a solar array. 2 firefighters were killed, 1 injured. The BESS consisted of two sections, North and South: whilst dealing with a fire in the Southern section and explosion occurred in the Northern section, killing the firefighters. ^l
Invenenergy storage facility, LaSalle County, USA	July 2021	Fire in one of the 18 containers at a LFP BESS near the La Salle Generation Station nuclear power plant. ^m
“Victorian Big Battery”, Moorabool, Geelong, Australia	July/August 2021	The Moorabool installation is the largest LiBESS in Australia. The fire started in one container and spread to a second, paired container which was adjacent to the first. The firefighters adopted a defensive strategy due to the challenges of the installation, and allowed the containers to burn out in a controlled manner over 3 days. ⁿ
Maritime incidents		
Place	Date	Comments
Hybrid tug Campbell Foss, USA	November 2012	Fire in BESS of the vessel after it had finished assisting a second vessel in the port of Long Beach. The fire started in the battery compartment and spread to the engine room via a ventilation duct. The vessel's engineer was hospitalized. The incident has been attributed to long term overcharging of the battery. ^o
Boat Carila Sis, Sneek harbour, Netherlands	May 2019	The explosion occurred on board a pleasure craft whilst moored in the harbour. A fireball was observed above the boat by local residents. ^p
Russian nuclear submarine Losharik, Barents Sea	July 2019	An electrical short circuit occurred while the nuclear submarine was docking with the Podmoskovye, its mothership. This caused lithium ion cells to go into thermal runaway resulting in explosions and fire, killing 14 high-ranking officers on board. ^q
Hybrid electric ferry Ytterøyningen, Norway	October 2019	Coolant leaked from the 1989 kW h BESS on the vessel causing a small fire. This was extinguished by the seawater sprinkler system. However, the seawater then caused short circuits in the battery which exploded on the following day. 12 firefighters were hospitalized due to exposure to hazardous gases. ^r
Hybrid passenger vessel Brim, Norway	March 2021	Fire in the 790 kW h battery compartment of the 24-meter hybrid catamaran passenger vessel Brim in Oslofjord. ^s

^a <https://www.greentechmedia.com/articles/read/what-we-know-and-dont-know-about-the-fire-at-an-aps-battery-facility>. ^b <https://www.fox6now.com/news/damage-may-exceed-3-million-after-lithium-ion-battery-fire-at-sc-electric-in-franklin>. ^c Deign J. In: Media G, editor. Engie investigates source of Belgian battery blaze. Boston, MA, USA: Greentech Media Headquarters; 2017. <https://www.greentechmedia.com/articles/read/engie-investigates-source-of-belgian-battery-blaze>, (accessed 25th May 2020). ^d Yoon-seung K. Faulty batteries blamed for ESS fires: panel. South Korea: Yonhap News Agency; 2020. ^e DNV GL, *McMicken Battery Energy Storage System Event Technical Analysis and Recommendations*, Arizona Public Service, <https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/McMickenFinalTechnicalReport.aspx?la=en&hash=50335FB5098D9858BFD276C40FA54FCE>, 2020. ^f Dennien M. Firefighter 'knocked on his back' in fire blast at Griffith University. Brisbane, Australia: Brisbane Times; 2020. ^g <https://www.energy-storage.news/news/fire-at-20mw-uk-battery-storage-plant-in-liverpool>. ^h <https://www.ouest-france.fr/region-occitanie/ariege/ariege-un-incendie-dans-un-container-de-batteries-au-lithium-une-quarantaine-de-pompiers-mobilises-7070012>. ⁱ <https://www.datacenterdynamics.com/en/news/ovh-fire-update-four-halls-sbg1-destroyed-well-all-sbg2/>. ^j <https://www.datacenterknowledge.com/industry-perspectives/give-ovh-break-and-use-data-center-fire-teachable-moment>. ^k Fire at Solar Plant in Hongseong Involves EV Batteries from LG Energy Solution – Businesskorea. ^l <https://www.pv-magazine.com/2021/04/21/two-firefighters-killed-and-one-missing-after-beijing-battery-blaze/>. ^m <https://www.shawlocal.com/mywebtimes/news/local/2021/07/19/no-evacuations-for-battery-fire-at-energy-storage-facility-east-of-grand-ridge/>. ⁿ <https://www.theage.com.au/national/victoria/blaze-at-tesla-big-battery-extinguished-after-three-day-battle-for-control-20210802-p58f6x.html>. ^o <https://www.professionalmariner.com/battery-related-fire-damages-famed-hybrid-tug-puts-it-out-of-service/>. ^p <https://112-water.nl/inzetten-verslagen/201-brand-aan-boord-bij-hybride-boot>. ^q <https://www.wsws.org/en/articles/2019/07/12/russ-j12.html>. ^r <https://captain.com/fire-and-gas-explosion-in-battery-room-of-norwegian-ferry-prompts-lithium-ion-power-warning/>. ^s <https://maritime-executive.com/article/newly-built-hybrid-passenger-vessel-suffers-battery-fire-under-way>.



health risks associated with heavy metals.^{74,150–154} The disposal and processing of LIBs, as well as their properties (e.g. chemistries), will have a significant impact on various environmental compartments (Fig. 3). LIBs contain a variety of chemicals including reactive salts, volatile organic electrolytes and additives: the latter are often commercial secrets and hence their toxicity and combustion products are largely unknown.^{155,156} Moreover, battery fires, in combination with biogas from landfills, may release toxins into the air or leach the harmful contents into the soil, groundwater and surface water.^{118,157,158} Once released, they pose risks to the surrounding environment alone or in combination with other pollutants.^{159–165}

Fig. 3 shows likely pollution routes (originated from EoL LIBs disposal/processing) to the environment and possible cross-contamination within different compartments. Pollutants once released from LIBs may enter one compartment first and later be transported to another one. For instance, heavy metals may be collected by dumpsite leachate and transported into the soil or groundwater outside the initial site. On the other hand, if a battery leaches onto open ground, heavy metals may run-off with the rain to a nearby river or lake. However, due to knowledge and data gaps, not all routes could be fully reviewed in this work.

3.1 Emissions to air

3.1.1 Dust. Fine particles may be released from LIBs to the air during disassembly and recycling processes; from a landfill or dumpsite by degradation or fire/explosion; and are considered as a part of the total dust emissions.¹⁶⁶ Generally, dust is a mixture of solid particles and liquid droplets of a wide range of sizes (nanometres to few micrometres) and chemical composition, all together suspended in the atmosphere.^{167,168} Particulate matter with aerodynamic diameters of less than 10 or 2.5 μm (PM_{10} and $\text{PM}_{2.5}$) can jeopardize human health, adversely affect climate and reduce visibility at local and regional scales.^{169–171} Particulates may contain matter-bound metals such as arsenic, cadmium, chromium, cobalt, copper or lead due to the decomposition of recyclable batteries, scrap metals and electronic waste.^{172–174} Dust can enter the respiratory system causing adverse health effects such as cardiovascular

and respiratory diseases, carcinogenicity, or disruption of the endocrine system.^{175–187}

During disassembly and material recovery of LIBs, shredding is the main mechanical processing option²⁵ that could generate dust emissions. These emissions could potentially cause a respiratory hazard to workers in recycling centres as well as those living or working in the vicinity. Moreover, particles and chemicals (e.g. PAHs) released from batteries may aggregate together in the atmosphere, be transported on larger distances and settled down causing for example soil pollution. As LIBs particles may be of different materials and sizes, it is mandatory to assess and investigate their possible toxicity and respiratory hazard.

The potential negative effect of three battery materials: lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium cobalt oxide (LCO) was studied utilizing mouse bioassays.¹⁸⁸ The mixed metal oxides present in the cathodes of LIBs could release particles small enough to penetrate the lungs and induce inflammation. The extent of the impact varies depending on the chemistry of the LIB. From the materials tested by Sironval *et al.* (2018), LTO was the least harmful, whereas LCO induced the strongest inflammation. As a result, the fibrotic responses were observed in cells with higher inflammation rates.¹⁸⁸

Another generator of dust and particles are explosions and fires. During thermal runaway the particles are first ejected from the safety vent together with other gases, resulting in heavy smoke with black colour.^{189,190} After cooling down, they settled as surface dust. The composition of these powders from lithium nickel cobalt manganese (NMC) cells was mainly C, O, Al, Mn, and F. This result suggests that it is mostly the negative carbon particles of the battery, as well as the oxidized positive substances of the electrode, that are ejected during gas venting.¹⁹⁰ Another study¹⁹¹ found that thermally abused prismatic automotive NMC cells released PM that contained heavy metals. The authors found that nickel and copper were detected in all collected fractions (1.45 to 500 μm) whereas zinc and chromium settled with bigger fractions (50 to 500 μm). Ni had the largest mass percentage followed by Cu, Zn and Cr. In terms of the total emitted quantity, PM accounted for 1.7% of the cell mass. Once settled, such particulates may interact with surrounding waters and soil and ultimately be of threat to crops.

3.1.2 Hydrofluoric acid. Out of various hazardous gases released from LIBs to air, HF is of the highest concern and must be treated with high caution. It can enter the human body *via* the skin or respiratory systems and causes severe corrosive effects and systemic toxicity.¹⁹² Inhalation of just a few ppm of HF can result in serious toxic effects. HF readily penetrates the skin and moves quickly to the deeper tissue layers where it releases the freely dissociable fluoride ion. This ion is extremely toxic, due to its strong reactivity.¹⁹³ Moreover, HF gas is hygroscopic and readily soluble in water.^{158,194,195} Concentrated solutions of HF are highly corrosive to the skin and underlying tissues and accidental dermal exposure has been reported to cause death in humans.^{148,196}

HF is generated in LIBs during the first charge and by subsequent cycling, a phenomenon known as gassing.^{197–200}

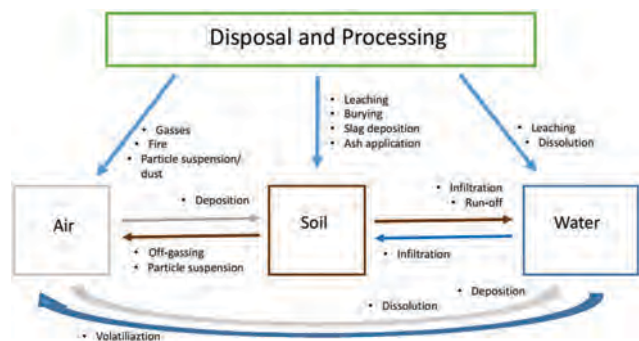
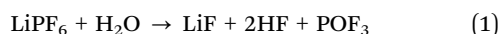


Fig. 3 Possible emission routes of pollutants from LIBs into the environment.

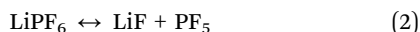


The acid can also be produced due to accidental spillage and hence the exposure of the LiPF_6 in the electrolyte to humid air¹⁵⁸ according to:

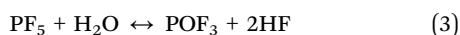


although this is disputed.²⁰¹

As well as the direct reaction of LiPF_6 with water, at ambient temperature in the organic carbonate solvents employed, LiPF_6 exists in equilibrium with its decomposition products according to:



PF_5 is prone to degradation upon exposure to traces of water, moisture or alcohols²⁰² to form HF which is also highly toxic:¹⁵⁸



To mitigate the effect of reaction (3), commercial LIB electrolytes often contain additives, up to 5% by mass or volume, some of which suppress PF_5 formation. Others are added to protect against overcharge, provide fire-retarding protection or improve Solid Electrolyte Interphase (SEI) formation or quality.²⁰³ It is not clear what effect these may have on reaction (2) or other decomposition reactions, or their toxicity or the identity of the products from their combustion.

The second likely source of HF from LIBs is a thermal runaway and fire. The amount of HF produced during an incident depends on the size of the cell and its chemistry^{21,23,142,204–206} and may incorporate endothermal decomposition of the binder – polyvinylidene fluoride (PVDF).¹⁵⁹

Sturk *et al.* (2015) detected significant quantities of HF from burning NMC and LFP type pouch cells.¹⁴¹ Surprisingly, LFP cells produced the highest levels of hydrofluoric acid fumes. So far this type of chemistry was regarded as one of the safest as having the highest cathode decomposition temperature;¹³⁵ however, the cells employed in the LIBESS that exploded at Griffiths University in March 2020 were LFP cells.²⁰⁷

Larsson *et al.* (2017) have estimated that between 20 and 200 mg of HF could be released per W h of an EV battery pack.²² Thus, the amount of HF could be greater than 80–800 times the US National Institute for Occupational Safety and Health Immediate Danger to Life or Health (IDLH) level.²⁰⁸

3.1.3 Vapours and gases. It is now apparent that thermal runaway generates a white vapour during venting the cells, essentially independent of chemistry, form factor and manufacturer.¹³⁹ This white vapour contains H_2 , SO_2 , NO_2 , HF, HCl, CO, CO_2 , droplets of organic solvent (giving the white colour) and a large range of small chain alkanes and alkenes.^{7,20–24} The exact composition of the white vapour appears to depend on the State of Charge (SoC) and battery chemistry.^{20,142,209,210} The white vapour is produced when cell is venting as a result of various chemical processes, triggered at successively higher temperatures.¹³⁵ There is insufficient oxygen produced when the cathode structure collapses to sustain fire, but when the white vapour vents from the cells it may or may not ignite: at $\text{SoC} > 50\%$ and if sufficient oxygen is present, the vapour can

ignite to produce jet-like flames.¹⁴⁴ However, if there is insufficient oxygen, *e.g.* inside a LIBESS with air displaced by the vapour and/or a suppressant,¹³⁸ the vapour represents a wholly novel hazard concerning LIBs; if the white vapour contacts an ignition source, there could be a possibility of a flash fire, fireballs developing, or in extreme cases even a vapour cloud explosion.²¹¹

3.2 Emissions to soil and water

Once physically disposed of, LIBs will leach their contents into the surrounding soils, infiltrate to deeper layers, pollute groundwater and can run-off into surface waters. As water is very often a carrier of pollutants in the soil, it is challenging to ascertain the individual impact of LIBs on these two spheres alone, and hence we discuss the impact on them jointly.

3.2.1 Landfill/dump leachate. One of the most important hazards associated with landfilling and illegal processing is the generation of leachate: it is formed as a result of various biological and chemical degradation processes, and rain percolating through waste. Non-LIB related leachates are a complex mixture of substantial amounts of dissolved organics, inorganic salts, ammonia, heavy metals and xenobiotic organic compounds that are remains of personal care products, pharmaceuticals, industrial, household chemicals, their transformation and degradation products, especially from landfills.^{212–214} Leachate could impose a serious environmental impact as it can act as a transportation medium for hazardous species. It may pollute soils or groundwater and transport contaminants over considerable distances, often many kilometres from the site^{215–219} potentially contaminating groundwater.²¹²

LIB leachates will potentially carry various pollutants such as heavy metals, additives, electrolyte degradation products but also dissolved gases. The latter, such as HF, HCl or SO_2 (in form of sulphuric acid) not only have a straightforward toxic effect but also alter the properties of receiving waters and solutions in soil. The acidification caused by these corrosive species may have the same effect as “acid rain”, lowering the pH and thus strongly impacting plants and animals.²²⁰ They would also enhance the release of soil-bound heavy metals. Under more acidic conditions the actual toxicity of heavy metals is higher than it would be predicted from the metal concentration alone.²²¹

3.2.2 Heavy metals. The content of metals in batteries depends upon their design and size (*i.e.* cylindrical, prismatic or pouch cells), as well as their chemistry (*i.e.* NMC, LCO *etc.*). Typically they are in the range of 0.05–0.37 kg Co per kW h, 0.25–0.86 kg Ni per kW h and 0.46–0.9 kg Li per kW h.^{222–225} These figures translate to tens of kilograms of such materials in EV packs that potentially may be released to the environment if improperly disposed of, representing a series of threats to human health and the environment.

The toxicity of heavy metals from LIBs includes attaching, blocking and disturbing the conformational structure of carbohydrates, lipids, proteins or enzymes.^{226–228} Heavy metals polluting crops, fruits or dust are known to induce genetic damage in children^{229,230} and cause lower academic performance.²³¹



Nickel released into the environment binds strongly to small solid particles, especially containing iron or manganese. Ni has a low tendency to accumulate in fish and small animals. With respect to human health, nickel is the most common allergic metal. It may also cause respiratory disorders and even cancer at higher concentrations.²³² Lithium has relatively low toxicity and small dosages are beneficial for various trophic levels of organisms.²³³ Nevertheless, it is quite an active element and, in higher concentrations, may cause digestive and neurologic systems disorders.^{234,235} Small dosages of cobalt are beneficial to humans (synthesis of vitamin B12) but larger dosages cause respiratory problems and skin rashes.²³⁶ In general, adverse reactions to Co exposure depend primarily on its chemical form.²³⁷

The leachate from LIBs penetrating through landfill or illegal dumpsites will collect and carry various metals, including lithium, cobalt, nickel, manganese, iron, chromium and copper.¹⁵⁵ A few studies have reviewed various leaching scenarios to assess the correlation of typical mass compositions in different types of LIBs to their contamination potential.^{238–241} Metals found in leachates (both real and artificial) that exceeded toxicity limits were lead, mercury, cobalt, copper, nickel, chromium and thallium – depending on the type of test used. One of the studies²⁴² analysed the leachate from a landfill containing NMC batteries: the authors found that less than 4% of the total cobalt, nickel, aluminium, copper, and iron from the battery were in solution, whilst 11.45% of the manganese and 42.50% of the lithium were present.

It is unlikely that metals will be released only in metallic or ionic form from buried LIBs: they will likely be mobilized as nanoparticles (NPs) as well. Such nanomaterials (mostly of cathode origin) and their ecotoxicological potential towards various organisms were assessed by several studies. Thus Hang *et al.* (2017) studied the impact of NMC on the soil bacteria *Shewanella oneidensis* MR-1 and found that exposure to 5 mg L⁻¹ NMC significantly impaired bacterial population growth and respiration.²⁴³ The authors showed that these effects were due to the release of metal ions from the NMC, with the largest effects arising from Ni²⁺ and Co²⁺ species. Gunsolus *et al.* (2017) also investigated the toxicity of NMC towards the same bacteria, varying the relative composition of the metals in the mixed metal oxide.²⁴⁴ The authors found that lowering the Ni and Co content and increasing the Mn content, lowered the biological impact significantly. In fact, reducing the cobalt content and increasing Ni has been a key aspect of NMC battery development over the last few years, driven by safety considerations^{245,246} and global supply chain issues.^{247,248} Another study assessed the biological impact of NMC on a Gram-positive model bacterium, *Bacillus subtilis*.²⁴⁹ Growth and cellular respiration of the bacteria were inhibited significantly by free Ni²⁺ and Co²⁺ ions released from the incongruent dissolution of the NMC. DNA damage tests at the single-cell level confirmed that the toxicity caused by the re-designed NMC (enriched in Mn) was lower in comparison to solutions containing either free Ni and Co or original NMC material. A recent paper²⁵⁰ reported a study on the influence of multiphase lithiated cobalt phosphate (mLCP) nanomaterial on

Shewanella oneidensis MR-1 and *Bacillus subtilis*. The authors found that mLCP was toxic to both species due to the release of cobalt ions.

The toxicity of NMC and LCO materials towards eukaryotic organisms was studied using *Daphnia magna*.²⁵¹ The work showed that there is negligible acute toxicity to daphnid at the highest concentrations of 25 mg L⁻¹, whereas there is a significant impact on daphnid reproduction and survival during chronic exposure (21 days) at concentrations of 0.25 mg L⁻¹ for LCO and 1.0 mg L⁻¹ for NMC. They confirmed that toxicity depends on chemical composition – the replacement of Co by Ni and Mn resulted in better daphnid survival, reproduction, and body size. Finally, the authors highlighted there was a strong nanomaterial-specific impact – probably due to adhesion.²⁵² Although, the effect could not be fully confirmed by experiments with just free Li, Ni, Mn, and Co ions dissolved in suspension metal.

LCO and NMC have been shown to have adverse effects on the benthic invertebrate *Chironomus riparius*²⁵³ by inhibiting growth and development. The increased toxicity of these materials was associated with quick sedimentation of nanoparticles and thus faster interaction with benthic organisms. As in previous studies, a reduction in the biological impact of NMC versus LCO was observed.

On the higher trophic level, the fish class, there is an evident impact of LCO on rainbow trout gill epithelial cells.²⁵⁴ It was found that exposure to Li⁺ and Co²⁺ alone, did not reduce cell viability, however strong toxic effects were observed for LCO nanoparticles and these were found to increase the concentration of reactive oxygen species (ROS). Overproduction of ROS may cause biochemical damage, overstress to cells and ultimately, their damage.²⁵⁵ These negative effects were measured at sub-toxic concentrations of LCO which are close to predicted environmental levels. Finally, it was found that the nanomaterials were internalized in cellular organelles, which was not the case for bacteria.²⁴³ A subsequent paper²⁵⁶ reported studies on the response of the same type of cells to LCO-induced oxidative stress. The authors postulated a “two-hit” model for LCO toxicity. Initially, the intact LCO material induces high levels of ROS leading to gradual engagement of stress response genes (“first hit”). In the next step, the gradual release of metal ions from NPs starts to suppress the expression of these genes, disrupting the cell response to elevated ROS levels (“second hit”). This mode of action ultimately confuses the cell response to stress and may lead to severe damage.

The take-home message from all ecotoxicity studies is that the replacement of toxic metals (Co and Ni) with less toxic ones (Mn) may increase the environmental compatibility and sustainability of the next generation of LIB materials.

Heavy metals from LIBs may also enter the natural environment due to materials recovery processes, as well as legal and illegal disposal routes. Due to the lack of valid data concerning the recycling of LIBs, for analytical purposes, we can consider other well-established processing of automotive batteries. Critical analysis of the lead-acid batteries recovery reveals that large quantities of potentially toxic slag have to be dealt with. In most countries,



such wastes are often disposed of in waste dumps that may lack properly designed engineered landfills, especially in emerging economies. Analysis of slag revealed that apart from high pH (12.22) it contained also high concentrations (g kg^{-1}) of Pb (>101), Cu (>2.5), Cr (>1.2), Zn (0.5), Cd (>0.5) and Ni (0.1), indicating a poor metal recovery in the recycling processes.²⁵⁷ The authors suggested that there was a greater risk of release of these heavy metals over the long-term following disposal into the environment. Fujimori *et al.* (2016) found elevated levels of Pb in some China soils located next to recycling plants.²⁵⁸ In the case of LIB recycling, we also have to deal with the slag resulting from the pyrometallurgical route, mainly containing Mn, Li, and Al.²⁵⁹

3.2.3 Battery degradation products. The study undertaken by Grütze *et al.* (2015) may give indications of the fate of processed battery material when kept in storage (*i.e.* prior to recycling) or landfilled.⁵⁹ The authors shredded NMC LIBs from EVs and enclosed them in sealed tinfoil and plastic cans. Their main goal was to assess which compounds are released from spent, processed material, and if there is any further degradation of original compounds, and the possible emergence of hazardous transformation products. The so-called “black mass” was monitored for over 20 months with regular analyses of gases, liquids and remaining salts. Their results showed that the tinfoil cans underwent fast corrosion – first spots were visible after a few days, and after five months some of the cans were already perforated by rusting. Plastic cans did not show any visual signs of degradation. In addition to HF, the authors found traces of phosphoric acids, LiPF_6 , other additives (*i.e.* cyclohexylbenzene) and solvents – DMC, EC, EMC and their degradation products. More importantly, they identified several alkylfluorophosphates, including dimethyl fluorophosphate (DMFP) and diethylfluorophosphate (DEFP). Alkylfluorophosphates are of concern as they have similar structures to the chemical warfare agents such as sarin.²⁶⁰ DMFP and DEFP were also detected by Kraft *et al.* (2015 and 2016) who investigated the thermal degradation of LIB electrolytes.^{160,261} Although present in manageable low concentrations, they still may have toxic potential both to humans and the environment.

These studies highlight the important issue of storing spent and processed battery materials. If real-life scenarios are envisaged, such as temporary storage in the canister or landfilling, certainly, the corrosion of containers or battery metal case (module or pack) will be speeded up by external environmental factors such as leachate or humid air. It also indicates that spent degraded battery already contains harmful content – these products may enter the air or be transported with the solution to other compartments.

3.2.4 Additives. Finally, LIBs may also leach the remains of electrolyte and its additives.^{262,263} The most common additives are polymers, Lewis acids, sulphur-containing and phosphorous containing additives, polyfluoroalkyl substituted ethylene carbonates or ionic liquids (ILs). The latter, ILs, are particularly interesting as they can play many roles in the battery system: as a pure electrolyte; in mixture with conventional solvents; as a gel polymer electrolyte or as a binder.^{264,265} ILs are non-volatile and a non-flammable class of organic salts consisting of an organic cation

and an organic or inorganic anion and there is a broad spectrum of cations (*i.e.* imidazolium, pyridinium, choline *etc.*) and anions (organic and inorganic).²⁶⁶ Therefore, there is a very broad spectrum of the environmental impact of these compounds depending on their structure. However, due to their properties, the routes of exposure and potential hazards are limited to interactions with solutions. The distribution of ionic liquids in the environment is governed by their structure *e.g.* ILs with longer alkyl chains absorb more easily on the soil surface. Therefore, some ionic liquids may be quite mobile in water or soil columns whereas others may bind strongly to various environmental compartments and may become persistent pollutants. Additionally, the properties of soil such as high cation exchange capacity and/or abundance of organic matter will greatly increase the uptake of ILs.^{267–275} Although their use is usually restricted to small quantities, ILs could still have considerable negative effects on wildlife and human health. For instance, most of the ionic liquids in battery systems are considered toxic and poorly biodegradable compounds.^{276,277} As in the case of the mobility and transport in environmental media, the toxicity of ILs depends on the lipophilicity and alkyl chain length, the direct interaction with the biological system (membrane, cell or organism) and trophic levels (bacteria, plants, invertebrates or human cells). Usually, the longer the derivative the more toxic it is but there is also a strong impact of the counter-ion, especially fluorinated ones.^{278–287}

4. Recommendations for future studies

Table 3 illustrates the possible routes of emission and pollutants released from LIBs. Although partially supported by the existing literature (see Sections 2 and 3), this is more of an indicative list. There are lots of unknowns, incomplete data, not yet researched specific topics or even contradictory results that need to be clarified to mitigate any negative impact of spent batteries.

Therefore, we identified some of the main knowledge gaps and probe the following questions on the environmental impacts of spent LIBs that might help to manage these better in the future:

- (1) What are the current and prospective volumes of spent LIBs?
- (2) How much spent batteries reach the relevant disposal stream?
- (3) Where spent batteries will be processed/disposed of/abandoned?
- (4) In what form: as a whole, partitioned, shredded *etc.* LIBs will be processed/disposed of/abandoned?
- (5) What is the impact of changing chemistries on the waste streams in terms of needed technology but also in terms of the life span?
- (6) What, how, where and in which volumes are hazards released from the spent batteries?
- (7) What is the prevalence and distribution of battery pollutants once being released into the natural environment?



Table 3 Possible pollutants and routes of their emission released from LiBs

Battery component	Source of pollutant	Specific pollutant	Route	Affected environment	Hazard
Pack casing	– Steel	<i>i.e.</i> Fe, Al, Ni, Cr other	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops
Module casing	– Steel	– Fe, Ni, Cr other	Leaching	Land	– In excess toxic to wildlife
	– Aluminium	– Al		Natural waters	– Accumulation in plants and crops
Cell packing	– Aluminium foil	– Al, Ni	Leaching	Natural waters	– In excess toxic to wildlife
	– Polymers	– PET, PP	Fire	Land	– Accumulation in plants and crops
	– Ni-Coated steel			Air	
Cathode	– Metal	– Al	Leaching	Land	– Toxic to the various organism
	– Metal oxides	– LMO – Li/Mn/O – LFP – Li/Fe/P/O – NMC – Li/Ni/Mn/Co/O – LCO – Li/Co/O – NCA – Li/Ni/Co/Al/O	Dust	Natural waters Air	– Toxic to humans if breathed – In excess toxic to wildlife – Accumulation in plants and crops
Anode	– Copper	– Cu	Leaching	Land	– In excess toxic to wildlife
	– Graphite	– C (nanomaterial) – LTO – Li/Ti/O		Natural waters	– Accumulation in plants and crops – Toxic to humans if breathed
Separator	– Polymers	– Polyethylene (PE) – Polypropylene (PP)	Leaching Fire Dust Fire	Land Natural waters Air	– Microplastics accumulation
Binder	– PDVF	– HF		Air	– Toxic to humans if breathed – Toxic to humans if in contact
Electrolyte	– Ethylene carbonate	– HF	Fire	Air	– Toxic to humans if breathed
	– Propylene carbonate	– SO _x	Vapours/gases	Land	– Toxic to humans if in contact
	– Dimethyl carbonate	– HCN	Leaching	Natural waters	– Toxic to wildlife
	– Diethyl carbonate	– H ₂			– Accumulation in soils
	– Salts: LiPF ₆	– CO			
	– Additives	– CO ₂ – NO _x – COS – HCl – Degradation products of electrolyte (<i>i.e.</i> C ₂ H ₄ ; CH ₃ COCHO <i>etc.</i>) – Ionic liquids – Unknown additives/ degradation products			

(8) What is the circulation and interactions of battery pollutants among the land–water–air–emission pathways and the wildlife nexus?

(9) What is the (eco)toxicity and (bio)accumulation of LIBs materials to various organisms and humans?

(10) How should or would environmental studies support the design and disposal of spent LIBs?

Although, some of these questions could be partially answered already based on approximations *i.e.* prospective volumes are estimated on sales number; but there is an urgent need for reliable and verified data. Obtaining reliable and accurate data will have serious implications for the safety of the recycling and disposal facilities and helps to shape, implement and regulate appropriate practices and legislations. The real data should be supported by various Life Cycle Assessments methodology, cost-benefit studies and the use of more modelling in the prediction of *i.e.* life cycle of the specific battery in a given application.

As the growing demand for new LIBs will result in increased numbers of spent batteries, we recommend that this quantity must be appropriately managed and controlled across the various disposal routes. The best-case scenario assumes high collection rates of spent batteries with an almost full recovery of materials that can be reused (boosting the circular economy).

It is evident that domestic *i.e.* decentralised recycling will be more profitable than centralised recycling, however, it will take time for the industry to scale up collection, processes and infrastructures.⁶ It is also argued that latecomers will be threatened by the existing industry that may benefit more quickly from the larger economies of scale. Decentralised systems do require a substantial amount of spent LIBs (especially large EV) to reach economy of scale as it was estimated that recycling costs will decrease if between 1000 and 15 000 tonnes per year are recycled at one plant.⁶ Collection of spent and “second-life” large batteries, might be linked with some business model *e.g.* sale of the car but the lease of battery – then the responsibility is on dealer/seller or can be governed by local councils with *i.e.* specialized collection centre – responsibility on the user. To improve the collection and later decision on the re-use, recycling or landfilling knowing the usage history of “first life” of EV/BESS batteries would be of great use – the battery's condition can be determined much faster and more economically. That will speed up the streamlining of LIBs to an accurate route of processing. However, we must bear in mind that modules in the pack can age differently²⁸⁸ – so possible that the selection will be on the modules not pack level. Nevertheless, improving the reuse of the materials could reduce the environmental, economic and social burden of the existing



battery supply chain including disposal practices is inevitable. However, the challenges in the collection, dismantling and recycling of LIBs must be overcome. It is of crucial importance to develop innovative technologies to lower the cost of material recovery and reduce the environmental impacts of this industry.⁶ Furthermore, illegal disposal and informal processing that leads to serious pollution must be prevented. This could be achieved through better collection schemes, expansions, and improvements in the current recycling infrastructure and posing legal obstacles for exporting second-hand EVs or LIBs. The last anybody wants is that LIBs to become, for instance, a source of soil pollution by heavy metals. Moreover, there should be a constant drive to produce LiBs containing less hazardous and more “green” materials²⁸⁹ that not only improve the capacity and efficiency of the battery but also prevent destructive behaviour and have minimal negative impact on the environment if improperly disposed of.²⁹⁰ New LIBs should be designed for recycling meaning the materials can be easily separated from each other and able to be re-used in new batteries (direct recycling). That links to new technologies of material recovery that are less energy intensive, cheaper and produce less or no secondary pollution.

The improvements must be guided by appropriate legislation, regulations and management structures. These must encourage customers and manufacturers to properly handle spent batteries, highlighting the benefits of recycling (in light of the obligations for economic operators as regards the sourcing of raw materials) and promote the circular economy model and finally, must also clearly ensure where each liability lays.⁴⁸

Finally, we must address the problem of penetration of large “2nd life” LIBs into society. There is a general perception, particularly in Europe, that the re-use (using an EV battery without change in an EV), remanufacture (using an EV battery after replacing defective modules in an EV) and repurposing (using modules from an EV at end-of-life to assemble a battery for a purpose other than traction, *e.g.* stationary storage) of LIBs can make a positive contribution to the decarbonization of the planet.⁴⁸ The safety of new cells, modules and battery packs can be assessed using the “type tests” that form the basis of all codes, standards and regulations governing, for example, domestic and industrial battery energy storage systems. Type testing relies on testing a sample of cells from a batch, usually to destruction, and accepting the result as representative of the batch. The use of type testing on new cells is valid due to the extremely tight quality control of their manufacture, however, such type testing is now accepted as inappropriate to assess the safety of second life LIBs due to the wide variation in SoH across an EV pack during its life and possible exposure to extremes of temperature, overcharging and/or charging at high currents,^{291–293} all of which can increase the potential for thermal runaway.^{294,295} The draft standards IEC63330²⁹⁶ (Requirements for reuse of secondary batteries) and IEC63338²⁹⁷ (General guidance for reuse of secondary cells and batteries) fully acknowledge the fact that type tests cannot be employed to assess the safety of second life LiBs. The key challenge is determining the SoH, or more correctly, the State-of-Safety of second life LIBs.²⁹⁸

A part of the latter must be full knowledge of the first life of the LIB in the EV, including full details of any abuse (*e.g.* overcharging) maximum charge and discharge currents & operational temperatures. The draft standards IEC63330 and IEC63338 were intended to address this problem and hence facilitate the safe application of second life LiBs, but have failed to do so, as they do not require any testing and rely completely on the original manufacturers of the EVs passing on full BMS data (and hence potentially valuable intellectual property) to remanufacturers & repurposers, which is perceived as highly unlikely. The draft EU Batteries Regulation also sidesteps the safety issue of second-life batteries by requiring only that BMS data is made fully available.

It is generally accepted that the re-use, remanufacturing and repurposing of complete packs where the original EV manufacturer is retained in the supply chain is of low risk.²⁹⁹ However, second life cells, modules and even full battery packs are freely available from online retailers, such that inexperienced organisations and even the general public can repurpose LIBs. Thus, a major concern is the use of these suppliers by homeowners to build do-it-yourself domestic BESS: domestic battery energy storage systems are currently completely unregulated in the UK with respect to the application of lithium-ion batteries. Concerns over the hazards posed by such systems in the home environment have been addressed in other countries: thus the US NFPA 855 standard³⁰⁰ and the draft DR2 AS/NZS 5139:2019 Australian and New Zealand standard³⁰¹ do not permit domestic lithium-ion BESS inside the home, and NFPA 855 does not permit do-it-yourself lithium-ion BESS at all.

The online trade-in 2nd life LIBs is completely unregulated, and delivery of these devices is often offered by means illegal under UN 38.3³⁰² as they are classified as dangerous goods and hence require transportation in accordance with the European agreement “Accord européen relatif au transport international des marchandises dangereuses par route” (ADR) requirements.³⁰³

5. Conclusion

There is no doubt that the urgent need to decarbonise transportation puts LIBs at the forefront of the action. However, the growing stream of spent LIBs would impose an enormous threat to the natural environment and human health, as batteries contain hazardous materials. In this review, the current, possible and likely waste management practices of LIBs were identified – from collection and recycling to land-filling, through the EoL incidents up to illegal disposal. Currently, landfilling is the most common practice but there is a growing share of recycling. The current review also assessed the most likely hazards and incidents during each EoL practice. The fire and explosion incidents are currently the most common events that have been evidenced by real-life incidents. Leaching is another pollution pathway that will co-dominate in the future. Identified hazards released from LIBs contain vapours and gases (*i.e.* HF, CO or HCN), metal nanooxides (*i.e.* LMO, NMC), degradation products of the electrolyte



(alkylfluorophosphates) and possible traces of additives. These pollutants may be released to soil, water (groundwater) and air, depending on recycling, disposal method or abuse incident. Released pollutants may pose a serious threat to wildlife and humans with often immediate effects like in the case of contact with HF during EV fire. Degradation of the battery content (especially electrolyte) in some cases may lead to the emergence of chemicals structurally similar to chemical warfare agents. The initial studies on the (eco)toxicity of the cathode nanomaterials showed that LIBs may pose a threat to living organisms and human health. But the replacement of toxic metals (Co and Ni) with less toxic ones (Mn) may increase the environmental compatibility and sustainability of the next generation of lithium battery materials. Finally, we identified several urgent knowledge gaps that need to be covered to mitigate the negative impact on the environment of LIBs, and recommended some actions to tackle these issues.

Author contributions

Wojciech Mrozik: writing – original draft, writing – review & editing, conceptualization, visualization, investigation; methodology; Mohammad Ali Rajaeifar: writing – original draft, writing – review & editing; Oliver Heidrich: writing – original draft, writing – review & editing, conceptualization, funding; Paul Christensen: writing – original draft, writing – review & editing, funding.

Abbreviations

Aging	The loss of capacity due to, <i>e.g.</i> loss of lithium ions or spallation of the anodes. This can be due to use (charging and discharging) and/or sitting at open circuit (calendar aging)
Anode	The negative electrode. In lithium-ion batteries this is most typically small particles of graphite
Battery (pack)	The complete energy storage unit consisting of a number of modules
BESS	Battery energy storage system
Cathode	The positive electrode. These typically comprise lithium plus metal oxides: <i>e.g.</i> lithium nickel manganese cobalt oxide ($\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$)
Cell	The smallest unit of a battery
Electrolyte	In electrochemistry, this term is ambiguous as it can refer to the inorganic salt (<i>e.g.</i> LiPF_6) or to the salt + organic solvent
End of Life (EoL)	The point at which a battery ceases to be suitable for its current application. For automotive batteries this is typically 75–80% State-of-Health
GHG	Greenhouse gases, gases that cause the greenhouse effect <i>e.g.</i> CO_2 and CH_4

Landfill	A site for the disposal of waste materials
LCO cathode	Lithium cobalt oxide, LiCoO_2
LIB	Lithium-ion battery
LIBESS	Lithium-ion battery energy storage system
LFP cathode	Lithium iron (ferrous) phosphate, LiFePO_4
LMO cathode	Lithium manganese oxide LiMnO_2
LTO anode	Lithium titanium oxide $\text{Li}_4\text{Ti}_5\text{O}_{12}$
MRF	Material recovery facilities; solid-waste management plant that processes recyclable materials to sell to manufacturers as raw materials for new products
NCA cathode	(lithium) Nickel cobalt aluminium oxide, <i>e.g.</i> $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$
NMC cathode	(lithium) Nickel manganese cobalt oxide, <i>e.g.</i> $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$ (NMC 111), $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$ (NMC 622)
PAHs	Polycyclic aromatic hydrocarbons; made up of fused aromatic rings molecules
Recycling	The process of converting waste materials into new materials and objects
Separator	A plastic film permeable to lithium and hexafluorophosphate ions that prevents the anode and cathode from touching and causing a short-circuit
Solid Electrolyte Interphase (SEI)	The protective layer that forms on the anode during the first charge from reduction of the LiPF_6 and solvent which prevents further, explosive degradation of the electrolyte and thermal runaway
Solvent	Mixture of organic carbonates, containing ethylene carbonate, as this is essential for the formation of the SEI. Ethylene carbonate is a solid at room temperature and other carbonates are essential to reduce viscosity
State of Charge (SoC)	The amount of charge stored compared to that equivalent to full charge, expressed as %
State of Health (SoH)	The amount of charge stored currently when fully charged compared to that stored (when fully charged) at the beginning of the cell or battery life, expressed as %
VOCs	Volatile organic compounds; compounds that have a high vapour pressure and low water solubility

Conflicts of interest

There are no conflicts to declare.

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References

- H. E. Melin, M. A. Rajaeifar, A. Y. Ku, A. Kendall, G. Harper and O. Heidrich, *Science*, 2021, **373**, 384–387.
- European Commission, 2019, COM/2019/640 final.
- R. Harrabin, *Ban on new petrol and diesel cars in UK from 2030 under PM's green plan*, 2020, accessed 20.11.2020.
- UKRI, *Industrial Strategy Challenge Fund: Future of mobility*, 2020, accessed 20.09.2020.
- UKRI, *Industrial Strategy Challenge Fund*, 2020, accessed 20.09.2020.
- L. Lander, T. Cleaver, M. A. Rajaeifar, V. Nguyen-Tien, R. J. R. Elliott, O. Heidrich, E. Kendrick, J. S. Edge and G. Offer, *iScience*, 2021, **24**, 102787.
- G. Lombardo, B. Ebin, M. R. S. J. Foreman, B.-M. Steenari and M. Petranikova, *ACS Sustainable Chem. Eng.*, 2019, **7**, 13668–13679.
- M. A. Rajaeifar, O. Heidrich, P. Ghadimi, M. Rauegi and Y. Wu, *Resour., Conserv. Recycl.*, 2020, **161**, 104905.
- M. J. Smith and F. M. Gray, in *Alternative Energy and Shale Gas Encyclopedia*, ed. J. H. Lehr, J. Keeley and T. B. Kingery, 2016, pp. 566–577.
- J.-P. Skeete, P. Wells, X. Dong, O. Heidrich and G. Harper, *Energy Res. Soc. Sci.*, 2020, **69**, 101581.
- Veolia, 2020, <https://www.veolia.co.uk/press-releases/preventing-battery-fires>.
- B. Morris, 2020, <https://www.bbc.co.uk/news/business-54634802>, accessed 01.10.2021.
- D. Lisbona and T. Snee, *Process Saf. Environ. Prot.*, 2011, **89**, 434–442.
- FAA, *An Introduction to Lithium Batteries and the Challenges that they pose to the Waste and Recycling Industry*, <https://www.youtube.com/watch?v=OjFHYpI7GrM&feature=youtu.be>, accessed 15.11.2020.
- M. Reintjes, <https://recyclinginternational.com/business/at-least-one-scrap-fire-every-week-in-germany/28831/>, 2020, accessed 05.03.2021.
- BBC, <https://www.bbc.co.uk/news/uk-england-nottinghamshire-47976224>, 2019, accessed 20.09.2021.
- K. Akemi, 2020, <http://www.asahi.com/ajw/articles/AJ202001100077.html>, accessed 18.09.2021.
- P. A. Christensen, P. A. Anderson, G. D. J. Harper, S. M. Lambert, W. Mrozik, M. A. Rajaeifar, M. S. Wise and O. Heidrich, *Renewable Sustainable Energy Rev.*, 2021, **148**, 111240.
- H. E. Mellin, *State-of-the-art in reuse and recycling of lithium-ion batteries – A research review*, The Swedish Energy Agency, Circular Energy Storage, 2019.
- A. Lecocq, G. G. Eshetu, S. Grugeon, N. Martin, S. Laruelle and G. Marlair, *J. Power Sources*, 2016, **316**, 197–206.
- F. Larsson, S. Bertilsson, M. Furlani, I. Albinsson and B.-E. Mellander, *J. Power Sources*, 2018, **373**, 220–231.
- F. Larsson, P. Andersson, P. Blomqvist and B.-E. Mellander, *Sci. Rep.*, 2017, **7**, 10018.
- S. Chen, Z. Wang, J. Wang, X. Tong and W. Yan, *J. Loss Prev. Process Ind.*, 2020, **63**, 103992.
- G. Lombardo, B. Ebin, M. R. S. J. Foreman, B.-M. Steenari and M. Petranikova, *J. Hazard. Mater.*, 2020, **393**, 122372.
- G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines and P. Anderson, *Nature*, 2019, **575**, 75–86.
- C. M. Costa, J. C. Barbosa, R. Gonçalves, H. Castro, F. J. D. Campo and S. Lanceros-Méndez, *Energy Storage Mater.*, 2021, **37**, 433–465.
- C. J. Rydh and B. Svärd, *Sci. Total Environ.*, 2003, **302**, 167–184.
- Y. Hua, S. Zhou, Y. Huang, X. Liu, H. Ling, X. Zhou, C. Zhang and S. Yang, *J. Power Sources*, 2020, **478**, 228753.
- S. King and N. J. Boxall, *J. Cleaner Prod.*, 2019, **215**, 1279–1287.
- F. O. Ongondo, I. D. Williams and G. Whitlock, *Waste Manage.*, 2015, **45**, 4–9.
- X. Zeng, J. Li and N. Singh, *Crit. Rev. Environ. Sci. Technol.*, 2014, **44**, 1129–1165.
- European Commission, 2020, COM(2020) 474 final.
- D. Qiao, G. Wang, T. Gao, B. Wen and T. Dai, *Sci. Total Environ.*, 2021, **764**, 142835.
- S. Sun, C. Jin, W. He, G. Li, H. Zhu and J. Huang, *Sci. Total Environ.*, 2021, **776**, 145913.
- T. L. Curtis, L. Smith, H. Buchanan and G. Heath, *A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations*, Report NREL/TP-6A20-77035, National Renewable Energy Laboratory (NREL), 2021.
- Call2Recycle, *Recycling Laws By State*, <https://www.call2recycle.org/recycling-laws-by-state/>, accessed 25 Mar 2021.
- M. A. Rajaeifar, M. Rauegi, B. Steubing, A. Hartwell, P. Anderson and O. Heidrich, *J. Ind. Ecol.*, 2021, 1–12.
- J. Heelan, E. Gratz, Z. Zheng, Q. Wang, M. Chen, D. Apelian and Y. Wang, *JOM*, 2016, **68**, 2632–2638.
- Y. Bai, N. Muralidharan, Y.-K. Sun, S. Passerini, M. S. Whittingham and I. Belharouak, *Mater. Today*, 2020, **41**, 304–315.
- M. Chen, X. Ma, B. Chen, R. Arsenault, P. Karlson, N. Simon and Y. Wang, *Joule*, 2019, **3**, 2622–2646.
- H. E. Melin, *The lithium-ion battery end-of-life market 2018–2025*, Circular Energy Storage, United Kingdom, 2018.
- EBRA, *Noticeable Growth of the Quantity of Batteries Recycled*, European Battery Recycling Association, Brussels, Belgium, 2012.
- J. Song, W. Yan, H. Cao, Q. Song, H. Ding, Z. Lv, Y. Zhang and J. Sun, *J. Cleaner Prod.*, 2019, **215**, 570–581.



- 44 R. Danino-Perraud, *The Recycling of Lithium-ion Batteries: A Strategic Pillar for the European Battery Alliance*, Etudes de l'Ifri, Ifri, 2020.
- 45 A. Akcil, C. Erust, S. Ozdemiroglu, V. Fonti and F. Beolchini, *J. Cleaner Prod.*, 2015, **86**, 24–36.
- 46 A. P. Das, L. B. Sukla, N. Pradhan and S. Nayak, *Bioresour. Technol.*, 2011, **102**, 7381–7387.
- 47 European Commission, 2014 Directive 2006/66/EC.
- 48 European Commission, 2020, COM(2020) 798/3.
- 49 J. Baars, T. Domenech, R. Bleischwitz, H. E. Melin and O. Heidrich, *Nat. Sustainability*, 2021, **4**, 71–79.
- 50 R. Sommerville, P. Zhu, M. A. Rajaeifar, O. Heidrich, V. Goodship and E. Kendrick, *Resour., Conserv. Recycl.*, 2021, **165**, 105219.
- 51 X. Zeng and J. Li, *Front. Environ. Sci. Eng.*, 2014, **8**, 792–796.
- 52 C. Ekberg and M. Petranikova, in *Lithium Process Chemistry*, ed. A. Chagnes and J. Światowska, Elsevier, Amsterdam, 2015, pp. 233–267.
- 53 D. L. Thompson, J. M. Hartley, S. M. Lambert, M. Shiref, G. D. J. Harper, E. Kendrick, P. Anderson, K. S. Ryder, L. Gaines and A. P. Abbott, *Green Chem.*, 2020, **22**, 7585–7603.
- 54 L. Gaines, *Sustainable Mater. Technol.*, 2014, **1-2**, 2–7.
- 55 M. Fan, X. Chang, Y.-J. Guo, W.-P. Chen, Y.-X. Yin, X. Yang, Q. Meng, L.-J. Wan and Y.-G. Guo, *Energy Environ. Sci.*, 2021, **14**, 1461–1468.
- 56 M. Sethurajan and S. Gaydardzhiev, *Resour., Conserv. Recycl.*, 2021, **165**, 105225.
- 57 J. Yu, X. Wang, M. Zhou and Q. Wang, *Energy Environ. Sci.*, 2019, **12**, 2672–2677.
- 58 Y. He, X. Yuan, G. Zhang, H. Wang, T. Zhang, W. Xie and L. Li, *Sci. Total Environ.*, 2020, 142382.
- 59 M. Grützke, S. Krüger, V. Kraft, B. Vortmann, S. Rothermel, M. Winter and S. Nowak, *ChemSusChem*, 2015, **8**, 3433–3438.
- 60 M. Mohr, J. F. Peters, M. Baumann and M. Weil, *J. Ind. Ecol.*, 2020, **24**, 1310–1322.
- 61 J. B. Dunn, L. Gaines, J. C. Kelly, C. James and K. G. Gallagher, *Energy Environ. Sci.*, 2015, **8**, 158–168.
- 62 T. J. van der Kuip, L. Huang and C. R. Cherry, *Environ. Health*, 2013, **12**, 61.
- 63 A. Manhart, T. Amera, G. Kuepouo, D. Mathai, S. Mng'anya and T. Schleicher, *The deadly business – Findings from the Lead Recycling Africa Project*, Oeko-Institut EV, Freiburg, Germany, 2016.
- 64 WHO, Recycling used lead-acid batteries: health considerations, World Health Organization, Geneva, 2017.
- 65 WHO, 2017, <https://www.who.int/publications/i/item/recycling-used-lead-acid-batteries-health-considerations>.
- 66 Y. Yu, J. Mao and X. Chen, *Sci. Total Environ.*, 2020, **746**, 140763.
- 67 F. Cerdas, R. Gerbers, S. Andrew, J. Schmitt, F. Dietrich, S. Thiede, K. Dröder and C. Herrmann, *Recycling of Lithium-Ion Batteries*, Springer, 2018, pp. 83–97.
- 68 M. D. Vaverková, *Geosciences*, 2019, **9**, 431.
- 69 W. Sun, X. Wang, J. F. DeCarolus and M. A. Barlaz, *Waste Manage.*, 2019, **91**, 120–127.
- 70 J. Havukainen, M. Zhan, J. Dong, M. Liikanen, I. Deviatkin, X. Li and M. Horttanainen, *J. Cleaner Prod.*, 2017, **141**, 453–461.
- 71 S. T. Tan, C. T. Lee, H. Hashim, W. S. Ho and J. S. Lim, *J. Cleaner Prod.*, 2014, **71**, 48–58.
- 72 V. Forti, C. P. Baldé, R. Kuehr and G. Bel, *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*, United Nations University (UNU), United Nations Institute for Training and Research (UNITAR), SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam, 2020.
- 73 S. Karnchanawong and P. Limpitprakan, *Waste Manage.*, 2009, **29**, 550–558.
- 74 A. D. Zand and M. A. Abdul, *Waste Manage.*, 2008, **28**, 2085–2090.
- 75 I. C. Nnorom and O. Osibanjo, *Int. J. Environ. Sci. Technol.*, 2009, **6**, 641–650.
- 76 N. Ferronato and V. Torretta, *Int. J. Environ. Res. Public Health*, 2019, **16**, 1060.
- 77 FEMA, *Landfill fires their magnitude, characteristics, and mitigation*, Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center, Arlington, 2002.
- 78 J. M. Torrente-Velásquez, M. Giampietro, M. Ripa and R. Chifari, *Sci. Total Environ.*, 2020, **706**, 135988.
- 79 P. Kjeldsen, M. A. Barlaz, A. P. Rooker, A. Baun, A. Ledin and T. H. Christensen, *Crit. Rev. Environ. Sci. Technol.*, 2002, **32**, 297–336.
- 80 K. Szymański, B. Janowska, A. Izewska, R. Siedko and I. Siebińska, *Environ. Monit. Assess.*, 2018, **190**, 415.
- 81 O. Bridges, J. W. Bridges and J. F. Potter, *Environmentalist*, 2000, **20**, 325–334.
- 82 A. E. Peter, S. M. Shiva Nagendra and I. M. Nambi, *Waste Manage.*, 2019, **85**, 151–163.
- 83 P. Ruokojärvi, M. Ettala, P. Rahkonen, J. Tarhanen and J. Ruuskanen, *Chemosphere*, 1995, **30**, 1697–1708.
- 84 P. M. Lemieux, C. C. Lutes and D. A. Santoianni, *Prog. Energy Combust. Sci.*, 2004, **30**, 1–32.
- 85 J. Downard, A. Singh, R. Bullard, T. Jayarathne, C. M. Rathnayake, D. L. Simmons, B. R. Wels, S. N. Spak, T. Peters, D. Beardsley, C. O. Stanier and E. A. Stone, *Atmos. Environ.*, 2015, **104**, 195–204.
- 86 J. K. Øygard, A. Måge, E. Gjengedal and T. Svane, *Waste Manage.*, 2005, **25**, 712–718.
- 87 S. Moqbel, D. Reinhart and R. H. Chen, *Waste Manage.*, 2010, **30**, 1600–1607.
- 88 D. Chavan, P. Lakshmikanthan, P. Mondal, S. Kumar and R. Kumar, *Waste Manage.*, 2019, **97**, 123–130.
- 89 ESA, 2020, http://www.esauk.org/application/files/2615/9783/3646/PRESS_RELEASE_Take_Charge_Campaign_v1.pdf.
- 90 Viridor, 2019, <https://www.viridor.co.uk/who-we-are/latest-news/2019-news/lithium-ion-battery-warning-issued-after-landfill-site-fire/>, accessed 29.09.2021.
- 91 H. Gans, *Shoreway Fire Hazard Mitigation Plan*, Rethink Waste South Bayside Waste Management Authority,



- https://rethinkwaste.org/wp-content/uploads/legacy_media/022317-shoreway-operations.original.pdf, 2017.
- 92 W. Liu, X. Zhong, J. Han, W. Qin, T. Liu, C. Zhao and Z. Chang, *ACS Sustainable Chem. Eng.*, 2019, **7**, 1289–1299.
 - 93 S. Morales, G. E. Raúl, A. Toro, R. Morales, L. Leiva and A. Manuel, *Air Qual., Atmos. Health*, 2018, **11**, 111–121.
 - 94 D. R. Nammari, W. Hogland, M. Marques, S. Nimmermark and V. Moutavtchi, *Waste Manage.*, 2004, **24**, 9–18.
 - 95 A. D. St-Amand, P. M. Mayer and J. M. Blais, *Atmos. Environ.*, 2008, **42**, 2948–2958.
 - 96 E. D. Vicente, A. M. Vicente, B. A. Musa Bandowe and C. A. Alves, *Air Qual., Atmos. Health*, 2016, **9**, 653–668.
 - 97 I. Vassiliadou, A. Papadopoulos, D. Costopoulou, S. Vasiliadou, S. Christoforou and L. Leondiadis, *Chemosphere*, 2009, **74**, 879–884.
 - 98 Y.-H. Shih, S. J. e. Kasaon, C.-H. Tseng, H.-C. Wang, L.-L. Chen and Y.-M. Chang, *Air Qual., Atmos. Health*, 2016, **9**, 201–211.
 - 99 L. Bastian, J. Yano, Y. Hirai and S.-I. Sakai, *J. Mater. Cycles Waste Manage.*, 2013, **15**, 229–241.
 - 100 B. K. Gullett, B. Wyrzykowska, E. Grandesso, A. Touati, D. G. Tabor and G. S. Ochoa, *Environ. Sci. Technol.*, 2010, **44**, 394–399.
 - 101 B. Gworek, A. Hajduk, E. Koda, A. Grochowalski and A. Jeske, *Chemosphere*, 2013, **92**, 753–759.
 - 102 S. Weichenthal, D. Van Rijswijk, R. Kulka, H. You, K. Van Ryswyk, J. Willey, R. Dugandzic, R. Sutcliffe, J. Moulton, M. Baike, L. White, J.-P. Charland and B. Jessiman, *Environ. Res.*, 2015, **142**, 46–50.
 - 103 A. T. Nair, J. Senthilnathan and S. M. S. Nagendra, *Process Saf. Environ. Prot.*, 2019, **121**, 143–154.
 - 104 L. Chrysikou, P. Gemenetis, A. Kouras, E. Manoli, E. Terzi and C. Samara, *Environ. Int.*, 2008, **34**, 210–225.
 - 105 B. Sahariah, L. Goswami, I. U. Farooqui, P. Raul, P. Bhattacharyya and S. Bhattacharya, *J. Geochem. Explor.*, 2015, **157**, 100–109.
 - 106 S. Kumar, S. G. Aggarwal, P. K. Gupta and K. Kawamura, *Atmos. Environ.*, 2015, **108**, 49–58.
 - 107 R. Agarwal, K. Shukla, S. Kumar, S. G. Aggarwal and K. Kawamura, *Atmos. Pollut. Res.*, 2020, **11**, 554–565.
 - 108 D. Perkins, M.-N. Brune Drisse, T. Nxele and D. Sly, *Ann. Global Health*, 2014, **80**, 286–295.
 - 109 M. Iqbal, K. Breivik, J. H. Syed, R. N. Malik, J. Li, G. Zhang and K. C. Jones, *Environm. Pollut.*, 2015, **207**, 308–318.
 - 110 M. Ackah, *Environ. Sci. Pollut. Res.*, 2017, **24**, 24092–24101.
 - 111 J. Huisman, I. Botezatu, L. Herreras, M. Liddane, J. Hints, V. Luda di Cor temiglia, P. Leroy, E. Vermeersch, S. Mohanty, S. van den Brink, B. Ghenciu, D. Dimitrova, E. Nash, T. Shryane, M. Wieting, J. Kehoe, C. P. Baldé, F. Magalini, A. Zanasi, F. Ruini and A. Bonzio, *Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap*, Lyon, France, 2015.
 - 112 V. Rotter, P. Maehlitz, N. Korf, P. Chancerel, J. Huisman, H. Habib, L. Herreras, S. Ljunggren and A. Hallberg, *Prospecting Secondary raw materials in the Urban mine and Mining waste – Deliverable 4.1 – Waste Flow Studies*, <http://www.prosumproject.eu/sites/default/files/160324%20ProSUM%20Deliverable%20Report%20%204%201%20FINAL%20Submitted.pdf>, 2016.
 - 113 S.-X. Quan, B. Yan, F. Yang, N. Li, X.-M. Xiao and J.-M. Fu, *Environ. Sci. Pollut. Res.*, 2015, **22**, 1290–1298.
 - 114 Y. Liu, X. Huo, L. Xu, X. Wei, W. Wu, X. Wu and X. Xu, *Sci. Total Environ.*, 2018, **624**, 621–627.
 - 115 Y. Wang, J. Hu, W. Lin, N. Wang, C. Li, P. Luo, M. Z. Hashmi, W. Wang, X. Su, C. Chen, Y. Liu, R. Huang and C. Shen, *Environ. Int.*, 2016, **87**, 33–41.
 - 116 Y. Lin, X. Xu, Y. Dai, Y. Zhang, W. Li and X. Huo, *Sci. Total Environ.*, 2016, **573**, 760–766.
 - 117 X. Tang, C. Shen, D. Shi, S. A. Cheema, M. I. Khan, C. Zhang and Y. Chen, *J. Hazard. Mater.*, 2010, **173**, 653–660.
 - 118 Z. Wu, G. Gao and Y. Wang, *Ecotoxicol. Environ. Saf.*, 2019, **180**, 705–714.
 - 119 A. K. Awasthi, M. Wang, M. K. Awasthi, Z. Wang and J. Li, *Environ. Pollut.*, 2018, **243**, 1310–1316.
 - 120 M. Vaccari, G. Vinti, A. Cesaro, V. Belgiorno, S. Salhofer, M. I. Dias and A. Jandric, *Int. J. Environ. Res. Public Health*, 2019, **16**, 1595.
 - 121 B. H. Robinson, *Sci. Total Environ.*, 2009, **408**, 183–191.
 - 122 B. Ericson, P. Landrigan, M. P. Taylor, J. Frostad and J. Caravanas, *Ann. Global Health*, 2017, **82**, 686–689.
 - 123 P. Gottesfeld, F. H. Were, L. Adogame, S. Gharbi, D. San, M. M. Nota and G. Kuepouo, *Environ. Res.*, 2018, **161**, 609–614.
 - 124 S. Mandić-Rajčević, Z. Bulat, V. Matović, M. Popević, M. Lepić, B. Mandić, M. Jovanović, V. Haufroid, M. Žarković and P. Bulat, *Environ. Res.*, 2018, **167**, 725–734.
 - 125 M. P. Taylor, C. F. Isley and J. Glover, *Environ. Int.*, 2019, **127**, 340–352.
 - 126 Y. Yan, S. Yang, Y. Zhou, Y. Song, J. Huang, Z. Liu, Y. Wang and S. Wei, *Environ. Int.*, 2020, **137**, 105553.
 - 127 K. Varshney, P. K. Varshney, K. Gautam, M. Tanwar and M. Chaudhary, *Mater. Today: Proc.*, 2020, **26**(2), 592–602.
 - 128 M. Singh, P. S. Thind and S. John, *Chemosphere*, 2018, **203**, 426–433.
 - 129 L. Carrizales, I. Razo, J. I. Téllez-Hernández, R. Torres-Nerio, A. Torres, L. E. Batres, A. C. Cubillas and F. Díaz-Barriga, *Environ. Res.*, 2006, **101**, 1–10.
 - 130 M. P. Taylor, D. Camenzuli, L. J. Kristensen, M. Forbes and S. Zahran, *Environ. Pollut.*, 2013, **178**, 447–454.
 - 131 ISO 26367-1:2011, Guidelines for assessing the adverse environmental impact of fire effluents – Part 1, General, 2011.
 - 132 A. A. Stec, K. Dickens, J. L. J. Barnes and C. Bedford, *Chemosphere*, 2019, **226**, 576–586.
 - 133 L. Bravo Diaz, H. He, Z. Hu, F. Restuccia, M. Marinescu, J. Varela Barreras, Y. Patel, G. Offer and G. Rein, *J. Electrochem. Soc.*, 2020, **167**, 090559.
 - 134 J. Hemmerdinger, 2020, <https://www.flightglobal.com/airframers/eviation-alice-fire-involved-lithium-ion-batteries-which-ignited-after-hours-of-powerplant-tests/141228.article>, accessed 27.08.2021.



- 135 X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia and X. He, *Energy Storage Mater.*, 2018, **10**, 246–267.
- 136 H. Mai, 2019, <https://www.utilitydive.com/news/aps-storage-facility-explosion-raises-questions-about-battery-safety/553540/>, accessed 01.09.2021.
- 137 G. Hering, 2019, <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/51900636>, accessed 01.09.2021.
- 138 DNV GL, McMicken Battery Energy Storage System Event Technical Analysis and Recommendations, Arizona Public Service, <https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/McMickenFinalTechnicalReport.ashx?la=en&hash=50335FB5098D9858BFD276C40FA54FCE>, 2020.
- 139 I. Exponent, Progress Report, APS McMicken, <https://docket.images.azcc.gov/E000007939.pdf>, 2020.
- 140 Q. Wang, B. Mao, S. I. Stolarov and J. Sun, *Prog. Energy Combust. Sci.*, 2019, **73**, 95–131.
- 141 D. Sturk, L. Hoffmann and A. Ahlberg Tidblad, *Traffic Inj. Prev.*, 2015, **16**, S159–S164.
- 142 J. Sun, J. Li, T. Zhou, K. Yang, S. Wei, N. Tang, N. Dang, H. Li, X. Qiu and L. Chen, *Nano Energy*, 2016, **27**, 313–319.
- 143 P. A. Christensen, Z. Milojevic, M. S. Wise, M. Ahmeid, P. S. Attidekou, W. Mrozik, N. A. Dickman, F. Restuccia, S. M. Lambert and P. K. Das Methology, *Appl. Therm. Eng.*, 2021, 116623.
- 144 P. A. Christensen, Z. Milojevic, M. S. Wise, M. Ahmeid, P. S. Attidekou, W. Mrozik, N. A. Dickman, F. Restuccia, S. M. Lambert and P. K. Das, *Appl. Therm. Eng.*, under review.
- 145 X. Vasseur, 2020, <https://www.navalnews.com/naval-news/2020/03/jmsdf-commissioned-its-1st-li-ion-battery-submarine-ss-511-js-oryu-%E3%81%8A%E3%81%86%E3%82%8A%E3%82%85%E3%81%86/>, accessed 17.08.2021.
- 146 Z. Zhou, M. Benbouzid, J. Frédéric Charpentier, F. Scullier and T. Tang, *Renewable Sustainable Energy Rev.*, 2013, **18**, 390–400.
- 147 M. Schuler, 2019, <https://gcaptain.com/fire-and-gas-explosion-in-battery-room-of-norwegian-ferry-prompts-lithium-ion-power-warning>, accessed 24.08.2021.
- 148 M. J. Derewku, S. C. Gad, F. Gavigan and B. J. Dunn, *J. Toxicol., Cutaneous Ocul. Toxicol.*, 1985, **4**, 73–85.
- 149 A. A. Stec, *Fire Saf. J.*, 2017, **91**, 79–90.
- 150 A. M. Bernardes, D. C. R. Espinosa and J. A. S. Tenório, *J. Power Sources*, 2004, **130**, 291–298.
- 151 J. A. Guevara-García and V. Montiel-Corona, *J. Environ. Manage.*, 2012, **95**, S154–S157.
- 152 M. Sun, X. Yang, D. Huisingh, R. Wang and Y. Wang, *J. Cleaner Prod.*, 2015, **107**, 775–785.
- 153 Y. Yu, X. Wang, D. Wang, K. Huang, L. Wang, L. Bao and F. Wu, *J. Hazard. Mater.*, 2012, **229–230**, 455–460.
- 154 Y. Choi, K.-J. Chen and T. L. Marsh, *J. Consum. Behav.*, 2020, **19**, 382–396.
- 155 K. M. Winslow, S. J. Laux and T. G. Townsend, *Resour., Conserv. Recycl.*, 2018, **129**, 263–277.
- 156 F. Rodrigues dos Santos, E. de Almeida, P. D. da Cunha Kemerich and F. L. Melquiades, *X-Ray Spectrom.*, 2017, **46**, 512–521.
- 157 H. Omar and S. Rohani, *Front. Chem. Sci. Eng.*, 2015, **9**, 15–32.
- 158 N. P. Lebedeva and L. Boon-Brett, *J. Electrochem. Soc.*, 2016, **163**, A821–A830.
- 159 J. Diekmann, M. Grützke, T. Loellhoeffel, M. Petermann, S. Rothermel, M. Winter, S. Nowak and A. Kwade, in *Recycling of Lithium-Ion Batteries: The LithoRec Way*, ed. A. Kwade and J. Diekmann, Springer International Publishing, Cham, 2018, pp. 39–51.
- 160 V. Kraft, W. Weber, B. Streipert, R. Wagner, C. Schultz, M. Winter and S. Nowak, *RSC Adv.*, 2016, **6**, 8–17.
- 161 L. Terborg, S. Weber, F. Blaske, S. Passerini, M. Winter, U. Karst and S. Nowak, *J. Power Sources*, 2013, **242**, 832–837.
- 162 M. Grützke, V. Kraft, B. Hoffmann, S. Klamor, J. Diekmann, A. Kwade, M. Winter and S. Nowak, *J. Power Sources*, 2015, **273**, 83–88.
- 163 U. Heider, R. Oesten and M. Jungnitz, *J. Power Sources*, 1999, **81–82**, 119–122.
- 164 A. V. Plakhotnyk, L. Ernst and R. Schmutzler, *J. Fluorine Chem.*, 2005, **126**, 27–31.
- 165 T. Kawamura, S. Okada and J.-I. Yamaki, *J. Power Sources*, 2006, **156**, 547–554.
- 166 E. Chalvatzaki, V. Aleksandropoulou and M. Lazaridis, *Water, Air, Soil Pollut.*, 2013, **225**, 1782.
- 167 E. Chalvatzaki, V. Aleksandropoulou, T. Glytsos and M. Lazaridis, *Waste Manage.*, 2012, **32**, 2456–2468.
- 168 K. H. Lui, T. Jones, K. Bérubé, S. S. H. Ho, S. H. L. Yim, J.-J. Cao, S. C. Lee, L. Tian, D. W. Min and K. F. Ho, *Chemosphere*, 2019, **230**, 578–586.
- 169 E. Chalvatzaki, I. Kopanakis, M. Kontaksakis, T. Glytsos, N. Kalogerakis and M. Lazaridis, *Waste Manage.*, 2010, **30**, 2058–2064.
- 170 L. Guan, Y. Liang, Y. Tian, Z. Yang, Y. Sun and Y. Feng, *Sci. Total Environ.*, 2019, **659**, 764–772.
- 171 S. Madhwal, V. Prabhu, S. Sundriyal and V. Shridhar, *Atmos. Pollut. Res.*, 2020, **11**, 156–169.
- 172 A. E. Peter, S. M. Shiva Nagendra and I. M. Nambi, *Atmos. Pollut. Res.*, 2018, **9**, 1021–1031.
- 173 G. Feuyit, S. Nzali, J. N. Lambi and S. Laminsi, *J. Chem.*, 2019, **2019**, 3021894.
- 174 Y. Wang, K. Cheng, W. Wu, H. Tian, P. Yi, G. Zhi, J. Fan and S. Liu, *Atmos. Environ.*, 2017, **152**, 6–15.
- 175 D. W. Dockery, *Ann. Epidemiol.*, 2009, **19**, 257–263.
- 176 S. K. Guttikunda and R. Goel, *Environ. Dev.*, 2013, **6**, 8–20.
- 177 L. Koshy, T. Jones and K. Bérubé, *Biomarkers*, 2009, **14**, 49–53.
- 178 A. D. Kappos, P. Bruckmann, T. Eikmann, N. Englert, U. Heinrich, P. Höppe, E. Koch, G. H. M. Krause, W. G. Kreyling, K. Rauchfuss, P. Rombout, V. Schulz-Klemp, W. R. Thiel and H. E. Wichmann, *Int. J. Hyg. Environ. Health*, 2004, **207**, 399–407.
- 179 N. Englert, *Toxicol. Lett.*, 2004, **149**, 235–242.
- 180 N. Li, G. Chen, F. Liu, S. Mao, Y. Liu, S. Liu, Z. Mao, Y. Lu, C. Wang, Y. Guo, H. Xiang and S. Li, *Environ. Res.*, 2020, **182**, 109109.



- 181 S. Lee, W. Lee, D. Kim, E. Kim, W. Myung, S. Y. Kim and H. Kim, *Environ. Res.*, 2019, **171**, 313–320.
- 182 X. Chen, X. Li, X. Yuan, G. Zeng, J. Liang, X. Li, W. Xu, Y. Luo and G. Chen, *Environ. Int.*, 2018, **116**, 92–100.
- 183 C. Chen, P. Zhu, L. Lan, L. Zhou, R. Liu, Q. Sun, J. Ban, W. Wang, D. Xu and T. Li, *Environ. Res.*, 2018, **161**, 188–194.
- 184 M. Kermani, M. Aghaei, M. Gholami, F. B. Asl, S. Karimzadeh, S. F. Jokandan and M. Dowlati, *Iran Occup. Health*, 2016, **13**, 49–61.
- 185 G. R. Zosky, C. E. Boylen, R. S. Wong, M. N. Smirk, L. Gutiérrez, R. C. Woodward, W. S. Siah, B. Devine, F. Maley and A. Cook, *Respirology*, 2014, **19**, 58–66.
- 186 M. Gualtieri, E. Longhin, M. Mattioli, P. Mantecchia, V. Tinaglia, E. Mangano, M. C. Proverbio, G. Bestetti, M. Camatini and C. Battaglia, *Toxicol. Lett.*, 2012, **209**, 136–145.
- 187 T. Maudgalya, A. Genaidy, G. Weckman, R. Shell, W. Karwowski and S. Wallace, *Hum. Factors Ergon. Manuf.*, 2008, **18**, 358–373.
- 188 V. Sironval, L. Reylandt, P. Chaurand, S. Ibouaadaten, M. Palmi-Pallag, Y. Yakoub, B. Ucar, J. Rose, C. Poleunis, R. Vanbever, E. Marbaix, D. Lison and S. van den Brule, *Arch. Toxicol.*, 2018, **92**, 1673–1684.
- 189 X. Feng, S. Zheng, X. He, L. Wang, Y. Wang, D. Ren and M. Ouyang, *Front. Energy Res.*, 2018, **6**.
- 190 Z. Liao, S. Zhang, K. Li, M. Zhao, Z. Qiu, D. Han, G. Zhang and T. G. Habetler, *J. Energy Storage*, 2020, **27**, 101065.
- 191 H. Wang, Y. Zhang, W. Li, C. Li and M. Ouyang, *WSEAS Trans. Syst. Control*, 2020, **15**, 30–38.
- 192 J. C. Bertolini, *J. Emerg. Med.*, 1992, **10**, 163–168.
- 193 J. J. R. Kirkpatrick, D. S. Enion and D. A. R. Burd, *Burns*, 1995, **21**, 483–493.
- 194 R. A. Smith and K. Othmer, *Encyclopedia of Chemical Technology*, 2003, DOI: 10.1002/0471238961.0825041819130920.a01.pub2.
- 195 S. E. Sloop, J. K. Pugh, S. Wang, J. B. Kerr and K. Kinoshita, *Electrochem. Solid-State Lett.*, 2001, **4**, A42.
- 196 K. Dennerlein, F. Kiesewetter, S. Kilo, T. Jäger, T. Göen, G. Korinith and H. Drexler, *Toxicol. Lett.*, 2016, **248**, 25–33.
- 197 C. R. Fell, L. Sun, P. B. Hallac, B. Metz and B. Sisk, *J. Electrochem. Soc.*, 2015, **162**, A1916–A1920.
- 198 J. Self, C. P. Aiken, R. Petibon and J. R. Dahn, *J. Electrochem. Soc.*, 2015, **162**, A796–A802.
- 199 Z. Mao, M. Farkhondeh, M. Pritzker, M. Fowler and Z. Chen, *J. Electrochem. Soc.*, 2017, **164**, A3469–A3483.
- 200 D. J. Xiong, L. D. Ellis, R. Petibon, T. Hynes, Q. Q. Liu and J. R. Dahn, *J. Electrochem. Soc.*, 2016, **164**, A340–A347.
- 201 H. Yang, G. V. Zhuang and P. N. Ross, *J. Power Sources*, 2006, **161**, 573–579.
- 202 K. Tasaki, K. Kanda, S. Nakamura and M. Ue, *J. Electrochem. Soc.*, 2003, **150**, A1628–A1636.
- 203 S. S. Zhang, *J. Power Sources*, 2006, **162**, 1379–1394.
- 204 A. R. Baird, E. J. Archibald, K. C. Marr and O. A. Ezekoye, *J. Power Sources*, 2020, **446**, 227257.
- 205 R. Spotnitz and J. Franklin, *J. Power Sources*, 2003, **113**, 81–100.
- 206 F. Diaz, Y. Wang, R. Weyhe and B. Friedrich, *Waste Manage.*, 2019, **84**, 102–111.
- 207 M. Dennien, 2020, <https://www.brisbanetimes.com.au/national/queensland/firefighter-injured-in-overnight-blaze-at-griffith-university-campus-20200316-p54aet.html>, accessed 12.08.2021.
- 208 CDC, Immediately Dangerous To Life or Health (IDLH) Values, <https://www.cdc.gov/niosh/idlh/default.html>.
- 209 P. Ribière, S. Grugeon, M. Morcrette, S. Boyanov, S. Laruelle and G. Marlair, *Energy Environ. Sci.*, 2012, **5**, 5271–5280.
- 210 A. Nedjalkov, J. Meyer, M. Köhring, A. Doering, M. Angelmahr, S. Dahle, A. Sander, A. Fischer and W. Schade, *Batteries*, 2016, **2**, 5.
- 211 G. Atkinson, J. Hall and A. McGillivray, *Review of Vapour Cloud Explosion Incidents*, HSE Research Report RR1113, 2017.
- 212 S. R. Samadder, R. Prabhakar, D. Khan, D. Kishan and M. S. Chauhan, *Sci. Total Environ.*, 2017, **580**, 593–601.
- 213 T. H. Christensen, P. Kjeldsen, P. L. Bjerg, D. L. Jensen, J. B. Christensen, A. Baun, H. J. Albrechtsen and G. Heron, *Appl. Geochem.*, 2001, **16**, 659–718.
- 214 P. Ghosh, I. S. Thakur and A. Kaushik, *Ecotoxicol. Environ. Saf.*, 2017, **141**, 259–270.
- 215 K. Szymański and B. Janowska, - Archives of Environmental Protection L1 - <http://journals.pan.pl/Content/102408/PDF/aep-2016-0026.pdf> L2 - <http://journals.pan.pl/Content/102408>, 2016, DOI: 10.1515/aep-2016-0026.
- 216 Y. Xu, X. Xue, L. Dong, C. Nai, Y. Liu and Q. Huang, *Waste Manage.*, 2018, **82**, 156–166.
- 217 I. A. Talalaj, *J. Water Chem. Technol.*, 2014, **36**, 144–151.
- 218 Y. Li, J. Li, S. Chen and W. Diao, *Environ. Pollut.*, 2012, **165**, 77–90.
- 219 J. Kapelewska, U. Kotowska, J. Karpińska, A. Astel, P. Zieliński, J. Suchta and K. Algrzym, *Chem. Eng. J.*, 2019, **359**, 790–800.
- 220 E. Bååth, *Water, Air, Soil Pollut.*, 1989, **47**, 335–379.
- 221 T. Pennanen, J. Perkiömäki, O. Kiikilä, P. Vanhala, S. Neuvonen and H. Fritze, *FEMS Microbiol. Ecol.*, 1998, **27**, 291–300.
- 222 P. Nelson, S. Ahmed, K. Gallagher and D. Dees, *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles*, Argonne National Laboratory, USA, 2019.
- 223 IEA, *Global EV Outlook 2018*, International Energy Agency, Paris, 2018.
- 224 M. Wentker, M. Greenwood and J. Leker, *Energies*, 2019, **12**, 504.
- 225 M. A. Cusenza, S. Bobba, F. Ardente, M. Cellura and F. Di Persio, *J. Cleaner Prod.*, 2019, **215**, 634–649.
- 226 A. Prabhakar, S. Mishra and A. P. Das, *Geomicrobiol. J.*, 2019, **36**, 894–903.
- 227 K. Chatham-Stephens, J. Caravanos, B. Ericson, J. Sunga-Amparo, B. Susilorini, P. Sharma, P. J. Landrigan and R. Fuller, *Environ. Health Perspect.*, 2013, **121**, 791–796.
- 228 S. Mishra, C. c. Rath and A. P. Das, *Mar. Pollut. Bull.*, 2019, **140**, 188–197.



- 229 X. Zeng, X. Xu, H. M. Boezen and X. Huo, *Chemosphere*, 2016, **148**, 408–415.
- 230 Y. Yu, X. Zhu, L. Li, B. Lin, M. Xiang, X. Zhang, X. Chen, Z. Yu, Z. Wang and Y. Wan, *Ecotoxicol. Environ. Saf.*, 2019, **169**, 178–184.
- 231 F. N. Soetrisno and J. M. Delgado-Saborit, *Sci. Total Environ.*, 2020, **717**, 137099.
- 232 ATSDRHealth Public Statement for Nickel, 2005, <https://www.atsdr.cdc.gov/ToxProfiles/tp15-c1-b.pdf>, accessed 15.01.2021.
- 233 H. Aral and A. Vecchio-Sadus, *Ecotoxicol. Environ. Saf.*, 2008, **70**, 349–356.
- 234 A. Chen, K. N. Dietrich, X. Huo and S.-M. Ho, *Environ. Health Perspect.*, 2011, **119**, 431–438.
- 235 D. Pant, D. Joshi, M. K. Upreti and R. K. Kotnala, *Waste Manage.*, 2012, **32**, 979–990.
- 236 ATSDRHealth Public Statement for Cobalt, 2004, <https://www.atsdr.cdc.gov/ToxProfiles/tp33-c1-b.pdf>, accessed 15.01.2021.
- 237 L. Leyssens, B. Vinck, C. Van Der Straeten, F. Wuyts and L. Maes, *Toxicology*, 2017, **387**, 43–56.
- 238 D. H. P. Kang, M. Chen and O. A. Ogunseitan, *Environ. Sci. Technol.*, 2013, **47**, 5495–5503.
- 239 Y. Li, J. B. Richardson, R. Mark Bricka, X. Niu, H. Yang, L. Li and A. Jimenez, *Waste Manage.*, 2009, **29**, 2147–2150.
- 240 S. Yadav and S. Yadav, *J. Environ. Manage.*, 2014, **144**, 101–107.
- 241 S. Yadav, S. Yadav and P. Kumar, *Waste Manage.*, 2014, **34**, 1274–1278.
- 242 K. Richa, C. W. Babbitt and G. Gaustad, *J. Ind. Ecol.*, 2017, **21**, 715–730.
- 243 M. N. Hang, I. L. Gunsolus, H. Wayland, E. S. Melby, A. C. Mensch, K. R. Hurley, J. A. Pedersen, C. L. Haynes and R. J. Hamers, *Chem. Mater.*, 2016, **28**, 1092–1100.
- 244 I. L. Gunsolus, M. N. Hang, N. V. Hudson-Smith, J. T. Buchman, J. W. Bennett, D. Conroy, S. E. Mason, R. J. Hamers and C. L. Haynes, *Environ. Sci.: Nano*, 2017, **4**, 636–646.
- 245 W. Yan, S. Yang, Y. Huang, Y. Yang and Y. Guohui, *J. Alloys Compd.*, 2020, **819**, 153048.
- 246 Q. Wang, L. Jiang, Y. Yu and J. Sun, *Nano Energy*, 2019, **55**, 93–114.
- 247 S. W. D. Gourley, T. Or and Z. Chen, *iScience*, 2020, **23**, 101505.
- 248 I. Overland, *Energy Res. Soc. Sci.*, 2019, **49**, 36–40.
- 249 Z. V. Feng, B. R. Miller, T. G. Linn, T. Pho, K. N. L. Hoang, M. N. Hang, S. L. Mitchell, R. T. Hernandez, E. E. Carlson and R. J. Hamers, *Environ. Sci.: Nano*, 2019, **6**, 305–314.
- 250 P. L. Clement, J. E. Kuether, J. R. Borgatta, J. T. Buchman, M. S. Cahill, T. A. Qiu, R. J. Hamers, Z. V. Feng and C. L. Haynes, *Chem. Res. Toxicol.*, 2020, **33**, 806–816.
- 251 J. Bozich, M. Hang, R. Hamers and R. Klaper, *Environ. Toxicol. Chem.*, 2017, **36**, 2493–2502.
- 252 J. Chen, Z. Xiu, G. V. Lowry and P. J. J. Alvarez, *Water Res.*, 2011, **45**, 1995–2001.
- 253 N. J. Niemuth, B. J. Curtis, M. N. Hang, M. J. Gallagher, D. H. Fairbrother, R. J. Hamers and R. D. Klaper, *Environ. Sci. Technol.*, 2019, **53**, 3860–3870.
- 254 E. S. Melby, Y. Cui, J. Borgatta, A. C. Mensch, M. N. Hang, W. B. Chrisler, A. Dohnalkova, J. M. Van Gilder, C. M. Alvarez, J. N. Smith, R. J. Hamers and G. Orr, *Nanotoxicology*, 2018, **12**, 1166–1181.
- 255 C. Mihai, W. B. Chrisler, Y. Xie, D. Hu, C. J. Szymanski, A. Tolic, J. A. Klein, J. N. Smith, B. J. Tarasevich and G. Orr, *Nanotoxicology*, 2015, **9**, 9–22.
- 256 Y. Cui, E. S. Melby, A. C. Mensch, E. D. Laudadio, M. N. Hang, A. Dohnalkova, D. Hu, R. J. Hamers and G. Orr, *Nano Lett.*, 2019, **19**, 1990–1997.
- 257 W. Gwenzi, G. T. Kosta and N. Chaukura, *Environ. Processes*, 2018, **5**, 611–629.
- 258 T. Fujimori, A. Eguchi, T. Agusa, N. M. Tue, G. Suzuki, S. Takahashi, P. H. Viet, S. Tanabe and H. Takigami, *J. Mater. Cycles Waste Manage.*, 2016, **18**, 599–607.
- 259 W. Lv, Z. Wang, H. Cao, Y. Sun, Y. Zhang and Z. Sun, *ACS Sustainable Chem. Eng.*, 2018, **6**, 1504–1521.
- 260 R. T. Delfino, T. S. Ribeiro and J. D. Figueroa-Villar, *J. Braz. Chem. Soc.*, 2009, **20**, 407–428.
- 261 V. Kraft, W. Weber, M. Grützke, M. Winter and S. Nowak, *RSC Adv.*, 2015, **5**, 80150–80157.
- 262 D. C. Agourakis, I. M. C. De Camargo, M. B. Cotrim and M. Flues, *Quim. Nova*, 2006, **29**, 960–964.
- 263 A. M. Haregewoin, A. S. Wotango and B.-J. Hwang, *Energy Environ. Sci.*, 2016, **9**, 1955–1988.
- 264 A. Eftekhari, Y. Liu and P. Chen, *J. Power Sources*, 2016, **334**, 221–239.
- 265 H. Qi, Y. Ren, S. Guo, Y. Wang, S. Li, Y. Hu and F. Yan, *ACS Appl. Mater. Interfaces*, 2020, **12**, 591–600.
- 266 N. V. Plechkova and K. R. Seddon, *Chem. Soc. Rev.*, 2008, **37**, 123–150.
- 267 P. Stepnowski, *Sorption, Lipophilicity and Partitioning phenomena of ionic liquids in environmental systems*, Elsevier BV, 2007.
- 268 P. Stepnowski, W. Mroziak and J. Nichthauser, *Environ. Sci. Technol.*, 2007, **41**, 511–516.
- 269 W. Mroziak, C. Jungnickel, M. Skup, P. Urbaszek and P. Stepnowski, *Environ. Chem.*, 2008, **5**, 299–306.
- 270 W. Mroziak, J. Nichthauser and P. Stepnowski, *Pol. J. Environ. Stud.*, 2008, **17**, 383–388.
- 271 W. Mroziak, A. Kotłowska, W. Kamysz and P. Stepnowski, *Chemosphere*, 2012, **88**, 1202–1207.
- 272 W. Mroziak, C. Jungnickel, M. Paszkiewicz and P. Stepnowski, *Water, Air, Soil Pollut.*, 2013, **224**, 1759.
- 273 W. Mroziak, J. Nichthauser and P. Stepnowski, *Pol. J. Environ. Stud.*, 2008, **17**, 383–388.
- 274 M. Markiewicz, W. Mroziak, K. Rezwan, J. Thöming, J. Hupka and C. Jungnickel, *Chemosphere*, 2013, **90**, 706–712.
- 275 Q. Miao and E. Bi, *J. Environ. Manage.*, 2018, **223**, 975–983.
- 276 D. Coleman and N. Gathergood, *Chem. Soc. Rev.*, 2010, **39**, 600–637.
- 277 A. Jordan and N. Gathergood, *Chem. Soc. Rev.*, 2015, **44**, 8200–8237.
- 278 S.-K. Ruokonen, C. Sanwald, M. Sundvik, S. Polnick, K. Vyavaharkar, F. Duša, A. J. Holding, A. W. T. King, I. Kilpeläinen, M. Lämmerhofer, P. Panula and S. K. Wiedmer, *Environ. Sci. Technol.*, 2016, **50**, 7116–7125.



- 279 T. P. Thuy Pham, C.-W. Cho and Y.-S. Yun, *Water Res.*, 2010, **44**, 352–372.
- 280 B. Kudłak, K. Owczarek and J. Namieśnik, *Environ. Sci. Pollut. Res.*, 2015, **22**, 11975–11992.
- 281 C.-W. Cho, S. Stolte and Y.-S. Yun, *Sci. Rep.*, 2016, **6**, 33403.
- 282 A. Latała, P. Stepnowski, M. Nędzi and W. Mroziński, *Aquat. Toxicol.*, 2005, **73**, 91–98.
- 283 M. Amde, J.-F. Liu and L. Pang, *Environ. Sci. Technol.*, 2015, **49**, 12611–12627.
- 284 C. Pretti, C. Chiappe, I. Baldetti, S. Brunini, G. Monni and L. Intorre, *Ecotoxicol. Environ. Saf.*, 2009, **72**, 1170–1176.
- 285 P. Stepnowski, A. C. Skladanowski, A. Ludwiczak and E. Leczyńska, *Hum. Exp. Toxicol.*, 2004, **23**, 513–517.
- 286 X.-D. Hou, Q.-P. Liu, T. J. Smith, N. Li and M.-H. Zong, *PLoS One*, 2013, **8**, e59145.
- 287 N. S. M. Vieira, S. Stolte, J. M. M. Araújo, L. P. N. Rebelo, A. B. Pereiro and M. Markiewicz, *ACS Sustainable Chem. Eng.*, 2019, **7**, 3733–3741.
- 288 Z. Milojevic, P. S. Attidekou, M. Muhammad, M. Ahmeid, S. Lambert and P. K. Das, *J. Power Sources*, 2021, **506**, 230242.
- 289 C. Jin, J. Nai, O. Sheng, H. Yuan, W. Zhang, X. Tao and X. W. Lou, *Energy Environ. Sci.*, 2021, **14**, 1326–1379.
- 290 S. S. Sharma and A. Manthiram, *Energy Environ. Sci.*, 2020, **13**, 4087–4097.
- 291 M. Fleischhammer, T. Waldmann, G. Bisle, B.-I. Hogg and M. Wohlfahrt-Mehrens, *J. Power Sources*, 2015, **274**, 432–439.
- 292 D. Ren, H. Hsu, R. Li, X. Feng, D. Guo, X. Han, L. Lu, X. He, S. Gao, J. Hou, Y. Li, Y. Wang and M. Ouyang, *eTransportation*, 2019, **2**, 100034.
- 293 S. Bertilsson, F. Larsson, M. Furlani, I. Albinsson and B.-E. Mellander, *J. Power Sources*, 2017, **365**, 446–455.
- 294 A. I. Ilieș, I. Ciascai and D. Pitiță, 2019 42nd International Spring Seminar on Electronics Technology (ISSE), 2019, DOI: 10.1109/ISSE.2019.8810304.
- 295 J. Liu, Q. Duan, M. Ma, C. Zhao, J. Sun and Q. Wang, *J. Power Sources*, 2020, **445**, 227263.
- 296 BSI_Group, BS EN 63330 Ed.1.0 Requirements for reuse of secondary batteries, 2021, accessed 30.08.2021.
- 297 BSI_Group, BS EN 63338 Ed.1.0 General guidance for reuse of secondary cells and batteries, 2021, accessed 30.08.2021.
- 298 E. Cabrera-Castillo, F. Niedermeier and A. Jossen, *J. Power Sources*, 2016, **324**, 509–520.
- 299 INERIS, DRA06 – Opération B3, Seconde vie des batteries Li-ion, INERIS, MINISTERE DE LA TRANSITION ECOLOGIQUE ET SOLIDAIRE, 2020.
- 300 NFPA, 2020, <https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=855>.
- 301 Electrical_Regulatory_Authorities_Council_(ERAC), 2021.
- 302 R. Coombes, Beginners guide: UN3480, UN3481 & IATA regulations, 2021, accessed 30.08.2021.
- 303 HSE, <https://www.hse.gov.uk/cdg/manual/index.htm>, 2011, accessed 14.09.2021.





Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery

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Abstract

Purpose Lithium-ion batteries (LIBs) have been criticized for contributing to negative social impacts along their life cycles, especially child labor and harsh working conditions during cobalt extraction. This study focuses on human health impacts — arguably the most fundamental of all social impacts. The aim is to quantify the potential life-cycle health impacts of an LIB cell of the type nickel-manganese-cobalt (NMC 811) in terms of disability-adjusted life years (DALY), as well as to identify hotspots and ways to reduce the health impacts.

Methods A cradle-to-gate attributional life-cycle assessment study is conducted with the functional unit of one LIB cell and human health as the sole endpoint considered. The studied LIB is produced in a large-scale “gigafactory” in Sweden, the cobalt sulfate for the cathode is produced in China, and the cobalt raw material is sourced from the Democratic Republic of the Congo (DRC). Potential health impacts from both emissions and occupational accidents are quantified in terms of DALY, making this an impact pathway (or type II) study with regard to social impact assessment. Two scenarios for fatality rates in the artisanal cobalt mining in the DRC are considered: a high scenario at 2000 fatalities/year and a low scenario at 65 fatalities/year.

Results Applying the high fatality rate, occupational accidents in the artisanal cobalt mining in the DRC contribute notably to the total life-cycle health impacts of the LIB cell (13%). However, emissions from production of nickel sulfate (used in the cathode) and of copper foil (the anode current collector) contribute even more (30% and 20%, respectively). These contributions are sensitive to the selected time horizon of the life-cycle assessment, with longer or shorter time horizons leading to considerably increased or decreased health impacts, respectively.

Conclusions In order to reduce the health impacts of the studied LIB, it is recommended to (i) investigate the feasibility of replacing the copper foil with another material able to provide anode current collector functionality, (ii) reduce emissions from metal extraction (particularly nickel and copper), (iii) increase the recycled content of metals supplied to the LIB manufacturing, and (iv) improve the occupational standards in artisanal mining in the DRC, in particular by reducing fatal accidents.

Keywords Life cycle assessment · Disability-adjusted life years · Occupational accidents · Cobalt mining · Nickel-manganese-cobalt (NMC) · Human health · Social risks

1 Introduction

Like diamonds of certain origins, cobalt mined from the Democratic Republic of the Congo (DRC) has been associated with the noun “blood” in news media (Kennedy 2017; Lindberg and Andersson 2019). The DRC currently provides around 70% of the global cobalt supply, partly through artisanal mining, which provides livelihood for almost 200,000 people (BGR 2019; OECD 2019). Although not counted among of the traditional 3TG conflict minerals (i.e., tantalum, tin, tungsten, and

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gold), cobalt mined in the DRC has been associated with numerous health and social impacts, including high exposure to cobalt and other toxicants from mining (including dust), occupational accidents, long working hours, child labor, corruption, and displacement of indigenous people (Banza et al. 2009; Elenge et al. 2011; Elenge and De Brouwer 2011; Tsurukawa et al. 2011; Amnesty International 2013; Elenge 2013; Amnesty International and Afreewatch 2016; Faber et al. 2017; Banza Lubaba Nkulu et al. 2018; BGR 2019; Lindberg and Andersson 2019; Sovacool 2019; Bamana et al. 2021). These impacts are particularly prevalent in artisanal, small-scale cobalt mining, which currently accounts for approximately 20% of the cobalt extracted in the DRC (Al Barazi et al. 2017), while the industrial, more mechanized extraction generally has a considerably lower occurrence of, e.g., child labor. At the same time, positive social externalities of artisanal mining have also been reported, including reduced poverty, increased state revenue, increased services, and collective occupational identity (Tsurukawa et al. 2011; de Haan and Geenen 2016; Sovacool 2019). For example, while many Congolese struggle to earn 1 US\$/day, artisanal miners generally earn more than 3 US\$/day (Tsurukawa et al. 2011; de Haan and Geenen 2016). There are also some social impacts occurring in other low-income countries which are seemingly absent in artisanal cobalt mining in the DRC, an example being forced labor (Tsurukawa et al. 2011; OECD 2019). This means that despite harsh conditions, the work is not undertaken without consent or under the threat of a penalty, such as violence or retention of identity papers (International Labour Office 2016).

The current main use of cobalt is in lithium-ion batteries (LIBs), which have become the dominant technology for rechargeable energy storage (OECD 2019). Commercialized by Sony Co. and others in the early 1990s, LIBs have enabled many products of high significance in contemporary societies, such as mobile phones, laptops, and electric vehicles (Li et al. 2018). Different LIB chemistries exist in the market today based on the type of application, such as lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), of which the NMC, NCA, and LCO chemistries contain cobalt in varying proportions (Porzio and Scown 2021). Most of the currently used LIBs in electric vehicles are NMC 111 (sometimes called NMC 333), NMC 532, or NMC 622, where the numbers represent the relative shares of nickel, manganese, and cobalt in the cathode, respectively (Harper et al. 2019). However, there is a strive towards further reducing the cobalt content of NMC batteries, as in the more recently developed NMC 811 cathode material (Fan et al. 2020).

This study focuses on the contribution of LIBs to human health impacts — arguably the most fundamental of all social impacts. The question that the study aims to answer is as follow: How large are the potential negative health impacts from an LIB along its life cycle, which are the hotspots and how can the health impacts be reduced? In particular, the study seeks to investigate the relative contribution to potential health impacts from cobalt in a modern low-cobalt LIB. To answer this question, an LCA of an LIB of the type NMC 811 is performed from cradle to gate, with human health as the endpoint. Specifically, potential health impacts from emissions and occupational accidents are assessed using the quantitative disability-adjusted life years (DALY) indicator. Since there is a causal link from the release of emissions and accidents to DALY, this study applies a so-called impact pathway approach (Benoît Norris et al. 2020) to social impact assessment. The authors are not aware of any previous quantitative assessments of potential health impacts for LIBs, although there exist a few qualitative health assessments of LIBs and/or cobalt where a so-called reference scale approach (Benoît Norris et al. 2020) to social impact assessment is applied. Mancini et al. (2021) assessed “occupational health and safety” impacts of artisanal mining of cobalt together with 13 other social impacts, using a five-point ordinal scale going from “no noted risks” to “systematic and grave abuse.” The latter category was assigned to the occupational health and safety of artisanal cobalt mining. Thies et al. (2019) also assessed a range of social impacts of an LIB pack (NMC type), including “risks of occupational toxics and hazards,” using the ordinal-scale system from the Social Hotspots Database, which is a widely used database in social LCA. That scale contains “no risk” (which translates to 0.0), “low risk” (0.1), “medium risk” (1), “high risk” (5), and “very high risk” (10). They concluded that Chinese production of the LIBs yielded higher risks of occupational toxics and hazards than German production, even if the raw materials (including cobalt) were sources responsibly. Similarly, Sharma and Manthiram (2020) conducted a qualitative social assessment of an NMC 811 and an LFP battery based on publications from human rights organizations, newspapers, academics, and community members. They concluded that producing the cobalt required for 26 million electric vehicles by 2030 would result in 25,000 children needing to work by hand for 10 h per day in the DRC, as well as to toxic pollution of the local community from cobalt mining. Consequently, they recommend that the use of cobalt in LIBs must be eliminated entirely.

2 Method and materials

In order to assess the magnitude of the potential health impacts of an LIB cell containing cobalt, as well as the relative contribution of cobalt, a process-based or

attributional LCA was conducted (Yang 2019), with a cradle to gate scope (Fig. 1). The system boundary largely follows that of Chordia et al. (2021), who studied the environmental impacts of the same battery, with the notable exception of the cobalt sulfate production, as described in Sect. 2.4. The functional unit of that study was 1 kWh of theoretical energy storage capacity for a 21,700-type cylindrical LIB cell of the NMC 811 chemistry after the formation step, with the composition described in Table 1. The cell is intended for automobile applications, weighing 68 g and having a specific energy density value within the range of 210–240 Wh/kg (Chordia et al. 2021). In this study, the functional unit of one such battery cell is chosen as it is a more tangible functional unit for interpretation. However, it can be translated into kWh of energy storage approximately, for comparisons with other battery cells, by applying a factor of 65 cells/kWh.

The applied impact pathway (or type II) method for assessing potential health impacts in the context of social LCA was first conceptualized by Baumann et al. (2013) and then formalized by Arvidsson et al. (2018). It entails a quantification and relative comparison of health impacts along product life cycles, as well as a quantification of the potential net health impact of products:

Table 1 Approximate composition of the functional unit of the study — one cylindrical NMC 811 battery cell weighting about 68 g (Chordia et al. 2021)

Cell component	Share of weight
Positive current collector and tab (aluminum)	3%
Active cathode material (nickel, cobalt, and manganese)	37%
Negative current collector and tab (copper)	7%
Active anode material (synthetic graphite)	23%
Electrolyte (lithium hexafluorophosphate and organics)	10%
Separator (polyethylene)	2%
Cylindrical container (nickel-plated steel)	12%
Lid (nickel-plated steel)	3%
Fastening tape (polyethylene)	1%
Insulation ring (polyethylene)	2%

$$DALY_{net} = \sum_{positive} DALY + \sum_{negative} DALY \quad (1)$$

DALY stands for disability-adjusted life years (unit: years). Since DALY is a measure of years lost due to death

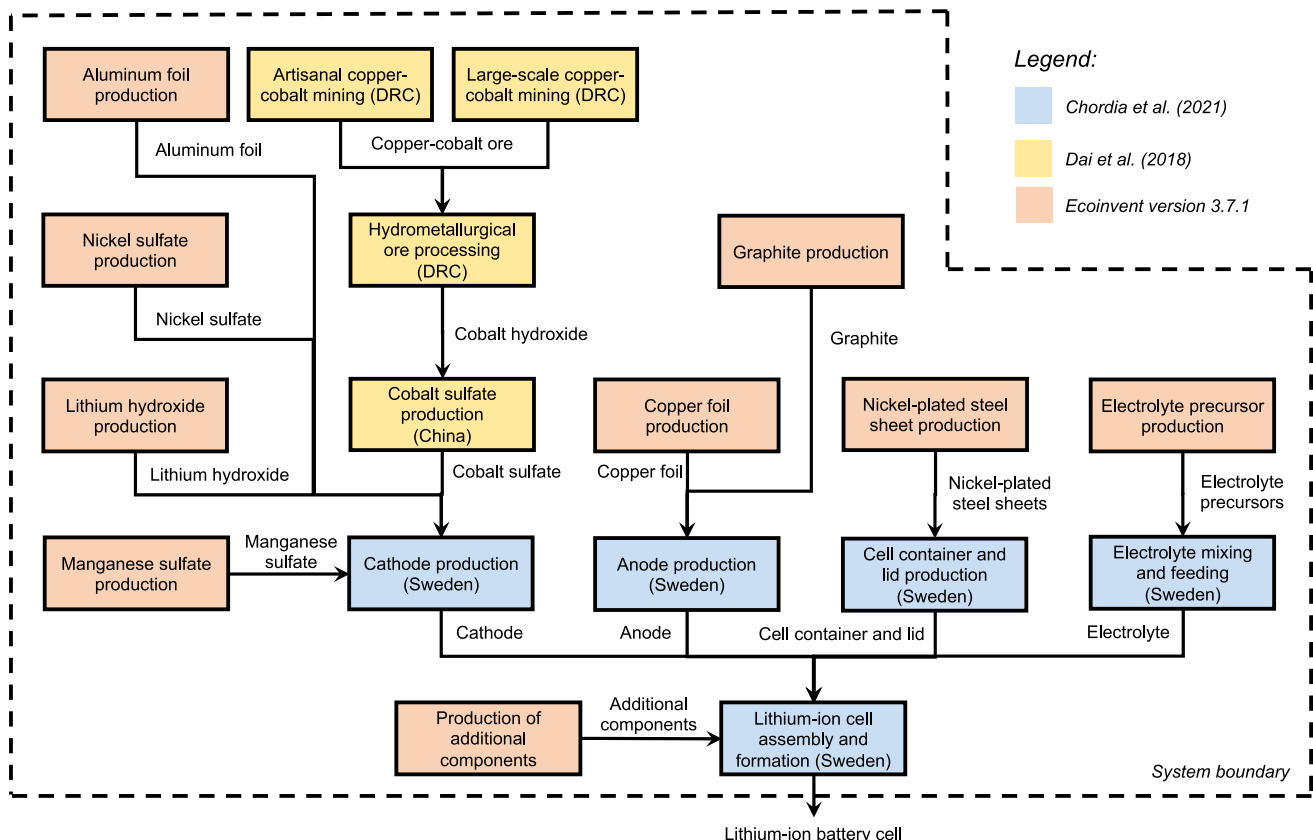


Fig. 1 Flow chart describing the main processes of the cradle-to-gate product system studied and main inventory data sources. The system boundary is shown as a dashed line. The cobalt sulfate supply chain is shown in higher resolution

or disability, DALY values with a positive sign imply a negative impact on human life and health, whereas negative DALY values imply a positive impact. Many different potential health impacts can occur along product life cycles and the analyst must *a priori* select those believed to be of significance for quantification. In the case of LIBs, based on existing reports of health impacts (Sect. 1), contributions from (i) emissions and (ii) occupational accidents are considered:

$$DALY_{net} = DALY_{emissions} + DALY_{accidents} \quad (2)$$

The quantification of potential health impacts from emissions ($DALY_{emissions}$) and occupational accidents ($DALY_{accidents}$) are described in Sects. 2.1 and 2.2, respectively. No positive potential health impacts are considered in this assessment, but some potentially positive contributions are discussed in Sect. 3.4. Health impacts from conflicts have been included in some previous studies of cobalt and gold from the DRC (Arvidsson et al. 2018; Furberg et al. 2018). However, the Katanga region of the DRC, where most cobalt is mined, has recently been reported to be the most stable part of the entire country, since the mineral wealth has created a middle class and provided political stability (Sovacool 2019). While the presence of valuable minerals in poor countries can spur conflict, this does not seem to be the case in the Katanga region. Reports suggest that the two Katangese provinces Haut-Katanga and Luabala “are not considered conflict zones” (OECD 2019), and that “cobalt has, opposite to gold, tin and coltan [a tantalum-containing mineral], not yet started any war in the DRC” (Lindberg and Andersson 2019). Therefore, health impacts from conflict are not included in this study.

The product system was modeled using OpenLCA (version 1.10.3) with most inventory data coming from the Ecoinvent database, version 3.7.1 with cutoff allocation of recycled materials (Wernet et al. 2016). However, two processes were modeled using other sources: (i) lithium-ion cell production and (ii) battery-grade cobalt sulfate production (Fig. 1). The modeling of these processes is described in more detail in Sects. 2.3 and 2.4, respectively.

2.1 Emission health impacts

Like previous studies on health impacts of products (Arvidsson et al. 2018; Furberg et al. 2018; Debaveye et al. 2020), this study relies on the impact assessment method ReCiPe (Huijbregts et al. 2017). ReCiPe considers health impacts related to the following emission-related midpoint impact categories: particulate matter, tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity, and global warming (Huijbregts et al. 2017). In addition, ReCiPe also considers health impacts from water scarcity, which is included here as

well. These potential health impacts from emissions and water use affect the general population. Potential health impacts of emissions ($DALY_{emissions}$) are quantified according to:

$$DALY_{emissions} = \sum_{i,m} Q_{i,m} \times CF_{i,m} \times CF_{m,e} \quad (3)$$

where $Q_{i,m}$ is a quantity of elementary flow i contributing to the midpoint impact category m , $CF_{i,m}$ is a characterization factor describing the contribution of i to m , and $CF_{m,e}$ is an endpoint characterization factor describing the contribution of m to the endpoint impact category e . Only the endpoint human health is considered in this study. The endpoint characterization factors are derived based on how much the midpoint impact categories contribute to potential health impacts as described in the ReCiPe 2016 report (Huijbregts et al. 2016). For example, in the case of stratospheric ozone depletion, it is based on the increase of UV light and subsequent diseases caused by ozone depletion. A hierarchist value perspective is chosen as main perspective in this study, reflecting the current scientific consensus on time frames and impact mechanisms (Huijbregts et al. 2016), although the implications of choosing other value perspectives (individualist or egalitarian) are also discussed. The emission and water use data for $Q_{i,m}$ come from Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database as shown in Fig. 1.

2.2 Occupational accidents

Potential health impacts from occupational accidents ($DALY_{accidents}$) were quantified using the approach by Scanlon et al. (2015), where work environment characterization factors (CF_{WE}) for industry sectors j are calculated according to:

$$CF_{WE,j} = \frac{DALY_j}{Q_j} \quad (4)$$

where $DALY_j$ is the total number of years lost due to injuries or premature death in industry sector j , and Q_j is the total output of the same sector. Such outputs can be in terms of units (e.g., number of cars), mass (e.g., kg of steel), energy (e.g., MJ of electricity), or some other measure reflecting the industry sector's output. The accidents included are based on reported occupational accident data from industries in the USA, and include both fatal and non-fatal accidents, such as bruises, wounds, and traumatic injuries. The industry sectors are often more aggregated than the typical unit process in an LCA, for example aggregating many types of metal mining into the category “All other metal ore mining.” Scanlon et al. (2015) provide 127 CF_{WE} , often in the orders of 10^{-7} to 10^{-10} year/kg for sectors where the output is quantified in terms of mass, which is the most common case. Such occupational health impacts affect workers along the life cycle.

The CF_{WE} provided by Scanlon et al. (2015) were deemed acceptable proxies for occupational accidents in the whole product system, except for one process: artisanal cobalt mining. Here, a specific CF_{WE} for artisanal cobalt mining in the DRC was instead calculated using Eq. (4), updating the value previously calculated by Furberg et al. (2018). The amount of cobalt extracted in artisanal mining in the DRC (Q_j in Eq. 4) was calculated using the reported cobalt production and artisanal share in the DRC, averaged over the years 2009–2015 (Al Barazi et al. 2017), resulting in about 26,000 ton/year. The DALY in Eq. (4) was calculated as the sum of the years of life disabled (YLD) and years of life lost (YLL):

$$DALY = YLD + YLL \quad (5)$$

The YLD is, in turn, calculated as:

$$YLD = I \times DW \times L \quad (6)$$

where I is the number of incidents, DW is a disability weight, and L is the duration of the disability. The number of incidents was estimated assuming 175,000 artisanal cobalt miners in the DRC, which is an average of ranges reported (BGR 2019; OECD 2019). The frequency of occupational accidents in artisanal cobalt mining in the Katanga region was obtained from the study by Elenge et al. (2013), who reported the frequency of wounds as well as fractures on upper and lower limbs. These are common injuries in artisanal mining, frequently reported also in, e.g., artisanal gold mining in Ghana (Kyeremateng-Amoah and Clarke 2015). The frequency of wounds is paired with DW and L values for open wounds provided by Haagsma et al. (2016). The frequency of fractures on upper and lower limbs are paired with average values of DW and L for different fractures: humerus, hand, radius, and ulna bones for upper limbs, as well as foot, femur, patella, tibia, fibula, and ankle bones for lower limbs (Haagsma et al. 2016). The resulting YLD obtained was about 370 years, or $1.4 \cdot 10^{-5}$ year/kg cobalt.

The YLL is calculated as:

$$YLL = N \times (LEX - L) \quad (7)$$

where N is the number of fatalities, LEX is the life expectancy at birth, and L is the age of death. The number of fatalities in artisanal cobalt mining the DRC has been estimated at up to 2000 per year based on a questionnaire administered in cobalt-producing provinces by Siddharath Kara (MacDonald and Pokharel 2020), who is a researcher and expert on modern slavery. A much lower estimate of 65 fatalities per year have been published by the World Bank (2020), based on cases reported in media. However, due to limited access and coverage by media on these matters, this value is presumed to be a clear underestimation. In fact, Kara claims to have personally witnessed the collapse of a

single mining tunnel in the DRC, alone leading to more than 60 deaths (MacDonald and Pokharel 2020). Given the workforce estimated above, a rate of 2000 fatalities means that almost 1% of the workforce die every year. Approximately 1% fatality rate per year was similarly reported for small-scale tin mining cooperatives in Bolivia (ILO 1999). The median age of artisanal cobalt miners in the DRC is 25 years (Elenge et al. 2013), and the life expectancy in the DRC is 61 years in 2021. The resulting YLL becomes 72,000 years, corresponding to $2.8 \cdot 10^{-3}$ year/kg cobalt. The lower estimate of fatal accidents in artisanal cobalt mining in the DRC of 65 per years gives a YLL at $1.0 \cdot 10^{-4}$ year/kg cobalt. Even though this lower estimate is considered unreasonably low, results based on this estimate are still presented in this study for comparison.

When adding the YLD and YLL (high estimate) per kg cobalt, the CF_{WE} for artisanal cobalt mining in the DRC can be obtained at $2.8 \cdot 10^{-3}$ year/kg cobalt. Given a 0.47% cobalt content of the extracted ore (Dai et al. 2018), this becomes $1.3 \cdot 10^{-5}$ year/kg copper-cobalt ore. This can be compared to the several orders of magnitude lower CF_{WE} for (industrial) copper ore and nickel ore mining in Scanlon et al. (2015) at $8.4 \cdot 10^{-9}$ year/kg.

Since the CF_{WE} are not implemented in the Ecoinvent database, they need to be added manually. Unfortunately, manually adding CF_{WE} to all linked upstream processes in the Ecoinvent database is not feasible. Thus, the CF_{WE} are added for all processes in the cobalt production system and the battery cell production, as well as for all direct inputs to these (which might also be present in other places upstream in the system). Table S1 in the Supporting Information (SI) lists all processes for which the CF_{WE} are implemented. Although this means that a number of upstream processes are not accounted for regarding their work environment impacts, this approach is judged to account for a significant share of the total work environment impacts since all major inputs to the studied system are included.

2.3 Lithium-ion cell production

The LIB cell production is modeled according to Chordia et al. (2021), since that study considers a presumably benign scenario regarding potential health impacts of cobalt-containing LIBs. First, they assess a cylindrical NMC 811 cell, which contains cobalt but in lower amounts than, e.g., the currently more common NMC 111 cell. Second, they model a large-scale “gigafactory,” which has lower impacts compared to smaller-scale cell production. Third, the location of the gigafactory in Sweden means an electricity mix based mainly on hydropower and nuclear, which leads to lower potential health impacts compared to more fossil-based electricity mixes. Using this context for the study,

which represents an estimate of potential health impacts from upcoming LIB cell production in northern Europe, the focus is intentionally set on the mineral extraction and cell precursor materials production life-cycle stages, in line with the overall aim of investigating the role of cobalt, rather than health impacts of the energy supply to later production steps.

The gigafactory model is based on data from environmental permit applications and technical reports published by the company Northvolt AB for a facility currently being put into operation in Northern Sweden, representing an annual production of 16 GWh of battery cell storage capacity (Chordia et al. 2021). The factory will produce both cylindrical and prismatic cells, but only cylindrical cells were considered by Chordia et al. (2021), as well as in this study. The model includes the complete cell production and assembly from input chemicals and materials, ending with the formation of the cells, which is the finishing process where the cells are charged and discharged a number of times. For this study, one significant change was made to the model: the battery-grade cobalt-sulfate supply was changed, as described in Sect. 2.4.

2.4 Battery-grade cobalt sulfate production

The Ecoinvent database contains a dataset for cobalt sulfate production provided by the cobalt development institute, which was applied in the study by Chordia et al. (2021). This dataset reportedly covers 30% of the global production of refined cobalt products in 2012 and includes cobalt ore mining in Canada, Cuba, the DRC, New Caledonia, and the Philippines (Environmental Resource Management 2016). However, this dataset does not distinguish cobalt extraction from its refining and is therefore considered too aggregated for this study with a focus on health impacts along the cobalt supply chain. In addition, the dataset does not include refined cobalt production in China, even though China is currently the largest producer of refined cobalt products. Consequently, less aggregated inventory data on battery-grade cobalt sulfate production from Dai et al. (2018) are used instead. They provide datasets for three main processes: (i) large-scale copper-cobalt ore mining in the DRC, (ii) crude cobalt hydroxide production in the DRC, and (iii) battery-grade cobalt sulfate in China. In addition, we added a fourth dataset for artisanal copper-cobalt ore mining. However, since this artisanal mining occurs without any modern mining equipment, using basic tools for digging and sometimes only hands (Sovacool 2019), the dataset does not have any inputs except for the cobalt, copper, and rock mined (Table S3). Together, these four processes cover the main route of cobalt sulfate production, since most (70%) of the cobalt is mined in the DRC (Table S2) and most (80%) refined cobalt products are produced in China after import from the DRC in the form of crude cobalt hydroxide

(OECD 2019; Sovacool 2019). A process for copper-cobalt ore production in the DRC is created, consisting of 20% artisanal ore input as reported by Al Barazi et al. (2017) and the remaining 80% ore input from industrial-scale extraction. For all upstream processes linked to material and energy inputs, datasets from the Ecoinvent database were used. Congolese or Chinese datasets were used if available, otherwise global or rest-of-the-world datasets were used. An exception to this is the sodium metabisulfite, as described below.

For the large-scale copper-cobalt ore mining in the DRC, the data in Dai et al. (2018) is based on the Tenke Fungurume Mine, where both oxide and sulfide ores are mined. The unit-process dataset was scaled from 1 ton copper-cobalt ore to 1 kg copper-cobalt ore. The diesel input reported is mainly for large mining vehicles like caterpillars according to the report and was therefore approximated using the Ecoinvent process “diesel, burned in agricultural machinery.” The water input was assumed to come from “natural unspecified origin,” since it is unknown if the water comes from, e.g., rivers or lakes. The ore reportedly contains 2.44% copper and 0.47% cobalt, while the rest of the ore was assumed to consist of inert rock. No losses during the mining are reported in the source. The resulting unit process for large-scale copper-cobalt ore mining in the DRC is shown in Table S4.

The production of crude cobalt hydroxide from the copper-cobalt ore occurs through hydrometallurgical ore processing, again modeled based on the operation at the Tenke Fungurume Mine in the DRC. However, the data in Dai et al. (2018) had to be reworked into a unit process dataset for the purpose of this study. The cobalt output is first calculated based on a 0.47% cobalt content in the ore and an 80% cobalt yield. The copper output was calculated in the same way. Economic allocation between copper and cobalt is then conducted based on 10-year average prices as described in Dai et al. (2018). Finally, the cobalt output is recalculated into a crude cobalt hydroxide output based on a 35% cobalt content and all flows are scaled to 1 kg crude cobalt hydroxide. Electricity is assumed to be medium voltage. The limestone input is assumed to be crushed when purchased. Transport of the crude cobalt hydroxide to China (about 16,000 km, 17% truck and 83% ocean tanker) is included in the dataset. While not reported in Dai et al. (2018), tailings are formed during refining of copper ores in the DRC (Adrianto et al. 2022). The difference in mass between the ore input and the crude cobalt hydroxide output is therefore assumed to become tailings. Both oxidic and sulfidic copper-cobalt ores are mined in the DRC (Dai et al. 2018; Shengo et al. 2020), but since the shares are unknown, 50% of oxidic and sulfidic tailings each are assumed. Treatment processes from the Ecoinvent database are applied for these tailings, with a global geographical scope for the oxidic tailings and a

dataset representing tailings treatment in the neighboring country of Zambia for the sulfidic tailings. The resulting unit process for the hydrometallurgical ore processing in the DRC is shown in Table S5.

The production of battery-grade cobalt sulfate is modeled specifically based on the Tongxiang plant run by Huayou Cobalt and the data are considered “conservative” estimates. The unit-process data provided by in Dai et al. (2018) are scaled from per ton cobalt equivalent to per kg battery-grade cobalt sulfate. The resulting unit process for the battery-grade cobalt sulfate in China is shown in Table S6. One of the inputs to the battery-grade cobalt sulfate production — sodium metabisulfite — does currently not have a dataset in the Ecoinvent database. Therefore, its production was approximated as an input of sodium hydroxide based on Dai et al. (2018), see Table S7.

3 Results and discussion

Figure 1a shows the potential health impacts of the assessed LIB cell divided into four contributions. The first two are accidents in artisanal cobalt mining in the DRC based on the two different fatality estimates used in the study — the higher estimate at 2000 fatalities/year and the more conservative media reporting of 65 fatalities/year. The third is the contribution from emissions and water use throughout the product system, as calculated using the ReCiPe impact assessment method. The fourth is accidents in other parts of the product system based on the accident data from Scanlon et al. (2015). A main observation is that emissions and water use constitute the highest contribution by approximately one order of magnitude. The second largest contribution is

from occupational accidents in artisanal cobalt mining in the DRC, when the high fatality estimate is used. The contribution from occupational accidents in other parts of the product system is notably lower — about 30 times lower than the high estimate for accidents in artisanal cobalt mining and about 200 times lower than the contribution from emission and water use. The low estimate of the accidents in artisanal cobalt mining in the DRC is about 30 times lower than the high estimate, making the contribution comparable to accidents in other parts of the product system.

Figure 2b shows a more detailed contribution analysis for the higher and presumably more relevant estimate of fatalities in artisanal cobalt mining in the DRC. It shows that these accidents contribute with about 13% of the potential health impacts of the LIB cell. Other accidents, i.e., meaning accidents in the product system other than the artisanal cobalt mining, contribute with < 1%. The majority of the contributions (87%) make up the various green bars, which represent emissions and water use in different parts of the product system. Here, there are four distinct inputs to the gigafactory for which the production contribute with > 5% of the potential health impacts: (i) production of the nickel sulfate used for making the nickel-containing cathode (30%), (ii) production of the copper foil used in the current collector of the anode (20%), (iii) production of the cell container and lid made from nickel-plated steel (8%), and (iv) production of the cobalt sulfate, which is also part of the cathode (6%). In addition, several smaller contributions, each contributing less than 5%, together amount to 23% of the potential health impacts. The vast majority of these contributions are from impacts occurring upstream of the gigafactory. Considering that the nickel sulfate and copper foil productions constitute the two main contributors — even in this case with the high

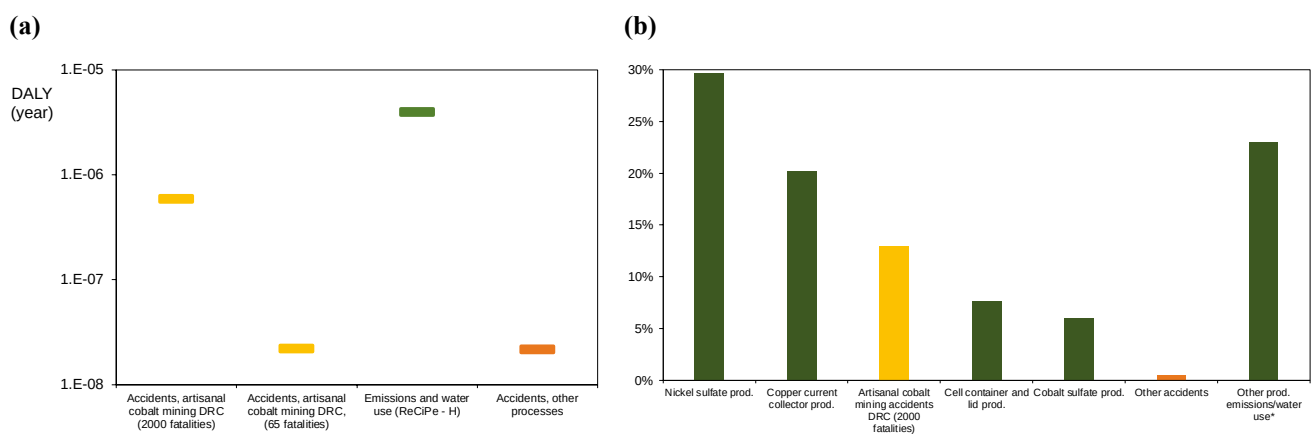


Fig. 2 Potential health impacts from the lithium-ion battery cell. **a** Contributions from the main types of health impacts are shown as absolute results on a logarithmic scale. **b** Relative contributions given the high estimate for fatalities in artisanal cobalt mining in the DRC. Green bars represent emission and water use impacts from ReCiPe,

the yellow bar represents accidents in artisanal cobalt mining in the DRC (high estimate), and the orange bar represents other occupational accidents. *The contributions to this category are all < 5% each and mostly upstream to the gigafactory

estimate of fatalities in artisanal cobalt mining in the DRC — these two input materials are analyzed in more detail in Sects. 3.1 and 3.2, respectively.

3.1 Nickel sulfate production

The inventory data for nickel sulfate production was taken from the Ecoinvent database, specifically the global dataset “market for nickel sulfate.” About 92% of the nickel sulfate in that process is produced jointly with cobalt during extraction of ores containing both the metals and the data originates from LCA work commissioned by the Cobalt Development Institute (Environmental Resource Management 2016). A final 8% is produced by reacting nickel (class 1) with sulfuric acid. The nickel supply to this Ecoinvent process comes mainly from cobalt–nickel ores, nickel–copper ores, and as a byproduct from platinum group metal mining and refining. The two midpoint impact categories that contribute the most to the potential health impacts of the nickel sulfate market process are fine particulate matter formation (51%) and human non-carcinogenic toxicity (21%). For the fine particulate matter formation, the dominating elementary flow is sulfur dioxide, mainly occurring during the production of nickel from platinum group metal mining and cobalt–nickel ore mining. Here, it can be noted that sulfur dioxide is considered differently between the three value perspectives of the ReCiPe method (Huijbregts et al. 2016). Direct emissions of fine particulate matter obviously contribute to fine particulate matter formation. Sulfur dioxide, however, only contributes indirectly by constituting condensation nuclei that leads to the formation of secondary particulate matter. In the individualist, short-term value

perspective in ReCiPe, only primary particulate matter is considered. In the hierarchist, medium-term perspective, the main perspective selected for this study, indirect particulate matter from sulfur dioxide is included. In addition, in the egalitarian, long-term perspective, indirect particulate matter from other emissions besides sulfur dioxide is also considered (i.e., nitrogen oxides and ammonia). Figure 3a shows that the potential health impacts from nickel sulfate go down by 80% from the hierarchist to the individualist perspective. Reduction in fine particulate matter formation due to the omission of indirect particulate matter from sulfur dioxide is the biggest reason for this decrease in potential health impacts. An egalitarian value perspective (not shown in Fig. 3a), on the other hand, increases potential health impacts of nickel sulfate by a factor of 40 compared to the hierarchist perspective.

For the human non-carcinogenic toxicity, the main contributing elementary flows are arsenic and zinc ions originating from the treatment of sulfidic tailings. Again, as shown in Fig. 3a, these potential health impacts depend considerably on the selected value perspective and become notably reduced if a more short-term perspective is chosen. For example, a limited number of exposure routes (drinking water and air) is considered in ReCiPe’s individualist perspective (Huijbregts et al. 2016). Also, the time horizon in the individualist perspective is only 20 years, versus 100 years in the hierarchist perspective, which means that the toxic substances have less time to cause harm.

In terms of data representativeness, it can be noted that the unit process dataset for treatment of sulfidic tailings in the Ecoinvent database, which includes the leaching of several toxic metals, is generic and applied to many

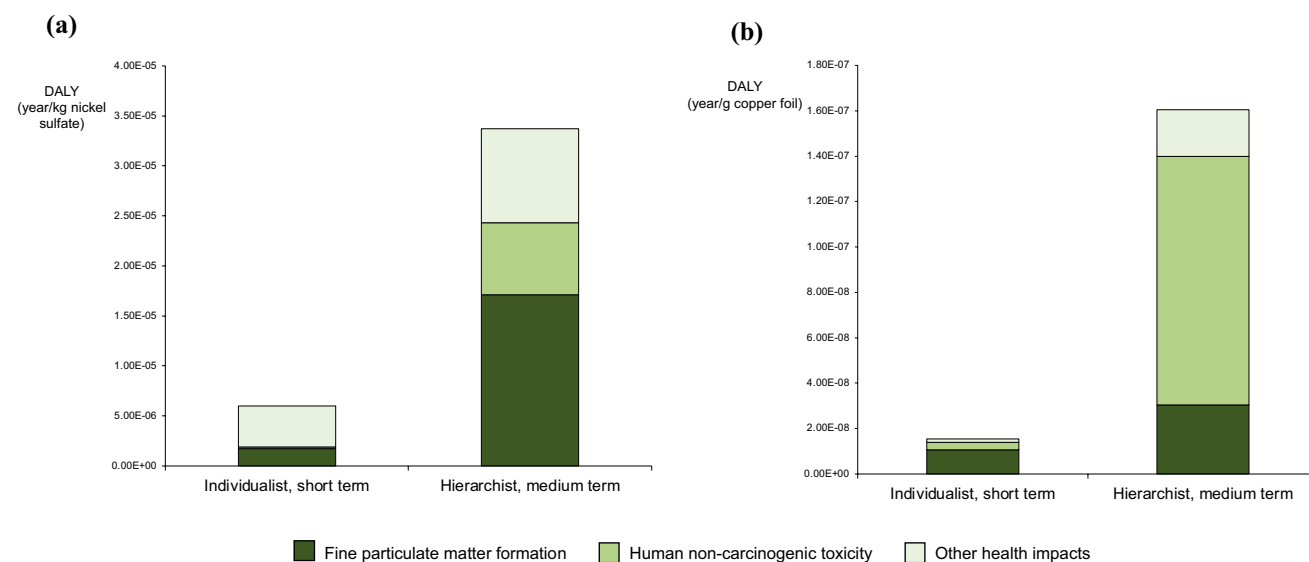


Fig. 3 Potential health impacts from two main contributors to the health impacts of the studied LIB cell, **a** nickel sulfate production and **b** copper foil production, given two different value perspectives. The hierarchist perspective is the chosen main perspective of this study

non-ferrous metal extraction processes in the database. As a result, sulfidic tailings are identified as a large contributor to toxicity impacts in many product systems (Reinhard et al. 2019). Hence, collection of more data with higher specificity regarding the treatment of tailings from different extractions could influence the results of this study.

3.2 Copper foil production

The production of copper foil, which serves as the current collector for the graphite anode, is modeled as sheet rolling of so-called cathode copper. The two midpoint impact categories that contribute the most to the potential health impacts of the copper foil production are the same as for nickel sulfate production, but in reversed order: human non-carcinogenic toxicity (68%) and fine particulate matter formation (19%). For the human non-carcinogenic toxicity, the main contributing processes are treatment of sulfidic tailings due to zinc ion emissions and treatment of copper slag due to arsenic ion emissions. For the fine particulate matter formation, the main contribution comes from the mining of platinum group metals, from which copper is a byproduct, specifically from sulfur dioxide emissions. Nickel sulfate and copper foil production thus mostly have the same main contributing midpoint impact categories, processes, and elementary flows. Unsurprisingly, there are large differences in potential health impacts depending on the value perspective for the copper foil production as well. As shown in Fig. 3b, the individualist perspective gives approximately a factor of 10 lower health impact compared to the hierarchist perspective, mainly due to reductions in human non-carcinogenic toxicity and fine particulate matter formation. Again, the individualist perspective gives lower potential health impacts due to shorter time horizons, fewer exposure routes, and exclusion of indirect particulate matter formation. The egalitarian perspective (not shown in Fig. 3b), on the other hand, gives more than 100 times higher potential health impacts compared to the hierarchist perspective. This is due to longer time horizons and inclusion of additional types of indirect particulate formation.

3.3 Potential improvements

Considering first the design of the studied LIB cell, one option for health improvements could be to lower the cobalt content further, i.e., in line with the generally ongoing efforts for LIBs by moving away from the cobalt-rich NMC 333 chemistry (Fan et al. 2020). However, as shown in Fig. 1b, if nickel is used instead, as in the studied NMC 811 chemistry, that also brings considerable potential health impacts. If the reduction of cobalt is done at the expense of increased nickel content, a net reduction in potential health impacts might not occur. Possibly, the copper current collector foil

could be replaced by some other conductive material. Any such changes must, however, not compromise the technical performance of the LIB cell significantly, in relation to its prerequisites for use. Materials that might be investigated as potential alternatives include aluminum, nickel, titanium, stainless steel, and possibly also carbon-based nanomaterials such as carbon nanotubes and graphene (Zhu et al. 2021).

Moving upstream in the product system, the analyses in Sects. 3.1 and 3.2 showed that much of the potential health impacts along the life cycle of the studied LIB cell are related to mining of metals and the treatment of tailings. Emission reductions in metal mining and tailings treatment would thus reduce the potential health impacts of the studied LIB cell. For example, in the dataset where nickel is produced as a by-product during platinum group metal mining, each kg of nickel produced causes about 7 kg of sulfur dioxide emissions. The sulfur originates from sulfidic ores and is emitted as sulfur dioxide during several refining steps, such as roasting (Classen et al. 2009). Recovering that sulfur dioxide would reduce potential health impacts from the nickel sulfate production process. In addition, increased recycled content of metals such as nickel and copper would also reduce upstream impacts. The current recycled contents in the Ecoinvent datasets for cathode copper and nickel (class 1) datasets are approximately 20% and < 1%, respectively. Battery manufacturers could investigate the possibility of sourcing metal supplies with higher recycled contents.

Accidents during artisanal cobalt mining in the DRC also contribute notably to the potential health impacts of the studied LIB cell. Sovacool (2019) proposed seven policy recommendations for better governing of cobalt mining in the DRC. These include to: (i) enforce better occupational standards for artisanal and small-scale mining operations, (ii) form joint ventures with artisanal and small-scale mining and large-scale and industrial mining interests, (iii) implement better dust and tailings management at large-scale and industrial mining, (iv) pursue broader and more robust community benefit sharing agreements, (v) support training for alternative livelihoods, (vi) recognize the limitations of traceability schemes and formalization, and (vii) do not ban artisanal and small-scale cobalt mining. Some of these recommendations, such as enforcing better occupational standards, might directly lead to reductions in potential health impacts. For example, Elenge (2013) suggested that it would be possible to introduce some degree of mechanization in artisanal cobalt mining, since the costs would be offset by a more or less guaranteed production level over time, which would reduce the physical strain of the artisanal miners. For other recommendations, an indirect effect might occur, e.g., if training for alternative livelihoods reduces the need for wounded or tired miners to return to mining where they are at higher risk of suffering

from fatal accidents. Other publications generally provide similar recommendations, albeit formulated differently and at a different level of detail (Tsurukawa et al. 2011; BGR 2019; OECD 2019; Sovacool et al. 2020). The seventh recommendation by Sovacool (2019) — to not ban artisanal mining of cobalt — reflects that there are also benefits from artisanal cobalt mining in the DRC, which, given a ban, would disappear (see Sect. 1). Instead, Sovacool (2019) advocates efforts to improve the mining practices. This recommendation is also echoed in other sources, e.g., Tsurukawa et al. (2011). Notably, this is opposite to the recommendation by Sharma and Manthiram (2020), who recommended a complete elimination of cobalt in LIB cathodes.

3.4 Potential positive health impacts

The aim of this study has been to quantify the potential negative health impacts caused by the supply chain activities of a selected LIB cell. However, there might also be potential positive health impacts related to the life cycle of this LIB cell. These could occur during the use of the cell, in particular if it enables the replacement of fossil fuel-based vehicles (through electromobility) or fossil fuel-based electricity (through stationary storage of electricity from renewable energy sources). Investigating such health benefits would require studies with wider cradle-to-grave scopes. However, there might also be potential positive health impacts within the LIB cell production system studied here. For example, the income generated by artisanal cobalt miners in the DRC — and possibly income elsewhere in the product system as well — might lead to health benefits. Previous work by Feschet et al. (2013) has started to outline an impact pathway for positive health impacts from earning an income based on the so-called Preston curve, which shows how the life expectancy in low-income countries increases with higher income rates in general. However, this approach calculates changes in life expectancy rather than DALYs and it requires certain criteria to be fulfilled. For example, the added value of the activity must be distributed relatively equally among the population for this approach to apply. This is currently not fulfilled in the DRC, which has among the world's highest corruption levels. Therefore, this approach to quantifying positive health impacts from income can currently not be included in Eq. (2). However, there might be local and more direct health benefits from earning an income, which do not affect the general population of a region as per the Preston curve, but nevertheless affect, e.g., specific miners and their families. We recommend further studies to investigate this relationship between incomes and health status in more detail.

3.5 Limitations and uncertainties

The aim of assessing a wide range of potential health impacts inevitably bring sources of uncertainty. The main inventory data sources of this study are Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database, version 3.7.1. The data from Chordia et al. (2021) represent a modern gigafactory and is considered fit for the aim of this study. As explained in Sect. 2.4, Dai et al. (2018) is the only known source with cobalt supply data presented at the unit process level, which is considered valuable in a study with a particular interest in the contribution from cobalt. Still, the data from Dai et al. (2018) is limited, e.g., in terms of emissions reported and treatment of tailings, which are therefore important areas for further data gathering to reduce the uncertainty in potential health impacts from emissions. The Ecoinvent database has the explicit aim of providing background data to LCA studies (Wernet et al. 2016), and as such it is considered fit for the aim of this study. However, considering the large contribution from nickel sulfate and copper foil production to the potential health impacts of the studied battery cell (Fig. 2b), further detailed investigations of emissions and treatment of tailings from nickel and copper mining would be useful to reduce the uncertainty of this study and identify improvement opportunities.

The three main data sources when it comes to characterization factors for social impact assessment are ReCiPe for emissions and water use (Huijbregts et al. 2017), Scanlon et al. (2015) for occupational accidents for most processes and our own calculations for occupational accidents from artisanal cobalt mining. ReCiPe is widely used to assess potential health impacts from emissions and water use in LCA studies. The three value perspectives — individualist, hierarchist and egalitarian — represent different views on time perspective and inclusiveness when it comes to environmental and health impacts, with the individualist/short term and egalitarian/long term perspectives being the two extremes. While these perspectives can provide a wide range of potential health impacts (Fig. 3), they also illustrate how differences in fundamental values influence the results. The characterization factors from Scanlon et al. (2015) cover the most relevant industry sectors, but are aggregated, as in “copper ore and nickel ore mining.” Here, a further disaggregation and differentiation between different locations, e.g., industrial copper-cobalt ore mining in the DRC and nickel mining in Russia in that case, would reduce the uncertainty in the estimation of potential health impacts from occupational accidents. Regarding our calculations of work environment characterization factors for artisanal cobalt mining, the largest source of uncertainty is likely the 65–2000 fatalities/year range. Further investigations to reduce uncertainty in that value are strongly recommended.

4 Conclusions

This study has shown that the cobalt input to the NMC-type LIB production (in the form of cobalt sulfate) contributes notably to the battery's potential health impact, both through occupational accidents during artisanal cobalt mining in the DRC (13%) and through emissions and water use during the production of cobalt sulfate (6%). The occupational accidents impact artisanal miners in the Katanga region of the DRC specifically. However, cobalt is not the only contributor to the potential health impacts, nor necessarily the largest. Potential health impacts from the production of two other input materials to the production of the LIB contribute even more: nickel sulfate (30%) and copper foil (20%). The reason for these high potential health impacts are emissions of sulfur dioxide, zinc, and arsenic. However, the magnitudes of these impacts depend on the time horizon applied in the assessment — a long time horizon indicate even higher potential health impacts from nickel sulfate and copper production, whereas when using a shorter time horizon, these health impacts are notably reduced. Contrary to the occupational accidents in artisanal cobalt mining, these emissions impact the general population. In order to reduce potential health impacts of NMC batteries, a number of recommendations are proposed to LIB cell manufacturers: (i) investigate the feasibility of replacing the copper foil with another conductive material able to provide anode current collector functionality; (ii) reduce emissions from metals extraction; and (iii) increase the recycled content of sourced metals. Finally, improved occupational standards in artisanal mining in the DRC are recommended to reduce accident rates, in particular fatal accidents.

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Author contribution Rickard Arvidsson: conceptualization, methodology, formal analysis, investigation, data curation, writing — original draft, visualization, project administration, and funding acquisition. Mudit Chordia: methodology, investigation, data curation, and writing — review and editing. Anders Nordelöf: conceptualization, methodology, investigation, data curation, writing — review and editing, and funding acquisition.

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Data availability The data that supports the findings of this study are cited in Sect. 2 or available in the Supporting Information (SI), specifically Tables S1–S7. Access to some upstream data requires access to the Ecoinvent database.

Declarations

Conflict of interest The authors declare no competing interests.

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References

- Adrianto LR, Pfister S, Hellweg S (2022) Regionalized life cycle inventories of global sulfidic copper tailings. *Environ Sci Technol* 56(7):4553–4564
- Al Barazi S, Näher U, Vetter S, Schütte P, Liedtke M, Baier M, Franken G (2017) Cobalt from the DR Congo - potential, risks and significance for the global cobalt market, vol. 53 *Commodity Top News*. Federal Institute for Geosciences and Natural Resources, Hannover
- Amnesty International (2013) Profits and loss. Mining and human rights in Katanga, Democratic Republic of the Congo, London
- Amnesty International and Afreewatch (2016) “This is what we die for”. Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt. London
- Arvidsson R, Hildenbrand J, Baumann H, Islam KMN, Parsmo R (2018) A method for human health impact assessment in social LCA: lessons from three case studies. *Int J Life Cycle Assess* 23(3):690–699
- Bamana G, Miller JD, Young SL, Dunn JB (2021) Addressing the social life cycle inventory analysis data gap: insights from a case study of cobalt mining in the Democratic Republic of the Congo. *One Earth* 4(12):1704–1714
- Banza CLN, Nawrot TS, Haufroid V, Decrée S, De Putter T, Smolders E, Kabyla BI, Luboya ON, Ilunga AN, Mutombo AM, Nemery B (2009) High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environ Res* 109(6):745–752
- Banza Lubaba Nkulu C, Casas L, Haufroid V, De Putter T, Saenen ND, Kayembe-Kitenge T, Musa Obadia P, Kyanika Wa Mukoma D, Lunda Ilunga J-M, Nawrot TS, Luboya Numbi O, Smolders E, Nemery B (2018) Sustainability of artisanal mining of cobalt in DR Congo. *Nat Sustain* 1(9):495–504
- Baumann H, Arvidsson R, Tong H, Wang Y (2013) Does the production of an airbag injure more people than it saves in traffic? Discussing an alternative approach to S-LCA methodology. *J Ind Ecol* 17(4):517–527
- Benoît Norris C, Traverso M, Neugebauer S, Ekener E, Schaubroeck T, Russo Garrido S, Berger M, Valdivia S, Lehmann A, Finkbeiner M, Arcese G (2020) Guidelines for social life cycle assessment of products and organizations. United Nations Environment Programme (UNEP)

- BGR (2019) Mapping of the artisanal copper-cobalt mining sector in the provinces of Haut-Katanga and Luabala in the Democratic Republic of the Congo. German Federal Institute for Geosciences and Natural Resources, Hannover
- Chordia M, Nordelöf A, Ellingsen LA-W (2021) Environmental life cycle implications of upscaling lithium-ion battery production. *Int J Life Cycle Assess* 26:2024–2039
- Classen M, Althaus HJ, Blaser S, Scharnhorst W, Tuchschild M, Jungbluth N, Emmenegger MF (2009) Life cycle inventories of metals. Data v2.1. Ecoinvent Centre, Dübendorf
- Dai Q, Kelly JC, Elgowainy A (2018) Cobalt life cycle analysis update for the GREET® model. Argonne National Laboratory
- de Haan J, Geenen S (2016) Mining cooperatives in Eastern DRC The interplay between historical power relations and formal institutions. *Extr Ind Soc* 3(3):823–831
- Debaveye S, De Smedt D, Heirman B, Kavanagh S, Dewulf J (2020) Quantifying the handprint-footprint balance into a single score: the example of pharmaceuticals. *PLoS ONE* 15(2):e0229235
- Elenge M, Leveque A, De Brouwer C (2013) Occupational accidents in artisanal mining in Katanga, D.R.C. *Int J Occup Med Environ Health* 26(2):265–274
- Elenge MM (2013) Safety and health in mining in Congo (DRC). In: Englstrand K, Vingård E (eds) *Occupational Safety and Health in Mining - Anthology on the situation in 16 mining countries*. University of Gothenburg, Gothenburg, Sweden
- Elenge MM, Aubry J-C, Jacob L, De Brouwer C (2011) Heavy metal in hair samples of 109 non-industrial (miners) population in Katanga. *Sante* 21(1):41–46
- Elenge MM, De Brouwer C (2011) Identification of hazards in the workplaces of Artisanal mining in Katanga. *Int J Occup Med Environ Health* 24(1):57–66
- Environmental Resource Management (2016) The environmental performance of refined cobalt - life cycle inventory and life cycle assessment of refined cobalt cobalt development institute
- Faber B, Krause B, Sánchez de la Sierra R (2017) Artisanal mining, livelihoods, and child labour in the cobalt supply chain of the Democratic Republic of the Congo. UC Berkely, Berkely, United States
- Fan E, Li L, Wang Z, Lin J, Huang Y, Yao Y, Chen R, Wu F (2020) Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects. *Chem Rev* 120(14):7020–7063
- Feschet P, Macombe C, Garrabé M, Loeillet D, Saez A, Benhmad F (2013) Social impact assessment in LCA using the Preston pathway. *Int J Life Cycle Assess* 18(2):490–503
- Furberg A, Arvidsson R, Molander S (2018) Live and let die? Life cycle human health impacts from the use of tire studs. *Int J Environ Res Public Health* 15(8):1774
- Haagsma JA, Graetz N, Bolliger I, Naghavi M, Higashi H, Mullany EC, Abera SF, Abraham JP, Adofu K, Alsharif U, Ameh EA, Ammar W, Antonio CAT, Barrero LH, Bekele T, Bose D, Brazinova A, Catalá-López F, Dandona L, Dandona R, Dargan PI, De Leo D, Degenhardt L, Derrett S, Dharmaratne SD, Driscoll TR, Duan L, Petrovich Ermakov S, Farzadfar F, Feigin VL, Franklin RC, Gabbe B, Gosselin RA, Hafezi-Nejad N, Hamadeh RR, Hajar M, Hu G, Jayaraman SP, Jiang G, Khader YS, Khan EA, Krishnaswami S, Kulkarni C, Lecky FE, Leung R, Lunevicius R, Lyons RA, Majdan M, Mason-Jones AJ, Matzopoulos R, Meaney PA, Mekonnen W, Miller TR, Mock CN, Norman RE, Orozco R, Polinder S, Pourmalek F, Rahimi-Movaghar V, Refaat A, Rojas-Rueda D, Roy N, Schwebel DC, Shaheen A, Shahrz S, Skirbekk V, Søreide K, Soshnikov S, Stein DJ, Sykes BL, Tabb KM, Temesgen AM, Tenkorang EY, Theadom AM, Tran BX, Vasankari TJ, Vavilala MS, Vlassov VV, Woldeyohannes SM, Yip P, Yonemoto N, Younis MZ, Yu C, Murray CJL, Vos T, Balalla S, Phillips MR (2016) The global burden of injury: incidence, mortality, disability-adjusted life years and time trends from the Global Burden of Disease study 2013. *Inj Prev* 22(1):3–18
- Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, Walton A, Christensen P, Heidrich O, Lambert S, Abbott A, Ryder K, Gaines L, Anderson P (2019) Recycling lithium-ion batteries from electric vehicles. *Nat* 575(7781):75–86
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22(2):138–147
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Hollander A, Zijp M, van Zelm R (2016) ReCiPe 2016 - a harmonized life cycle impact assessment method at midpoint and endpoint level. Characterization. Dutch National Institute for Public Health and the Environment, Bilthoven, Report I
- ILO (1999) Social and labour issues in small-scale mines. International Labour Organization, Geneva
- International Labour Office (2016) ILO standards on forced labour - the new protocol and recommendation at a glance. Geneva
- Kennedy C (2017) Cobalt prices to rocket as tech giants scramble for supplies. <https://www.prnewswire.com/news-releases/cobalt-prices-to-rocket-as-tech-giants-scramble-for-supplies-657690933.html>. PR Newswire
- Kyeremateng-Amoah E, Clarke EE (2015) Injuries among artisanal and small-scale gold miners in Ghana. *Int J Environ Res Public Health* 12(9):10886–10896
- Li M, Lu J, Chen Z, Amine K (2018) 30 years of lithium-ion batteries. *Adv Mater* 30(33):1800561
- Lindberg S, Andersson U (2019) Blood batteries (in Swedish). *Aftonbladet*, <https://special.aftonbladet.se/blodsbaatterier/>
- MacDonald A, Pokharel K (2020) Many miners die, and it never shows up in safety data. The Wall Street Journal. <https://www.wsj.com/articles/many-miners-die-and-it-never-shows-up-in-safety-data-11582815186>
- Mancini L, Eslava NA, Traverso M, Mathieux F (2021) Assessing impacts of responsible sourcing initiatives for cobalt: insights from a case study. *Resour Policy* 71:102015
- OECD (2019) Interconnected supply chains: a comprehensive look at due diligence challenges and opportunities sourcing cobalt and copper from the Democratic Republic of the Congo
- Porzio J, Scown CD (2021) Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Adv Energy Mater* 2100771
- Reinhard J, Wernet G, Zah R, Heijungs R, Hilty LM (2019) Contribution-based prioritization of LCI database improvements: the most important unit processes in ecoinvent. *The Int J Life Cycle Assess* 24(10):1778–1792
- Scanlon KA, Lloyd SM, Gray GM, Francis RA, LaPuma P (2015) An approach to integrating occupational safety and health into life cycle assessment: development and application of work environment characterization factors. *J Ind Ecol* 19(1):27–37
- Sharma SS, Manthiram A (2020) Towards more environmentally and socially responsible batteries. *Energy Environ Sci* 13(11):4087–4097
- Shengo LM, Kitobo WS, Kime MB, Mambwe MP, Nyembo TK (2020) Mineralogical variations with the mining depth in the congo copperbelt: technical and environmental challenges in the hydrometallurgical processing of copper and cobalt ores. *J Sustain Min* 19(2):96–114
- Sovacool BK (2019) The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extr Ind Soc* 6(3):915–939
- Sovacool BK, Ali SH, Bazilian M, Radley B, Nemery B, Okatz J, Mulvaney D (2020) Sustainable minerals and metals for a low-carbon future. *Sci* 367(6473):30–33
- Thies C, Kieckhäfer K, Spengler TS, Sodhi MS (2019) Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. *Procedia CIRP* 80292–297

- Tsurukawa N, Prakash S, Manhart A (2011) Social impacts of artisanal cobalt mining in Katanga. Democratic Republic of Congo, Institute for Applied Ecology, Freiburg
- Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21(9):1218–1230
- World Bank (2020) State of the artisanal and small-scale mining sector. World Bank, Washinton, DC
- Yang Y (2019) A unified framework of life cycle assessment. *Int J Life Cycle Assess* 24(4):620–626
- Zhu P, Gastol D, Marshall J, Sommerville R, Goodship V, Kendrick E (2021) A review of current collectors for lithium-ion batteries. *J Power Sources* 485229321
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Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery

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Abstract

Purpose Lithium-ion batteries (LIBs) have been criticized for contributing to negative social impacts along their life cycles, especially child labor and harsh working conditions during cobalt extraction. This study focuses on human health impacts — arguably the most fundamental of all social impacts. The aim is to quantify the potential life-cycle health impacts of an LIB cell of the type nickel-manganese-cobalt (NMC 811) in terms of disability-adjusted life years (DALY), as well as to identify hotspots and ways to reduce the health impacts.

Methods A cradle-to-gate attributional life-cycle assessment study is conducted with the functional unit of one LIB cell and human health as the sole endpoint considered. The studied LIB is produced in a large-scale “gigafactory” in Sweden, the cobalt sulfate for the cathode is produced in China, and the cobalt raw material is sourced from the Democratic Republic of the Congo (DRC). Potential health impacts from both emissions and occupational accidents are quantified in terms of DALY, making this an impact pathway (or type II) study with regard to social impact assessment. Two scenarios for fatality rates in the artisanal cobalt mining in the DRC are considered: a high scenario at 2000 fatalities/year and a low scenario at 65 fatalities/year.

Results Applying the high fatality rate, occupational accidents in the artisanal cobalt mining in the DRC contribute notably to the total life-cycle health impacts of the LIB cell (13%). However, emissions from production of nickel sulfate (used in the cathode) and of copper foil (the anode current collector) contribute even more (30% and 20%, respectively). These contributions are sensitive to the selected time horizon of the life-cycle assessment, with longer or shorter time horizons leading to considerably increased or decreased health impacts, respectively.

Conclusions In order to reduce the health impacts of the studied LIB, it is recommended to (i) investigate the feasibility of replacing the copper foil with another material able to provide anode current collector functionality, (ii) reduce emissions from metal extraction (particularly nickel and copper), (iii) increase the recycled content of metals supplied to the LIB manufacturing, and (iv) improve the occupational standards in artisanal mining in the DRC, in particular by reducing fatal accidents.

Keywords Life cycle assessment · Disability-adjusted life years · Occupational accidents · Cobalt mining · Nickel-manganese-cobalt (NMC) · Human health · Social risks

1 Introduction

Like diamonds of certain origins, cobalt mined from the Democratic Republic of the Congo (DRC) has been associated with the noun “blood” in news media (Kennedy 2017; Lindberg and Andersson 2019). The DRC currently provides around 70% of the global cobalt supply, partly through artisanal mining, which provides livelihood for almost 200,000 people (BGR 2019; OECD 2019). Although not counted among of the traditional 3TG conflict minerals (i.e., tantalum, tin, tungsten, and

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gold), cobalt mined in the DRC has been associated with numerous health and social impacts, including high exposure to cobalt and other toxicants from mining (including dust), occupational accidents, long working hours, child labor, corruption, and displacement of indigenous people (Banza et al. 2009; Elenge et al. 2011; Elenge and De Brouwer 2011; Tsurukawa et al. 2011; Amnesty International 2013; Elenge 2013; Amnesty International and Afreewatch 2016; Faber et al. 2017; Banza Lubaba Nkulu et al. 2018; BGR 2019; Lindberg and Andersson 2019; Sovacool 2019; Bamana et al. 2021). These impacts are particularly prevalent in artisanal, small-scale cobalt mining, which currently accounts for approximately 20% of the cobalt extracted in the DRC (Al Barazi et al. 2017), while the industrial, more mechanized extraction generally has a considerably lower occurrence of, e.g., child labor. At the same time, positive social externalities of artisanal mining have also been reported, including reduced poverty, increased state revenue, increased services, and collective occupational identity (Tsurukawa et al. 2011; de Haan and Geenen 2016; Sovacool 2019). For example, while many Congolese struggle to earn 1 US\$/day, artisanal miners generally earn more than 3 US\$/day (Tsurukawa et al. 2011; de Haan and Geenen 2016). There are also some social impacts occurring in other low-income countries which are seemingly absent in artisanal cobalt mining in the DRC, an example being forced labor (Tsurukawa et al. 2011; OECD 2019). This means that despite harsh conditions, the work is not undertaken without consent or under the threat of a penalty, such as violence or retention of identity papers (International Labour Office 2016).

The current main use of cobalt is in lithium-ion batteries (LIBs), which have become the dominant technology for rechargeable energy storage (OECD 2019). Commercialized by Sony Co. and others in the early 1990s, LIBs have enabled many products of high significance in contemporary societies, such as mobile phones, laptops, and electric vehicles (Li et al. 2018). Different LIB chemistries exist in the market today based on the type of application, such as lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), of which the NMC, NCA, and LCO chemistries contain cobalt in varying proportions (Porzio and Scown 2021). Most of the currently used LIBs in electric vehicles are NMC 111 (sometimes called NMC 333), NMC 532, or NMC 622, where the numbers represent the relative shares of nickel, manganese, and cobalt in the cathode, respectively (Harper et al. 2019). However, there is a strive towards further reducing the cobalt content of NMC batteries, as in the more recently developed NMC 811 cathode material (Fan et al. 2020).

This study focuses on the contribution of LIBs to human health impacts — arguably the most fundamental of all social impacts. The question that the study aims to answer is as follow: How large are the potential negative health impacts from an LIB along its life cycle, which are the hotspots and how can the health impacts be reduced? In particular, the study seeks to investigate the relative contribution to potential health impacts from cobalt in a modern low-cobalt LIB. To answer this question, an LCA of an LIB of the type NMC 811 is performed from cradle to gate, with human health as the endpoint. Specifically, potential health impacts from emissions and occupational accidents are assessed using the quantitative disability-adjusted life years (DALY) indicator. Since there is a causal link from the release of emissions and accidents to DALY, this study applies a so-called impact pathway approach (Benoît Norris et al. 2020) to social impact assessment. The authors are not aware of any previous quantitative assessments of potential health impacts for LIBs, although there exist a few qualitative health assessments of LIBs and/or cobalt where a so-called reference scale approach (Benoît Norris et al. 2020) to social impact assessment is applied. Mancini et al. (2021) assessed “occupational health and safety” impacts of artisanal mining of cobalt together with 13 other social impacts, using a five-point ordinal scale going from “no noted risks” to “systematic and grave abuse.” The latter category was assigned to the occupational health and safety of artisanal cobalt mining. Thies et al. (2019) also assessed a range of social impacts of an LIB pack (NMC type), including “risks of occupational toxics and hazards,” using the ordinal-scale system from the Social Hotspots Database, which is a widely used database in social LCA. That scale contains “no risk” (which translates to 0.0), “low risk” (0.1), “medium risk” (1), “high risk” (5), and “very high risk” (10). They concluded that Chinese production of the LIBs yielded higher risks of occupational toxics and hazards than German production, even if the raw materials (including cobalt) were sources responsibly. Similarly, Sharma and Manthiram (2020) conducted a qualitative social assessment of an NMC 811 and an LFP battery based on publications from human rights organizations, newspapers, academics, and community members. They concluded that producing the cobalt required for 26 million electric vehicles by 2030 would result in 25,000 children needing to work by hand for 10 h per day in the DRC, as well as to toxic pollution of the local community from cobalt mining. Consequently, they recommend that the use of cobalt in LIBs must be eliminated entirely.

2 Method and materials

In order to assess the magnitude of the potential health impacts of an LIB cell containing cobalt, as well as the relative contribution of cobalt, a process-based or

attributional LCA was conducted (Yang 2019), with a cradle to gate scope (Fig. 1). The system boundary largely follows that of Chordia et al. (2021), who studied the environmental impacts of the same battery, with the notable exception of the cobalt sulfate production, as described in Sect. 2.4. The functional unit of that study was 1 kWh of theoretical energy storage capacity for a 21,700-type cylindrical LIB cell of the NMC 811 chemistry after the formation step, with the composition described in Table 1. The cell is intended for automobile applications, weighing 68 g and having a specific energy density value within the range of 210–240 Wh/kg (Chordia et al. 2021). In this study, the functional unit of one such battery cell is chosen as it is a more tangible functional unit for interpretation. However, it can be translated into kWh of energy storage approximately, for comparisons with other battery cells, by applying a factor of 65 cells/kWh.

The applied impact pathway (or type II) method for assessing potential health impacts in the context of social LCA was first conceptualized by Baumann et al. (2013) and then formalized by Arvidsson et al. (2018). It entails a quantification and relative comparison of health impacts along product life cycles, as well as a quantification of the potential net health impact of products:

Table 1 Approximate composition of the functional unit of the study — one cylindrical NMC 811 battery cell weighting about 68 g (Chordia et al. 2021)

Cell component	Share of weight
Positive current collector and tab (aluminum)	3%
Active cathode material (nickel, cobalt, and manganese)	37%
Negative current collector and tab (copper)	7%
Active anode material (synthetic graphite)	23%
Electrolyte (lithium hexafluorophosphate and organics)	10%
Separator (polyethylene)	2%
Cylindrical container (nickel-plated steel)	12%
Lid (nickel-plated steel)	3%
Fastening tape (polyethylene)	1%
Insulation ring (polyethylene)	2%

$$DALY_{net} = \sum_{positive} DALY + \sum_{negative} DALY \quad (1)$$

DALY stands for disability-adjusted life years (unit: years). Since DALY is a measure of years lost due to death

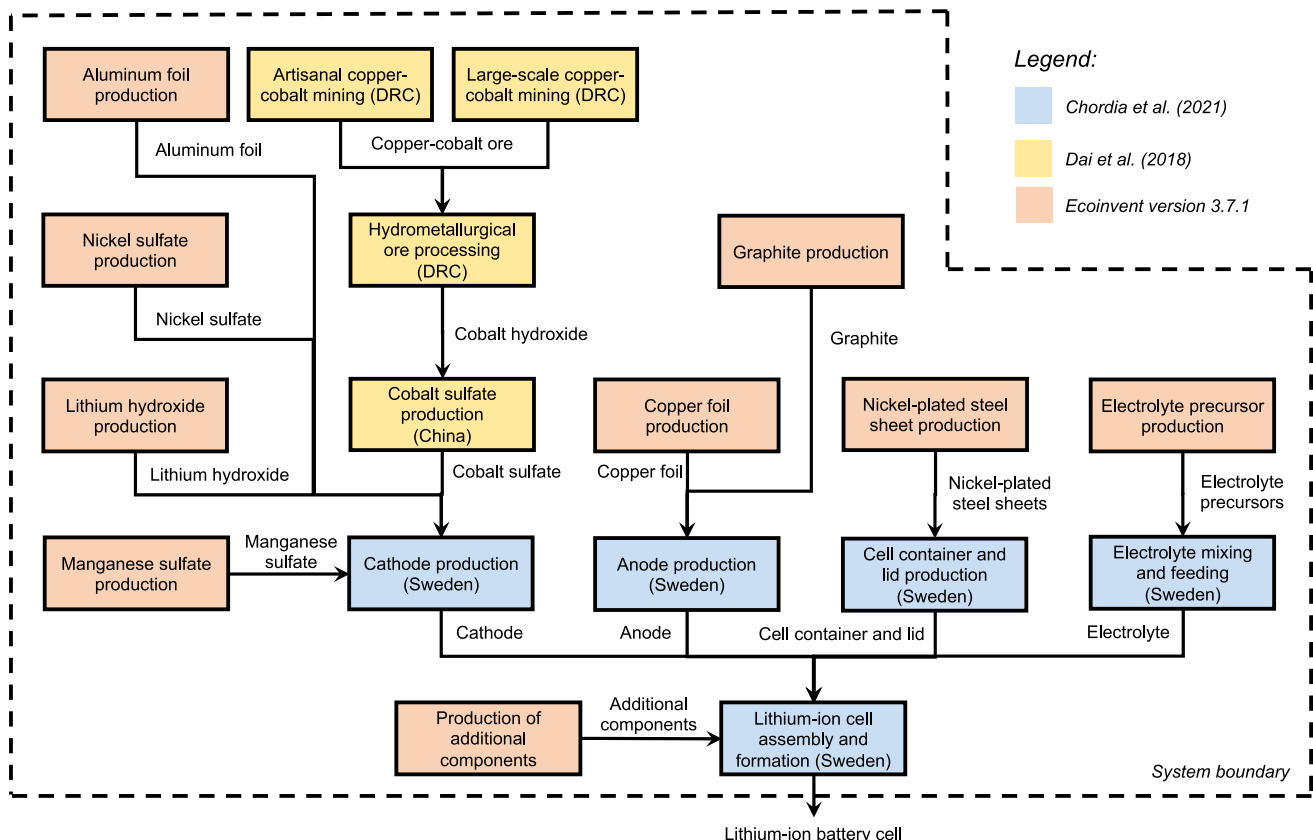


Fig. 1 Flow chart describing the main processes of the cradle-to-gate product system studied and main inventory data sources. The system boundary is shown as a dashed line. The cobalt sulfate supply chain is shown in higher resolution

or disability, DALY values with a positive sign imply a negative impact on human life and health, whereas negative DALY values imply a positive impact. Many different potential health impacts can occur along product life cycles and the analyst must *a priori* select those believed to be of significance for quantification. In the case of LIBs, based on existing reports of health impacts (Sect. 1), contributions from (i) emissions and (ii) occupational accidents are considered:

$$DALY_{net} = DALY_{emissions} + DALY_{accidents} \quad (2)$$

The quantification of potential health impacts from emissions ($DALY_{emissions}$) and occupational accidents ($DALY_{accidents}$) are described in Sects. 2.1 and 2.2, respectively. No positive potential health impacts are considered in this assessment, but some potentially positive contributions are discussed in Sect. 3.4. Health impacts from conflicts have been included in some previous studies of cobalt and gold from the DRC (Arvidsson et al. 2018; Furberg et al. 2018). However, the Katanga region of the DRC, where most cobalt is mined, has recently been reported to be the most stable part of the entire country, since the mineral wealth has created a middle class and provided political stability (Sovacool 2019). While the presence of valuable minerals in poor countries can spur conflict, this does not seem to be the case in the Katanga region. Reports suggest that the two Katangese provinces Haut-Katanga and Luabala “are not considered conflict zones” (OECD 2019), and that “cobalt has, opposite to gold, tin and coltan [a tantalum-containing mineral], not yet started any war in the DRC” (Lindberg and Andersson 2019). Therefore, health impacts from conflict are not included in this study.

The product system was modeled using OpenLCA (version 1.10.3) with most inventory data coming from the Ecoinvent database, version 3.7.1 with cutoff allocation of recycled materials (Wernet et al. 2016). However, two processes were modeled using other sources: (i) lithium-ion cell production and (ii) battery-grade cobalt sulfate production (Fig. 1). The modeling of these processes is described in more detail in Sects. 2.3 and 2.4, respectively.

2.1 Emission health impacts

Like previous studies on health impacts of products (Arvidsson et al. 2018; Furberg et al. 2018; Debaveye et al. 2020), this study relies on the impact assessment method ReCiPe (Huijbregts et al. 2017). ReCiPe considers health impacts related to the following emission-related midpoint impact categories: particulate matter, tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity, and global warming (Huijbregts et al. 2017). In addition, ReCiPe also considers health impacts from water scarcity, which is included here as

well. These potential health impacts from emissions and water use affect the general population. Potential health impacts of emissions ($DALY_{emissions}$) are quantified according to:

$$DALY_{emissions} = \sum_{i,m} Q_{i,m} \times CF_{i,m} \times CF_{m,e} \quad (3)$$

where $Q_{i,m}$ is a quantity of elementary flow i contributing to the midpoint impact category m , $CF_{i,m}$ is a characterization factor describing the contribution of i to m , and $CF_{m,e}$ is an endpoint characterization factor describing the contribution of m to the endpoint impact category e . Only the endpoint human health is considered in this study. The endpoint characterization factors are derived based on how much the midpoint impact categories contribute to potential health impacts as described in the ReCiPe 2016 report (Huijbregts et al. 2016). For example, in the case of stratospheric ozone depletion, it is based on the increase of UV light and subsequent diseases caused by ozone depletion. A hierarchist value perspective is chosen as main perspective in this study, reflecting the current scientific consensus on time frames and impact mechanisms (Huijbregts et al. 2016), although the implications of choosing other value perspectives (individualist or egalitarian) are also discussed. The emission and water use data for $Q_{i,m}$ come from Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database as shown in Fig. 1.

2.2 Occupational accidents

Potential health impacts from occupational accidents ($DALY_{accidents}$) were quantified using the approach by Scanlon et al. (2015), where work environment characterization factors (CF_{WE}) for industry sectors j are calculated according to:

$$CF_{WE,j} = \frac{DALY_j}{Q_j} \quad (4)$$

where $DALY_j$ is the total number of years lost due to injuries or premature death in industry sector j , and Q_j is the total output of the same sector. Such outputs can be in terms of units (e.g., number of cars), mass (e.g., kg of steel), energy (e.g., MJ of electricity), or some other measure reflecting the industry sector's output. The accidents included are based on reported occupational accident data from industries in the USA, and include both fatal and non-fatal accidents, such as bruises, wounds, and traumatic injuries. The industry sectors are often more aggregated than the typical unit process in an LCA, for example aggregating many types of metal mining into the category “All other metal ore mining.” Scanlon et al. (2015) provide 127 CF_{WE} , often in the orders of 10^{-7} to 10^{-10} year/kg for sectors where the output is quantified in terms of mass, which is the most common case. Such occupational health impacts affect workers along the life cycle.

The CF_{WE} provided by Scanlon et al. (2015) were deemed acceptable proxies for occupational accidents in the whole product system, except for one process: artisanal cobalt mining. Here, a specific CF_{WE} for artisanal cobalt mining in the DRC was instead calculated using Eq. (4), updating the value previously calculated by Furberg et al. (2018). The amount of cobalt extracted in artisanal mining in the DRC (Q_j in Eq. 4) was calculated using the reported cobalt production and artisanal share in the DRC, averaged over the years 2009–2015 (Al Barazi et al. 2017), resulting in about 26,000 ton/year. The DALY in Eq. (4) was calculated as the sum of the years of life disabled (YLD) and years of life lost (YLL):

$$DALY = YLD + YLL \quad (5)$$

The YLD is, in turn, calculated as:

$$YLD = I \times DW \times L \quad (6)$$

where I is the number of incidents, DW is a disability weight, and L is the duration of the disability. The number of incidents was estimated assuming 175,000 artisanal cobalt miners in the DRC, which is an average of ranges reported (BGR 2019; OECD 2019). The frequency of occupational accidents in artisanal cobalt mining in the Katanga region was obtained from the study by Elenge et al. (2013), who reported the frequency of wounds as well as fractures on upper and lower limbs. These are common injuries in artisanal mining, frequently reported also in, e.g., artisanal gold mining in Ghana (Kyeremateng-Amoah and Clarke 2015). The frequency of wounds is paired with DW and L values for open wounds provided by Haagsma et al. (2016). The frequency of fractures on upper and lower limbs are paired with average values of DW and L for different fractures: humerus, hand, radius, and ulna bones for upper limbs, as well as foot, femur, patella, tibia, fibula, and ankle bones for lower limbs (Haagsma et al. 2016). The resulting YLD obtained was about 370 years, or $1.4 \cdot 10^{-5}$ year/kg cobalt.

The YLL is calculated as:

$$YLL = N \times (LEX - L) \quad (7)$$

where N is the number of fatalities, LEX is the life expectancy at birth, and L is the age of death. The number of fatalities in artisanal cobalt mining the DRC has been estimated at up to 2000 per year based on a questionnaire administered in cobalt-producing provinces by Siddharath Kara (MacDonald and Pokharel 2020), who is a researcher and expert on modern slavery. A much lower estimate of 65 fatalities per year have been published by the World Bank (2020), based on cases reported in media. However, due to limited access and coverage by media on these matters, this value is presumed to be a clear underestimation. In fact, Kara claims to have personally witnessed the collapse of a

single mining tunnel in the DRC, alone leading to more than 60 deaths (MacDonald and Pokharel 2020). Given the workforce estimated above, a rate of 2000 fatalities means that almost 1% of the workforce die every year. Approximately 1% fatality rate per year was similarly reported for small-scale tin mining cooperatives in Bolivia (ILO 1999). The median age of artisanal cobalt miners in the DRC is 25 years (Elenge et al. 2013), and the life expectancy in the DRC is 61 years in 2021. The resulting YLL becomes 72,000 years, corresponding to $2.8 \cdot 10^{-3}$ year/kg cobalt. The lower estimate of fatal accidents in artisanal cobalt mining in the DRC of 65 per years gives a YLL at $1.0 \cdot 10^{-4}$ year/kg cobalt. Even though this lower estimate is considered unreasonably low, results based on this estimate are still presented in this study for comparison.

When adding the YLD and YLL (high estimate) per kg cobalt, the CF_{WE} for artisanal cobalt mining in the DRC can be obtained at $2.8 \cdot 10^{-3}$ year/kg cobalt. Given a 0.47% cobalt content of the extracted ore (Dai et al. 2018), this becomes $1.3 \cdot 10^{-5}$ year/kg copper-cobalt ore. This can be compared to the several orders of magnitude lower CF_{WE} for (industrial) copper ore and nickel ore mining in Scanlon et al. (2015) at $8.4 \cdot 10^{-9}$ year/kg.

Since the CF_{WE} are not implemented in the Ecoinvent database, they need to be added manually. Unfortunately, manually adding CF_{WE} to all linked upstream processes in the Ecoinvent database is not feasible. Thus, the CF_{WE} are added for all processes in the cobalt production system and the battery cell production, as well as for all direct inputs to these (which might also be present in other places upstream in the system). Table S1 in the Supporting Information (SI) lists all processes for which the CF_{WE} are implemented. Although this means that a number of upstream processes are not accounted for regarding their work environment impacts, this approach is judged to account for a significant share of the total work environment impacts since all major inputs to the studied system are included.

2.3 Lithium-ion cell production

The LIB cell production is modeled according to Chordia et al. (2021), since that study considers a presumably benign scenario regarding potential health impacts of cobalt-containing LIBs. First, they assess a cylindrical NMC 811 cell, which contains cobalt but in lower amounts than, e.g., the currently more common NMC 111 cell. Second, they model a large-scale “gigafactory,” which has lower impacts compared to smaller-scale cell production. Third, the location of the gigafactory in Sweden means an electricity mix based mainly on hydropower and nuclear, which leads to lower potential health impacts compared to more fossil-based electricity mixes. Using this context for the study,

which represents an estimate of potential health impacts from upcoming LIB cell production in northern Europe, the focus is intentionally set on the mineral extraction and cell precursor materials production life-cycle stages, in line with the overall aim of investigating the role of cobalt, rather than health impacts of the energy supply to later production steps.

The gigafactory model is based on data from environmental permit applications and technical reports published by the company Northvolt AB for a facility currently being put into operation in Northern Sweden, representing an annual production of 16 GWh of battery cell storage capacity (Chordia et al. 2021). The factory will produce both cylindrical and prismatic cells, but only cylindrical cells were considered by Chordia et al. (2021), as well as in this study. The model includes the complete cell production and assembly from input chemicals and materials, ending with the formation of the cells, which is the finishing process where the cells are charged and discharged a number of times. For this study, one significant change was made to the model: the battery-grade cobalt-sulfate supply was changed, as described in Sect. 2.4.

2.4 Battery-grade cobalt sulfate production

The Ecoinvent database contains a dataset for cobalt sulfate production provided by the cobalt development institute, which was applied in the study by Chordia et al. (2021). This dataset reportedly covers 30% of the global production of refined cobalt products in 2012 and includes cobalt ore mining in Canada, Cuba, the DRC, New Caledonia, and the Philippines (Environmental Resource Management 2016). However, this dataset does not distinguish cobalt extraction from its refining and is therefore considered too aggregated for this study with a focus on health impacts along the cobalt supply chain. In addition, the dataset does not include refined cobalt production in China, even though China is currently the largest producer of refined cobalt products. Consequently, less aggregated inventory data on battery-grade cobalt sulfate production from Dai et al. (2018) are used instead. They provide datasets for three main processes: (i) large-scale copper-cobalt ore mining in the DRC, (ii) crude cobalt hydroxide production in the DRC, and (iii) battery-grade cobalt sulfate in China. In addition, we added a fourth dataset for artisanal copper-cobalt ore mining. However, since this artisanal mining occurs without any modern mining equipment, using basic tools for digging and sometimes only hands (Sovacool 2019), the dataset does not have any inputs except for the cobalt, copper, and rock mined (Table S3). Together, these four processes cover the main route of cobalt sulfate production, since most (70%) of the cobalt is mined in the DRC (Table S2) and most (80%) refined cobalt products are produced in China after import from the DRC in the form of crude cobalt hydroxide

(OECD 2019; Sovacool 2019). A process for copper-cobalt ore production in the DRC is created, consisting of 20% artisanal ore input as reported by Al Barazi et al. (2017) and the remaining 80% ore input from industrial-scale extraction. For all upstream processes linked to material and energy inputs, datasets from the Ecoinvent database were used. Congolese or Chinese datasets were used if available, otherwise global or rest-of-the-world datasets were used. An exception to this is the sodium metabisulfite, as described below.

For the large-scale copper-cobalt ore mining in the DRC, the data in Dai et al. (2018) is based on the Tenke Fungurume Mine, where both oxide and sulfide ores are mined. The unit-process dataset was scaled from 1 ton copper-cobalt ore to 1 kg copper-cobalt ore. The diesel input reported is mainly for large mining vehicles like caterpillars according to the report and was therefore approximated using the Ecoinvent process “diesel, burned in agricultural machinery.” The water input was assumed to come from “natural unspecified origin,” since it is unknown if the water comes from, e.g., rivers or lakes. The ore reportedly contains 2.44% copper and 0.47% cobalt, while the rest of the ore was assumed to consist of inert rock. No losses during the mining are reported in the source. The resulting unit process for large-scale copper-cobalt ore mining in the DRC is shown in Table S4.

The production of crude cobalt hydroxide from the copper-cobalt ore occurs through hydrometallurgical ore processing, again modeled based on the operation at the Tenke Fungurume Mine in the DRC. However, the data in Dai et al. (2018) had to be reworked into a unit process dataset for the purpose of this study. The cobalt output is first calculated based on a 0.47% cobalt content in the ore and an 80% cobalt yield. The copper output was calculated in the same way. Economic allocation between copper and cobalt is then conducted based on 10-year average prices as described in Dai et al. (2018). Finally, the cobalt output is recalculated into a crude cobalt hydroxide output based on a 35% cobalt content and all flows are scaled to 1 kg crude cobalt hydroxide. Electricity is assumed to be medium voltage. The limestone input is assumed to be crushed when purchased. Transport of the crude cobalt hydroxide to China (about 16,000 km, 17% truck and 83% ocean tanker) is included in the dataset. While not reported in Dai et al. (2018), tailings are formed during refining of copper ores in the DRC (Adrianto et al. 2022). The difference in mass between the ore input and the crude cobalt hydroxide output is therefore assumed to become tailings. Both oxidic and sulfidic copper-cobalt ores are mined in the DRC (Dai et al. 2018; Shengo et al. 2020), but since the shares are unknown, 50% of oxidic and sulfidic tailings each are assumed. Treatment processes from the Ecoinvent database are applied for these tailings, with a global geographical scope for the oxidic tailings and a

dataset representing tailings treatment in the neighboring country of Zambia for the sulfidic tailings. The resulting unit process for the hydrometallurgical ore processing in the DRC is shown in Table S5.

The production of battery-grade cobalt sulfate is modeled specifically based on the Tongxiang plant run by Huayou Cobalt and the data are considered “conservative” estimates. The unit-process data provided by in Dai et al. (2018) are scaled from per ton cobalt equivalent to per kg battery-grade cobalt sulfate. The resulting unit process for the battery-grade cobalt sulfate in China is shown in Table S6. One of the inputs to the battery-grade cobalt sulfate production — sodium metabisulfite — does currently not have a dataset in the Ecoinvent database. Therefore, its production was approximated as an input of sodium hydroxide based on Dai et al. (2018), see Table S7.

3 Results and discussion

Figure 1a shows the potential health impacts of the assessed LIB cell divided into four contributions. The first two are accidents in artisanal cobalt mining in the DRC based on the two different fatality estimates used in the study — the higher estimate at 2000 fatalities/year and the more conservative media reporting of 65 fatalities/year. The third is the contribution from emissions and water use throughout the product system, as calculated using the ReCiPe impact assessment method. The fourth is accidents in other parts of the product system based on the accident data from Scanlon et al. (2015). A main observation is that emissions and water use constitute the highest contribution by approximately one order of magnitude. The second largest contribution is

from occupational accidents in artisanal cobalt mining in the DRC, when the high fatality estimate is used. The contribution from occupational accidents in other parts of the product system is notably lower — about 30 times lower than the high estimate for accidents in artisanal cobalt mining and about 200 times lower than the contribution from emission and water use. The low estimate of the accidents in artisanal cobalt mining in the DRC is about 30 times lower than the high estimate, making the contribution comparable to accidents in other parts of the product system.

Figure 2b shows a more detailed contribution analysis for the higher and presumably more relevant estimate of fatalities in artisanal cobalt mining in the DRC. It shows that these accidents contribute with about 13% of the potential health impacts of the LIB cell. Other accidents, i.e., meaning accidents in the product system other than the artisanal cobalt mining, contribute with < 1%. The majority of the contributions (87%) make up the various green bars, which represent emissions and water use in different parts of the product system. Here, there are four distinct inputs to the gigafactory for which the production contribute with > 5% of the potential health impacts: (i) production of the nickel sulfate used for making the nickel-containing cathode (30%), (ii) production of the copper foil used in the current collector of the anode (20%), (iii) production of the cell container and lid made from nickel-plated steel (8%), and (iv) production of the cobalt sulfate, which is also part of the cathode (6%). In addition, several smaller contributions, each contributing less than 5%, together amount to 23% of the potential health impacts. The vast majority of these contributions are from impacts occurring upstream of the gigafactory. Considering that the nickel sulfate and copper foil productions constitute the two main contributors — even in this case with the high

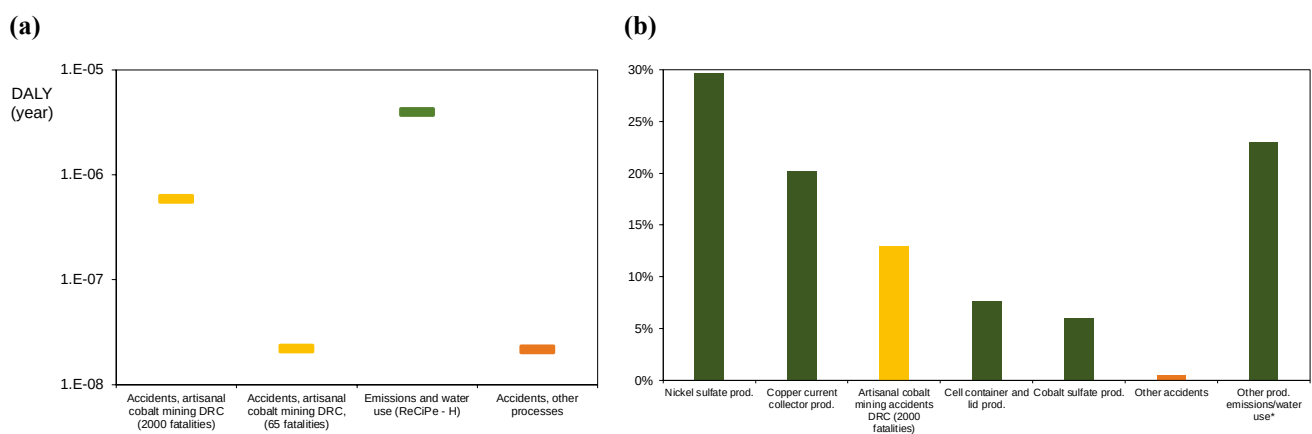


Fig. 2 Potential health impacts from the lithium-ion battery cell. **a** Contributions from the main types of health impacts are shown as absolute results on a logarithmic scale. **b** Relative contributions given the high estimate for fatalities in artisanal cobalt mining in the DRC. Green bars represent emission and water use impacts from ReCiPe,

the yellow bar represents accidents in artisanal cobalt mining in the DRC (high estimate), and the orange bar represents other occupational accidents. *The contributions to this category are all < 5% each and mostly upstream to the gigafactory

estimate of fatalities in artisanal cobalt mining in the DRC — these two input materials are analyzed in more detail in Sects. 3.1 and 3.2, respectively.

3.1 Nickel sulfate production

The inventory data for nickel sulfate production was taken from the Ecoinvent database, specifically the global dataset “market for nickel sulfate.” About 92% of the nickel sulfate in that process is produced jointly with cobalt during extraction of ores containing both the metals and the data originates from LCA work commissioned by the Cobalt Development Institute (Environmental Resource Management 2016). A final 8% is produced by reacting nickel (class 1) with sulfuric acid. The nickel supply to this Ecoinvent process comes mainly from cobalt–nickel ores, nickel–copper ores, and as a byproduct from platinum group metal mining and refining. The two midpoint impact categories that contribute the most to the potential health impacts of the nickel sulfate market process are fine particulate matter formation (51%) and human non-carcinogenic toxicity (21%). For the fine particulate matter formation, the dominating elementary flow is sulfur dioxide, mainly occurring during the production of nickel from platinum group metal mining and cobalt–nickel ore mining. Here, it can be noted that sulfur dioxide is considered differently between the three value perspectives of the ReCiPe method (Huijbregts et al. 2016). Direct emissions of fine particulate matter obviously contribute to fine particulate matter formation. Sulfur dioxide, however, only contributes indirectly by constituting condensation nuclei that leads to the formation of secondary particulate matter. In the individualist, short-term value

perspective in ReCiPe, only primary particulate matter is considered. In the hierarchist, medium-term perspective, the main perspective selected for this study, indirect particulate matter from sulfur dioxide is included. In addition, in the egalitarian, long-term perspective, indirect particulate matter from other emissions besides sulfur dioxide is also considered (i.e., nitrogen oxides and ammonia). Figure 3a shows that the potential health impacts from nickel sulfate go down by 80% from the hierarchist to the individualist perspective. Reduction in fine particulate matter formation due to the omission of indirect particulate matter from sulfur dioxide is the biggest reason for this decrease in potential health impacts. An egalitarian value perspective (not shown in Fig. 3a), on the other hand, increases potential health impacts of nickel sulfate by a factor of 40 compared to the hierarchist perspective.

For the human non-carcinogenic toxicity, the main contributing elementary flows are arsenic and zinc ions originating from the treatment of sulfidic tailings. Again, as shown in Fig. 3a, these potential health impacts depend considerably on the selected value perspective and become notably reduced if a more short-term perspective is chosen. For example, a limited number of exposure routes (drinking water and air) is considered in ReCiPe’s individualist perspective (Huijbregts et al. 2016). Also, the time horizon in the individualist perspective is only 20 years, versus 100 years in the hierarchist perspective, which means that the toxic substances have less time to cause harm.

In terms of data representativeness, it can be noted that the unit process dataset for treatment of sulfidic tailings in the Ecoinvent database, which includes the leaching of several toxic metals, is generic and applied to many

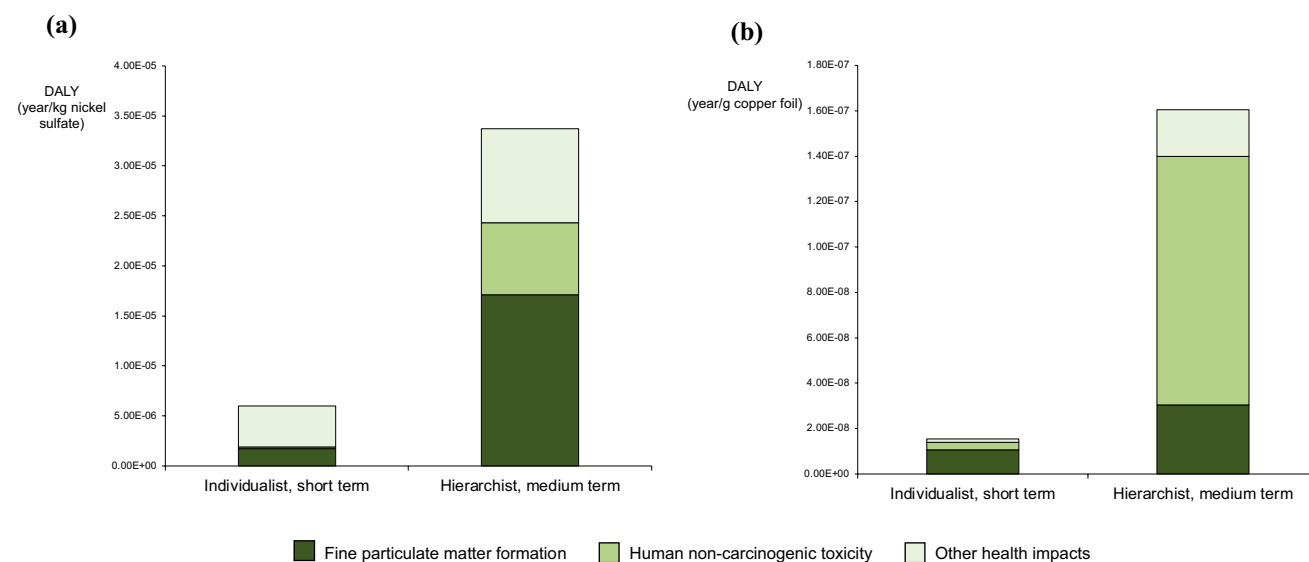


Fig. 3 Potential health impacts from two main contributors to the health impacts of the studied LIB cell, **a** nickel sulfate production and **b** copper foil production, given two different value perspectives. The hierarchist perspective is the chosen main perspective of this study

non-ferrous metal extraction processes in the database. As a result, sulfidic tailings are identified as a large contributor to toxicity impacts in many product systems (Reinhard et al. 2019). Hence, collection of more data with higher specificity regarding the treatment of tailings from different extractions could influence the results of this study.

3.2 Copper foil production

The production of copper foil, which serves as the current collector for the graphite anode, is modeled as sheet rolling of so-called cathode copper. The two midpoint impact categories that contribute the most to the potential health impacts of the copper foil production are the same as for nickel sulfate production, but in reversed order: human non-carcinogenic toxicity (68%) and fine particulate matter formation (19%). For the human non-carcinogenic toxicity, the main contributing processes are treatment of sulfidic tailings due to zinc ion emissions and treatment of copper slag due to arsenic ion emissions. For the fine particulate matter formation, the main contribution comes from the mining of platinum group metals, from which copper is a byproduct, specifically from sulfur dioxide emissions. Nickel sulfate and copper foil production thus mostly have the same main contributing midpoint impact categories, processes, and elementary flows. Unsurprisingly, there are large differences in potential health impacts depending on the value perspective for the copper foil production as well. As shown in Fig. 3b, the individualist perspective gives approximately a factor of 10 lower health impact compared to the hierarchist perspective, mainly due to reductions in human non-carcinogenic toxicity and fine particulate matter formation. Again, the individualist perspective gives lower potential health impacts due to shorter time horizons, fewer exposure routes, and exclusion of indirect particulate matter formation. The egalitarian perspective (not shown in Fig. 3b), on the other hand, gives more than 100 times higher potential health impacts compared to the hierarchist perspective. This is due to longer time horizons and inclusion of additional types of indirect particulate formation.

3.3 Potential improvements

Considering first the design of the studied LIB cell, one option for health improvements could be to lower the cobalt content further, i.e., in line with the generally ongoing efforts for LIBs by moving away from the cobalt-rich NMC 333 chemistry (Fan et al. 2020). However, as shown in Fig. 1b, if nickel is used instead, as in the studied NMC 811 chemistry, that also brings considerable potential health impacts. If the reduction of cobalt is done at the expense of increased nickel content, a net reduction in potential health impacts might not occur. Possibly, the copper current collector foil

could be replaced by some other conductive material. Any such changes must, however, not compromise the technical performance of the LIB cell significantly, in relation to its prerequisites for use. Materials that might be investigated as potential alternatives include aluminum, nickel, titanium, stainless steel, and possibly also carbon-based nanomaterials such as carbon nanotubes and graphene (Zhu et al. 2021).

Moving upstream in the product system, the analyses in Sects. 3.1 and 3.2 showed that much of the potential health impacts along the life cycle of the studied LIB cell are related to mining of metals and the treatment of tailings. Emission reductions in metal mining and tailings treatment would thus reduce the potential health impacts of the studied LIB cell. For example, in the dataset where nickel is produced as a by-product during platinum group metal mining, each kg of nickel produced causes about 7 kg of sulfur dioxide emissions. The sulfur originates from sulfidic ores and is emitted as sulfur dioxide during several refining steps, such as roasting (Classen et al. 2009). Recovering that sulfur dioxide would reduce potential health impacts from the nickel sulfate production process. In addition, increased recycled content of metals such as nickel and copper would also reduce upstream impacts. The current recycled contents in the Ecoinvent datasets for cathode copper and nickel (class 1) datasets are approximately 20% and < 1%, respectively. Battery manufacturers could investigate the possibility of sourcing metal supplies with higher recycled contents.

Accidents during artisanal cobalt mining in the DRC also contribute notably to the potential health impacts of the studied LIB cell. Sovacool (2019) proposed seven policy recommendations for better governing of cobalt mining in the DRC. These include to: (i) enforce better occupational standards for artisanal and small-scale mining operations, (ii) form joint ventures with artisanal and small-scale mining and large-scale and industrial mining interests, (iii) implement better dust and tailings management at large-scale and industrial mining, (iv) pursue broader and more robust community benefit sharing agreements, (v) support training for alternative livelihoods, (vi) recognize the limitations of traceability schemes and formalization, and (vii) do not ban artisanal and small-scale cobalt mining. Some of these recommendations, such as enforcing better occupational standards, might directly lead to reductions in potential health impacts. For example, Elenge (2013) suggested that it would be possible to introduce some degree of mechanization in artisanal cobalt mining, since the costs would be offset by a more or less guaranteed production level over time, which would reduce the physical strain of the artisanal miners. For other recommendations, an indirect effect might occur, e.g., if training for alternative livelihoods reduces the need for wounded or tired miners to return to mining where they are at higher risk of suffering

from fatal accidents. Other publications generally provide similar recommendations, albeit formulated differently and at a different level of detail (Tsurukawa et al. 2011; BGR 2019; OECD 2019; Sovacool et al. 2020). The seventh recommendation by Sovacool (2019) — to not ban artisanal mining of cobalt — reflects that there are also benefits from artisanal cobalt mining in the DRC, which, given a ban, would disappear (see Sect. 1). Instead, Sovacool (2019) advocates efforts to improve the mining practices. This recommendation is also echoed in other sources, e.g., Tsurukawa et al. (2011). Notably, this is opposite to the recommendation by Sharma and Manthiram (2020), who recommended a complete elimination of cobalt in LIB cathodes.

3.4 Potential positive health impacts

The aim of this study has been to quantify the potential negative health impacts caused by the supply chain activities of a selected LIB cell. However, there might also be potential positive health impacts related to the life cycle of this LIB cell. These could occur during the use of the cell, in particular if it enables the replacement of fossil fuel-based vehicles (through electromobility) or fossil fuel-based electricity (through stationary storage of electricity from renewable energy sources). Investigating such health benefits would require studies with wider cradle-to-grave scopes. However, there might also be potential positive health impacts within the LIB cell production system studied here. For example, the income generated by artisanal cobalt miners in the DRC — and possibly income elsewhere in the product system as well — might lead to health benefits. Previous work by Feschet et al. (2013) has started to outline an impact pathway for positive health impacts from earning an income based on the so-called Preston curve, which shows how the life expectancy in low-income countries increases with higher income rates in general. However, this approach calculates changes in life expectancy rather than DALYs and it requires certain criteria to be fulfilled. For example, the added value of the activity must be distributed relatively equally among the population for this approach to apply. This is currently not fulfilled in the DRC, which has among the world's highest corruption levels. Therefore, this approach to quantifying positive health impacts from income can currently not be included in Eq. (2). However, there might be local and more direct health benefits from earning an income, which do not affect the general population of a region as per the Preston curve, but nevertheless affect, e.g., specific miners and their families. We recommend further studies to investigate this relationship between incomes and health status in more detail.

3.5 Limitations and uncertainties

The aim of assessing a wide range of potential health impacts inevitably bring sources of uncertainty. The main inventory data sources of this study are Chordia et al. (2021), Dai et al. (2018), and the Ecoinvent database, version 3.7.1. The data from Chordia et al. (2021) represent a modern gigafactory and is considered fit for the aim of this study. As explained in Sect. 2.4, Dai et al. (2018) is the only known source with cobalt supply data presented at the unit process level, which is considered valuable in a study with a particular interest in the contribution from cobalt. Still, the data from Dai et al. (2018) is limited, e.g., in terms of emissions reported and treatment of tailings, which are therefore important areas for further data gathering to reduce the uncertainty in potential health impacts from emissions. The Ecoinvent database has the explicit aim of providing background data to LCA studies (Wernet et al. 2016), and as such it is considered fit for the aim of this study. However, considering the large contribution from nickel sulfate and copper foil production to the potential health impacts of the studied battery cell (Fig. 2b), further detailed investigations of emissions and treatment of tailings from nickel and copper mining would be useful to reduce the uncertainty of this study and identify improvement opportunities.

The three main data sources when it comes to characterization factors for social impact assessment are ReCiPe for emissions and water use (Huijbregts et al. 2017), Scanlon et al. (2015) for occupational accidents for most processes and our own calculations for occupational accidents from artisanal cobalt mining. ReCiPe is widely used to assess potential health impacts from emissions and water use in LCA studies. The three value perspectives — individualist, hierarchist and egalitarian — represent different views on time perspective and inclusiveness when it comes to environmental and health impacts, with the individualist/short term and egalitarian/long term perspectives being the two extremes. While these perspectives can provide a wide range of potential health impacts (Fig. 3), they also illustrate how differences in fundamental values influence the results. The characterization factors from Scanlon et al. (2015) cover the most relevant industry sectors, but are aggregated, as in “copper ore and nickel ore mining.” Here, a further disaggregation and differentiation between different locations, e.g., industrial copper-cobalt ore mining in the DRC and nickel mining in Russia in that case, would reduce the uncertainty in the estimation of potential health impacts from occupational accidents. Regarding our calculations of work environment characterization factors for artisanal cobalt mining, the largest source of uncertainty is likely the 65–2000 fatalities/year range. Further investigations to reduce uncertainty in that value are strongly recommended.

4 Conclusions

This study has shown that the cobalt input to the NMC-type LIB production (in the form of cobalt sulfate) contributes notably to the battery's potential health impact, both through occupational accidents during artisanal cobalt mining in the DRC (13%) and through emissions and water use during the production of cobalt sulfate (6%). The occupational accidents impact artisanal miners in the Katanga region of the DRC specifically. However, cobalt is not the only contributor to the potential health impacts, nor necessarily the largest. Potential health impacts from the production of two other input materials to the production of the LIB contribute even more: nickel sulfate (30%) and copper foil (20%). The reason for these high potential health impacts are emissions of sulfur dioxide, zinc, and arsenic. However, the magnitudes of these impacts depend on the time horizon applied in the assessment — a long time horizon indicate even higher potential health impacts from nickel sulfate and copper production, whereas when using a shorter time horizon, these health impacts are notably reduced. Contrary to the occupational accidents in artisanal cobalt mining, these emissions impact the general population. In order to reduce potential health impacts of NMC batteries, a number of recommendations are proposed to LIB cell manufacturers: (i) investigate the feasibility of replacing the copper foil with another conductive material able to provide anode current collector functionality; (ii) reduce emissions from metals extraction; and (iii) increase the recycled content of sourced metals. Finally, improved occupational standards in artisanal mining in the DRC are recommended to reduce accident rates, in particular fatal accidents.

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Author contribution Rickard Arvidsson: conceptualization, methodology, formal analysis, investigation, data curation, writing — original draft, visualization, project administration, and funding acquisition. Mudit Chordia: methodology, investigation, data curation, and writing — review and editing. Anders Nordelöf: conceptualization, methodology, investigation, data curation, writing — review and editing, and funding acquisition.

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Data availability The data that supports the findings of this study are cited in Sect. 2 or available in the Supporting Information (SI), specifically Tables S1–S7. Access to some upstream data requires access to the Ecoinvent database.

Declarations

Conflict of interest The authors declare no competing interests.

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References

- Adrianto LR, Pfister S, Hellweg S (2022) Regionalized life cycle inventories of global sulfidic copper tailings. *Environ Sci Technol* 56(7):4553–4564
- Al Barazi S, Näher U, Vetter S, Schütte P, Liedtke M, Baier M, Franken G (2017) Cobalt from the DR Congo - potential, risks and significance for the global cobalt market, vol. 53 *Commodity Top News*. Federal Institute for Geosciences and Natural Resources, Hannover
- Amnesty International (2013) Profits and loss. Mining and human rights in Katanga, Democratic Republic of the Congo, London
- Amnesty International and Afreewatch (2016) “This is what we die for”. Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt. London
- Arvidsson R, Hildenbrand J, Baumann H, Islam KMN, Parsmo R (2018) A method for human health impact assessment in social LCA: lessons from three case studies. *Int J Life Cycle Assess* 23(3):690–699
- Bamana G, Miller JD, Young SL, Dunn JB (2021) Addressing the social life cycle inventory analysis data gap: insights from a case study of cobalt mining in the Democratic Republic of the Congo. *One Earth* 4(12):1704–1714
- Banza CLN, Nawrot TS, Haufroid V, Decrée S, De Putter T, Smolders E, Kabyla BI, Luboya ON, Ilunga AN, Mutombo AM, Nemery B (2009) High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environ Res* 109(6):745–752
- Banza Lubaba Nkulu C, Casas L, Haufroid V, De Putter T, Saenen ND, Kayembe-Kitenge T, Musa Obadia P, Kyanika Wa Mukoma D, Lunda Ilunga J-M, Nawrot TS, Luboya Numbi O, Smolders E, Nemery B (2018) Sustainability of artisanal mining of cobalt in DR Congo. *Nat Sustain* 1(9):495–504
- Baumann H, Arvidsson R, Tong H, Wang Y (2013) Does the production of an airbag injure more people than it saves in traffic? Discussing an alternative approach to S-LCA methodology. *J Ind Ecol* 17(4):517–527
- Benoît Norris C, Traverso M, Neugebauer S, Ekener E, Schaubroeck T, Russo Garrido S, Berger M, Valdivia S, Lehmann A, Finkbeiner M, Arcese G (2020) Guidelines for social life cycle assessment of products and organizations. United Nations Environment Programme (UNEP)

- BGR (2019) Mapping of the artisanal copper-cobalt mining sector in the provinces of Haut-Katanga and Luabala in the Democratic Republic of the Congo. German Federal Institute for Geosciences and Natural Resources, Hannover
- Chordia M, Nordelöf A, Ellingsen LA-W (2021) Environmental life cycle implications of upscaling lithium-ion battery production. *Int J Life Cycle Assess* 26:2024–2039
- Classen M, Althaus HJ, Blaser S, Scharnhorst W, Tuchschild M, Jungbluth N, Emmenegger MF (2009) Life cycle inventories of metals. Data v2.1. Ecoinvent Centre, Dübendorf
- Dai Q, Kelly JC, Elgowainy A (2018) Cobalt life cycle analysis update for the GREET® model. Argonne National Laboratory
- de Haan J, Geenen S (2016) Mining cooperatives in Eastern DRC The interplay between historical power relations and formal institutions. *Extr Ind Soc* 3(3):823–831
- Debaveye S, De Smedt D, Heirman B, Kavanagh S, Dewulf J (2020) Quantifying the handprint-footprint balance into a single score: the example of pharmaceuticals. *PLoS ONE* 15(2):e0229235
- Elenge M, Leveque A, De Brouwer C (2013) Occupational accidents in artisanal mining in Katanga, D.R.C. *Int J Occup Med Environ Health* 26(2):265–274
- Elenge MM (2013) Safety and health in mining in Congo (DRC). In: Englstrand K, Vingård E (eds) *Occupational Safety and Health in Mining - Anthology on the situation in 16 mining countries*. University of Gothenburg, Gothenburg, Sweden
- Elenge MM, Aubry J-C, Jacob L, De Brouwer C (2011) Heavy metal in hair samples of 109 non-industrial (miners) population in Katanga. *Sante* 21(1):41–46
- Elenge MM, De Brouwer C (2011) Identification of hazards in the workplaces of Artisanal mining in Katanga. *Int J Occup Med Environ Health* 24(1):57–66
- Environmental Resource Management (2016) The environmental performance of refined cobalt - life cycle inventory and life cycle assessment of refined cobalt cobalt development institute
- Faber B, Krause B, Sánchez de la Sierra R (2017) Artisanal mining, livelihoods, and child labour in the cobalt supply chain of the Democratic Republic of the Congo. UC Berkely, Berkely, United States
- Fan E, Li L, Wang Z, Lin J, Huang Y, Yao Y, Chen R, Wu F (2020) Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects. *Chem Rev* 120(14):7020–7063
- Feschet P, Macombe C, Garrabé M, Loeillet D, Saez A, Benhmad F (2013) Social impact assessment in LCA using the Preston pathway. *Int J Life Cycle Assess* 18(2):490–503
- Furberg A, Arvidsson R, Molander S (2018) Live and let die? Life cycle human health impacts from the use of tire studs. *Int J Environ Res Public Health* 15(8):1774
- Haagsma JA, Graetz N, Bolliger I, Naghavi M, Higashi H, Mullany EC, Abera SF, Abraham JP, Adofu K, Alsharif U, Ameh EA, Ammar W, Antonio CAT, Barrero LH, Bekele T, Bose D, Brazinova A, Catalá-López F, Dandona L, Dandona R, Dargan PI, De Leo D, Degenhardt L, Derrett S, Dharmaratne SD, Driscoll TR, Duan L, Petrovich Ermakov S, Farzadfar F, Feigin VL, Franklin RC, Gabbe B, Gosselin RA, Hafezi-Nejad N, Hamadeh RR, Hajar M, Hu G, Jayaraman SP, Jiang G, Khader YS, Khan EA, Krishnaswami S, Kulkarni C, Lecky FE, Leung R, Lunevicius R, Lyons RA, Majdan M, Mason-Jones AJ, Matzopoulos R, Meaney PA, Mekonnen W, Miller TR, Mock CN, Norman RE, Orozco R, Polinder S, Pourmalek F, Rahimi-Movaghar V, Refaat A, Rojas-Rueda D, Roy N, Schwebel DC, Shaheen A, Shahrz S, Skirbekk V, Søreide K, Soshnikov S, Stein DJ, Sykes BL, Tabb KM, Temesgen AM, Tenkorang EY, Theadom AM, Tran BX, Vasankari TJ, Vavilala MS, Vlassov VV, Woldeyohannes SM, Yip P, Yonemoto N, Younis MZ, Yu C, Murray CJL, Vos T, Balalla S, Phillips MR (2016) The global burden of injury: incidence, mortality, disability-adjusted life years and time trends from the Global Burden of Disease study 2013. *Inj Prev* 22(1):3–18
- Harper G, Sommerville R, Kendrick E, Driscoll L, Slater P, Stolkin R, Walton A, Christensen P, Heidrich O, Lambert S, Abbott A, Ryder K, Gaines L, Anderson P (2019) Recycling lithium-ion batteries from electric vehicles. *Nat* 575(7781):75–86
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22(2):138–147
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Hollander A, Zijp M, van Zelm R (2016) ReCiPe 2016 - a harmonized life cycle impact assessment method at midpoint and endpoint level. Characterization. Dutch National Institute for Public Health and the Environment, Bilthoven, Report I
- ILO (1999) Social and labour issues in small-scale mines. International Labour Organization, Geneva
- International Labour Office (2016) ILO standards on forced labour - the new protocol and recommendation at a glance. Geneva
- Kennedy C (2017) Cobalt prices to rocket as tech giants scramble for supplies. <https://www.prnewswire.com/news-releases/cobalt-prices-to-rocket-as-tech-giants-scramble-for-supplies-657690933.html>. PR Newswire
- Kyeremateng-Amoah E, Clarke EE (2015) Injuries among artisanal and small-scale gold miners in Ghana. *Int J Environ Res Public Health* 12(9):10886–10896
- Li M, Lu J, Chen Z, Amine K (2018) 30 years of lithium-ion batteries. *Adv Mater* 30(33):1800561
- Lindberg S, Andersson U (2019) Blood batteries (in Swedish). *Aftonbladet*, <https://special.aftonbladet.se/blodsbaatterier/>
- MacDonald A, Pokharel K (2020) Many miners die, and it never shows up in safety data. The Wall Street Journal. <https://www.wsj.com/articles/many-miners-die-and-it-never-shows-up-in-safety-data-11582815186>
- Mancini L, Eslava NA, Traverso M, Mathieux F (2021) Assessing impacts of responsible sourcing initiatives for cobalt: insights from a case study. *Resour Policy* 71:102015
- OECD (2019) Interconnected supply chains: a comprehensive look at due diligence challenges and opportunities sourcing cobalt and copper from the Democratic Republic of the Congo
- Porzio J, Scown CD (2021) Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Adv Energy Mater* 2100771
- Reinhard J, Wernet G, Zah R, Heijungs R, Hilty LM (2019) Contribution-based prioritization of LCI database improvements: the most important unit processes in ecoinvent. *The Int J Life Cycle Assess* 24(10):1778–1792
- Scanlon KA, Lloyd SM, Gray GM, Francis RA, LaPuma P (2015) An approach to integrating occupational safety and health into life cycle assessment: development and application of work environment characterization factors. *J Ind Ecol* 19(1):27–37
- Sharma SS, Manthiram A (2020) Towards more environmentally and socially responsible batteries. *Energy Environ Sci* 13(11):4087–4097
- Shengo LM, Kitobo WS, Kime MB, Mambwe MP, Nyembo TK (2020) Mineralogical variations with the mining depth in the congo copperbelt: technical and environmental challenges in the hydrometallurgical processing of copper and cobalt ores. *J Sustain Min* 19(2):96–114
- Sovacool BK (2019) The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extr Ind Soc* 6(3):915–939
- Sovacool BK, Ali SH, Bazilian M, Radley B, Nemery B, Okatz J, Mulvaney D (2020) Sustainable minerals and metals for a low-carbon future. *Sci* 367(6473):30–33
- Thies C, Kieckhäfer K, Spengler TS, Sodhi MS (2019) Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. *Procedia CIRP* 80:292–297

- Tsurukawa N, Prakash S, Manhart A (2011) Social impacts of artisanal cobalt mining in Katanga. Democratic Republic of Congo, Institute for Applied Ecology, Freiburg
- Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21(9):1218–1230
- World Bank (2020) State of the artisanal and small-scale mining sector. World Bank, Washinton, DC
- Yang Y (2019) A unified framework of life cycle assessment. *Int J Life Cycle Assess* 24(4):620–626
- Zhu P, Gastol D, Marshall J, Sommerville R, Goodship V, Kendrick E (2021) A review of current collectors for lithium-ion batteries. *J Power Sources* 485229321
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Executive summary

◀ Recycling of Critical Minerals

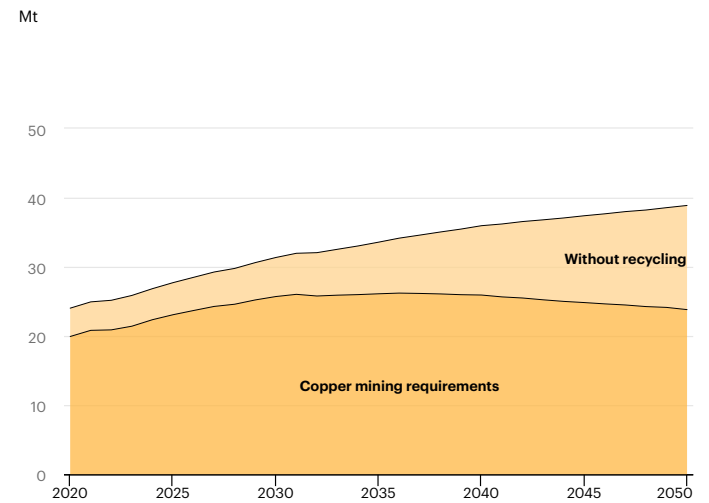
Recycling can bring multiple benefits in ensuring reliable and sustainable critical mineral supplies

Recycling is indispensable to the security and sustainability of critical minerals supply for clean energy transitions. As the shift to a clean energy system accelerates, substantial investments in new mines and refining capacity, especially in geographically diverse regions, will be required to produce essential minerals such as copper, lithium, nickel, cobalt and rare earths. While recycling does not eliminate the need for mining investment (or the associated revenues for resource-rich countries), it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security for countries importing minerals. This sets critical minerals apart from fossil fuels that cannot be reused (and whose use via combustion results in long-lived emissions in the atmosphere). Expanding recycling infrastructure can also help build reserves to buffer against future supply disruptions. Moreover, scaling up recycling mitigates the environmental and social impacts related to mining and refining while preventing waste from end-use technologies ending up in landfills.

This first-of-its-kind report on critical minerals recycling presents key policy recommendations to accelerate the uptake of recycling practices. Building on its landmark report (<https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>) in 2021, the International Energy Agency (IEA) has been deepening its analysis on the latest market trends and key policy issues around critical mineral supply chains through extensive data collection, modelling and close dialogue with industry stakeholders. At the IEA Critical Minerals and Clean Energy Summit (<https://www.iea.org/news/iea-critical-minerals-and-clean-energy-summit-delivers-six-key-actions-for-secure-sustainable-and-responsible-supply-chains>) in September 2023, participants highlighted the critical role of recycling in enhancing mineral security. Responding to this growing emphasis, the report assesses the current state of recycling, explores the potential for secondary supply, and presents policy recommendations to scale up recycling.

Copper: mining requirements in the Announced Pledges
Scenario, 2020-2050

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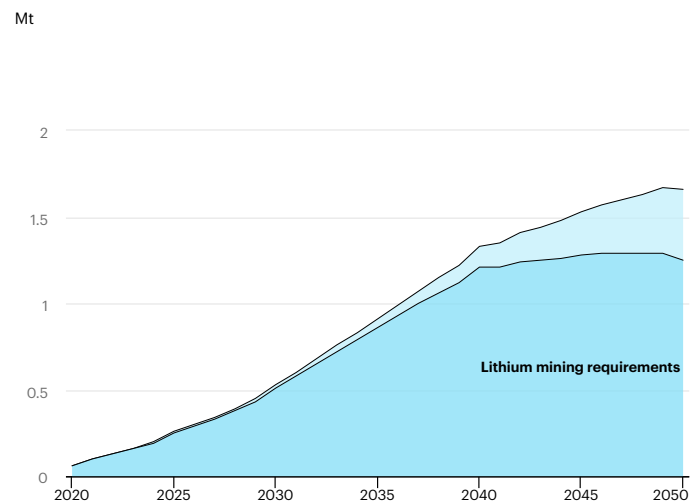


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● Copper mining requirements ● Without recycling

Lithium: mining requirements in the Announced Pledges Scenario, 2020-2050

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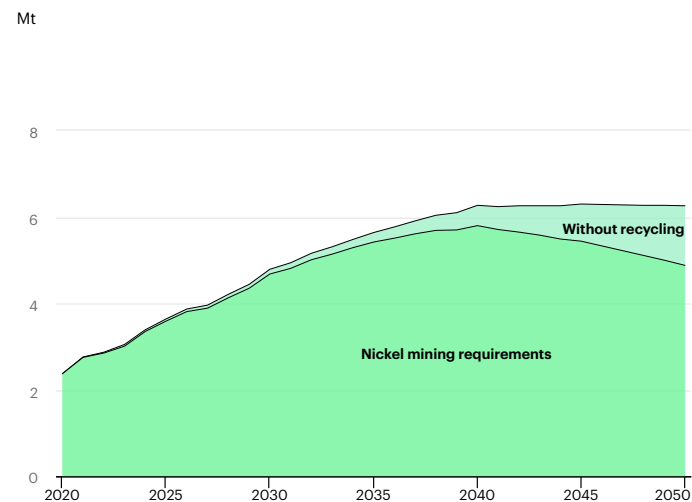


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● Lithium mining requirements ● Without recycling

Nickel: mining requirements in the Announced Pledges Scenario, 2020-2050

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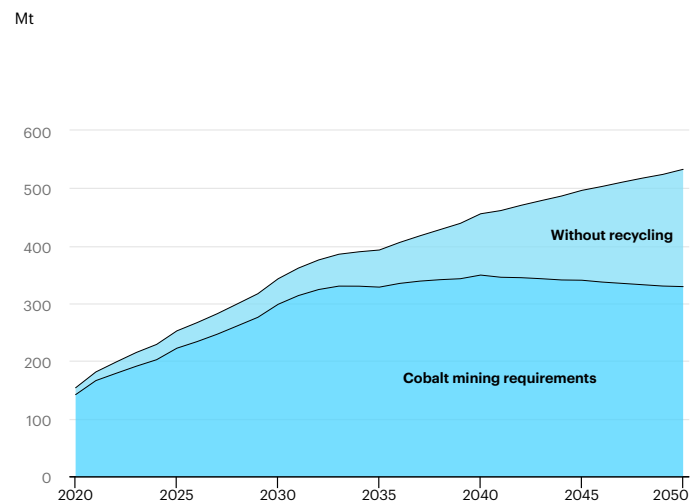


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● Nickel mining requirements ● Without recycling

Cobalt: mining requirements in the Announced Pledges Scenario, 2020-2050

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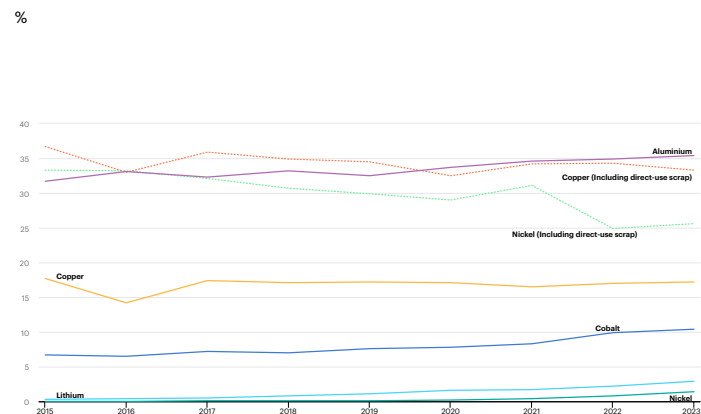
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● Cobalt mining requirements ● Without recycling

Despite growing policy ambitions, the use of recycled materials has so far failed to keep pace with rising material consumption. In the case of copper, which plays a central role in all electrical applications, the share of secondary supply (including direct use scrap) in total demand fell from 37% in 2015 to 33% in 2023. Similarly, the share for recycled nickel decreased from 35% to 31% over the same period. The main exception is aluminium, which benefits from well-established waste management programmes and supportive regulations, where the recycled share increased modestly from 24% to 26%.

Historical recycled input rate for selected materials, 2015-2023

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Aluminium Copper Nickel Cobalt Lithium
Copper (Including direct-use scrap) Nickel (Including direct-use scrap)

Recycling of battery metals is an emerging commercial opportunity and is growing fast. Production of recycled battery metals, such as nickel, cobalt and lithium, has recently seen rapid growth, albeit from a low base. When assessing recovered metal volumes relative to theoretically available feedstock, rates surged to over 40% for nickel and cobalt and to 20% for lithium in 2023. The market value of recycled battery metals also experienced nearly 11-fold growth between 2015 and 2023, with 40% of this growth occurring in the last three years. Although electric vehicle (EV) batteries are not yet available for recycling at scale, these developments indicate vast potential for expanding recycling, if the right policy incentives are in place.

Policy momentum is gaining strength, with a surge in new policies and regulations. According to the IEA's Critical Minerals Policy Tracker (<https://www.iea.org/data-and-statistics/data-tools/critical-minerals-policy-tracker>), more than 30 new policy measures related to critical mineral recycling have been introduced since 2022. These policies generally fall into four categories: strategic plans, extended producer responsibility (EPR), financial incentives and cross-border trade regulations. Some also include regulatory mandates such as industry-specific targets for material recovery, collection rates and minimum recycled content. However, most strategies are not yet comprehensive. Among the 22 countries and regions surveyed, only 3 had a broad framework that includes clear targets, implementation mechanisms, monitoring systems and economic incentives.

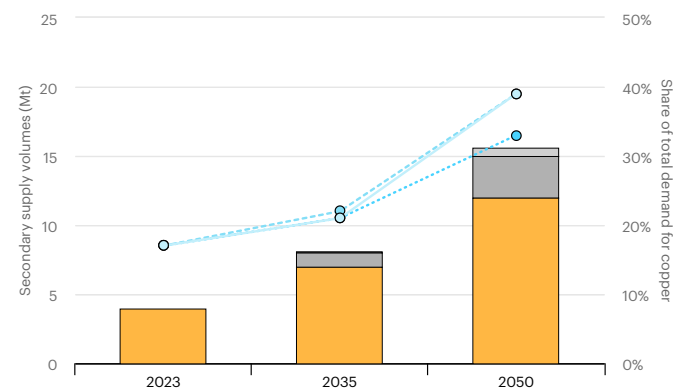
Recycling reduces the need for new mines, enhancing security and sustainability

A successful scale-up of recycling can lower the need for new mining activity by 25-40% by 2050 in a scenario that meets national climate pledges. While accelerated clean energy deployment calls for a substantial expansion of new mines and refineries to meet material demand, it also creates an opportunity for secondary supply to play an increasingly valuable role. In the Announced Pledges Scenario (APS), which reflects national climate pledges, recycling reduces new mine development needs by 40% for copper and cobalt, and by 25% for lithium and nickel by 2050. The market value of recycled energy transition minerals grows fivefold, reaching USD 200 billion by 2050. As a result, requirements for primary materials start to decline around mid-century. Nonetheless, investments in new mines remain essential as supply levels required by mid-century are still higher than today's production and existing mines face natural declines in output.

Enhancing critical minerals recycling offers substantial financial and sustainability benefits. In the APS, some USD 600 billion of mining investments is required through 2040, while achieving net zero emissions by 2050 necessitates around USD 800 billion. Without an increase in recycling, these amounts would be 30% higher, increasing the burden of mobilising the necessary financing. Recycling can also mitigate the environmental and social impacts associated with mineral production. On average, recycled energy transition minerals such as nickel, cobalt and lithium incur 80% less greenhouse gas emissions than primary materials produced from mining. This translates into a 35% cumulative reduction in emissions from the production of lithium, nickel and cobalt required to meet their needs in climate-driven scenarios over the period to 2040.

Secondary supply volumes and share of total demand for copper in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

Open ↗

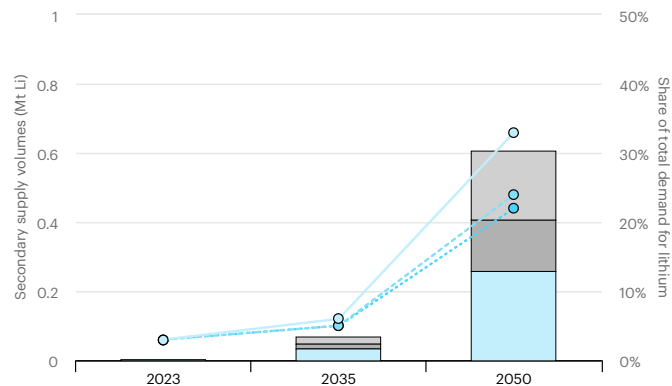


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- Secondary supply in STEPS
- Secondary supply in APS
- Secondary supply in NZE
- Share of secondary supply in STEPS
- Share of secondary supply in APS
- Share of secondary supply in NZE

Secondary supply volumes and share of total demand for lithium in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

Open ↗

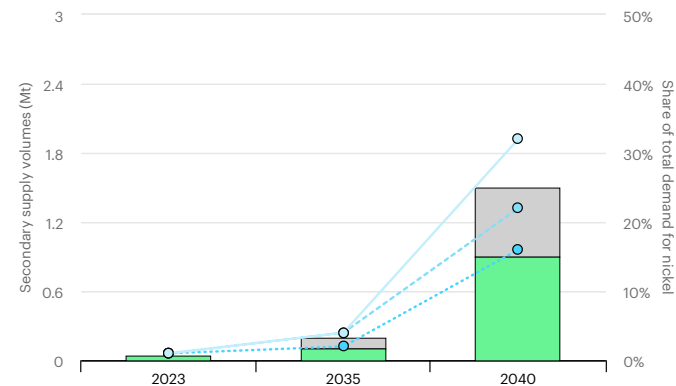


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- Secondary supply in STEPS
- Secondary supply in APS
- Secondary supply in NZE
- Share of secondary supply in STEPS
- Share of secondary supply in APS
- Share of secondary supply in NZE

Secondary supply volumes and share of total demand for nickel in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

Open ↗

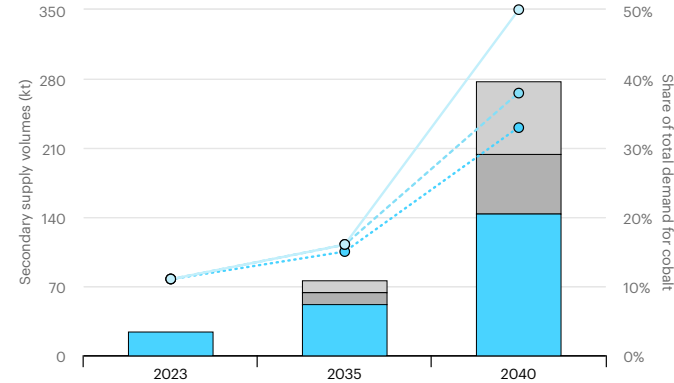


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- Secondary supply in STEPS
- Secondary supply in APS
- Secondary supply in NZE
- Share of secondary supply in STEPS
- Share of secondary supply in APS
- Share of secondary supply in NZE

Secondary supply volumes and share of total demand for cobalt in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

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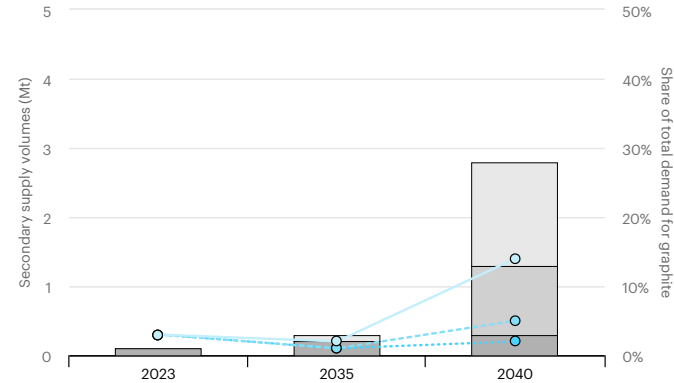


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- Secondary supply in STEPS
- Secondary supply in APS
- Secondary supply in NZE
- Share of secondary supply in STEPS
- Share of secondary supply in APS
- Share of secondary supply in NZE

Secondary supply volumes and share of total demand for graphite in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

Open ↗

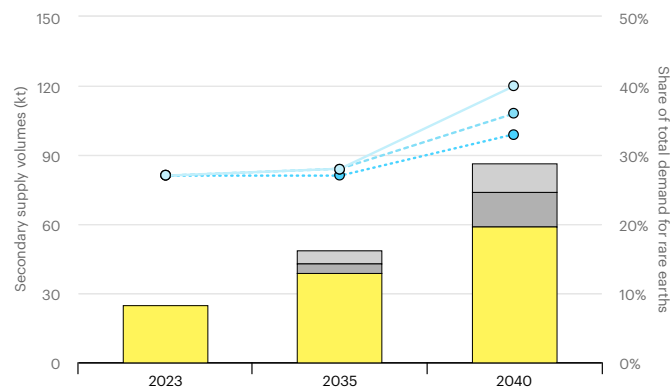


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- Secondary supply in STEPS
- Secondary supply in APS
- Secondary supply in NZE
- Share of secondary supply in STEPS
- Share of secondary supply in APS
- Share of secondary supply in NZE

Secondary supply volumes and share of total demand for rare earths in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario, 2023-2050

Open ↗



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- Secondary supply in STEPS ● Secondary supply in APS
- Secondary supply in NZE ● Share of secondary supply in STEPS
- Share of secondary supply in APS ○ Share of secondary supply in NZE

The energy security benefits of recycling are greatest in regions with limited mineral resources and high clean energy technology deployment.

In Europe, under the APS context, secondary supply from batteries is projected to meet about 30% of the region's lithium and nickel demand by 2050, notably higher than the global average of around 20%. This could substantially reduce either import bills or investment needs for domestic supply.

There is a major gap in today's recycling rates between advanced and developing economies.

In the case of electronic waste (e-waste), collection rates are notably higher in advanced economies than in emerging and developing economies. Collection rates in developing economies in Asia and Latin America are below 5%, and just 1% in Africa, with little improvement since 2010, whereas rates stand at 30% in Japan and Korea and 40-50% in Europe and North America. Support to strengthen collection and recycling infrastructure in developing economies, along with technology and skill transfer, can help prevent waste from ending up in landfills while fostering economic development in these regions.

Battery recycling is key to boosting overall recycling rates

Manufacturing scrap currently dominates the feedstock for battery recycling, but this balance shifts rapidly towards end-of-life EV batteries. Scrap from manufacturing processes still accounts for two-thirds of available recycling feedstock in 2030. From 2035 onwards, however, end-of-life EV and storage batteries take over as the largest source and represent over 90% of available feedstock by 2050. Lithium-ion batteries are one of the key technologies pushing up demand for critical minerals, but they also promise to be a major source for metal recovery.

Developments in battery chemistries have major implications for recycling. In the past few years, lithium iron phosphate (LFP) cathodes have gained significant market share from nickel-based chemistries, making up around 40% of EV batteries deployed in 2023, with their share expected to remain high. This shift impacts recycling economics due to LFP's lower material value. This underscores the need for tailored business models, such as toll-based recycling, supported by regulation and strict mandates to prevent LFP batteries from ending up in landfills. Lessons from the 99% recycling rate of lead-acid batteries in the United States, achieved despite their low residual value, illustrate that well-designed policy measures can overcome economic hurdles in recycling.

Battery recycling capacity is expanding rapidly, led by the People's Republic of China (hereafter, "China"). In 2023, global capacity for pretreatment and material recovery grew by 50% year-on-year, with China accounting for 80% of both. Analysis of the project pipeline indicates that China is on track to retain 75% of global pretreatment capacity and 70% of material recovery capacity in 2030. China recently announced the formation of China Resources Recycling Group Ltd. (<https://www.alcicle.com/news/china-resources-recycling-group-debuts-with-chalco-minerals-and-baowu-as-major-shareholders-112283>), a state-owned enterprise dedicated to recycling and reusing end-of-life batteries, scrap steel and e-waste.

Battery recycling capacity is outpacing available feedstock, although the picture varies by region. If all announced projects come online as scheduled, global recycling capacity in 2030 could be seven times the available feedstock, even with the rapid levels of battery deployment achieved in the APS. However, the picture changes rapidly after 2030 as EVs reach end of life and feedstock availability increases sharply, surpassing announced capacity by 60% by 2040. There are major regional differences. China continues to see excess capacity relative to domestic feedstock. In Europe and the United States, excess capacity dissipates after 2030, and announced recycling capacity covers only 30% of feedstock by 2040. This is higher than in India, where the coverage in 2040 is just 10%.

Battery recycling could meet 20-30% of lithium, nickel and cobalt demand by 2050, but this depends on improving collection rates. The recovered metal volumes from available feedstock are influenced by many factors, with collection rates being the most critical. Under the assumption of continued increases in collection rates, in the APS, recycled volumes from batteries could reach 20-30% of demand for lithium, nickel and cobalt by 2050. However, the range varies depending on plausible variations in collection rates, from 30-40% with higher collection rates and 15-25% with lower rates. The reuse of EV batteries in storage applications meets around 10% of global storage demand by 2050.

The export of used EVs can significantly affect the global volume of recycling feedstock. A significant number of used conventional cars are exported from advanced to developing economies, but it is uncertain if this trend will continue with EVs, with major implications for battery recycling. In the APS, if EV exports mirror patterns of conventional cars, available battery feedstock for recycling in advanced economies and China could drop by 25% (1 terawatt-hour [TWh]) by 2050, while developing economies see a 50% increase (0.5 TWh); this is less than the decrease in advanced economies and China due to delayed battery retirement. Additional recycling capacity will be needed in importing regions, particularly for pretreatment facilities, to avoid waste and loss of potential feedstock for recycling. Clarity on EV export rules and conditions is important to reduce uncertainties and encourage recycling investments in both exporting and importing regions.

Relatively slow development of midstream battery supply projects is a major uncertainty for recyclers.

While battery cell production projects are expanding in regions such as Europe and the United States (US), plans for the midstream supply chain such as precursor cathode active material (pCAM) and cathode active material (CAM) remain limited. By 2030, nearly 90% of these capacities are expected to remain concentrated in China, reducing the security benefits of recycling as recyclers need to compete to supply CAM producers, and cell manufacturers continue to import CAM. Strategic support for midstream development and vertically integrated projects could create more reliable domestic off-takers for recyclers. Strategic partnerships with countries with expanding CAM production, such as Korea, could provide a supplementary solution and serve as a valuable off-taker for European and US recyclers.

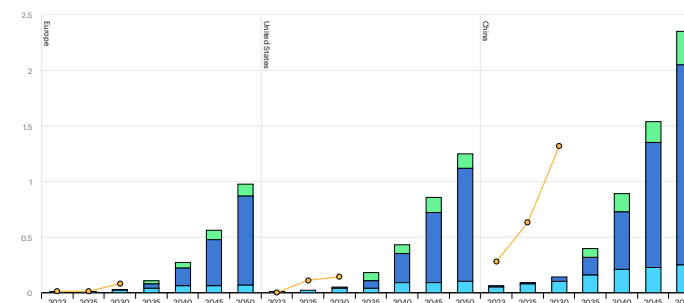
Greater clarity on policies and regulations is essential to support the uptake of battery recycling.

The absence of clear, long-term regulations including export rules for used batteries and EVs as well as the implementation and enforcement of EPR creates barriers to investment. Providing long-term visibility for policies and regulations is crucial for instilling confidence in investors and recycling companies.

Global available battery recycling feedstock and recycling capacity, 2023-2050

Open ↗

TWh



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● Manufacturing scrap ● EVs end of life ● Storage end of life
● Domestic recycling capacity

Traditional metal recycling matters, especially for copper

Scaling up the recycling of end-of-life scrap from traditional industries is essential to alleviate pressure on critical mineral supplies, particularly for copper. Copper is an essential material used in a wide range of electrical applications, but a supply deficit is beginning to appear on the horizon. By 2035 announced projects are sufficient only to meet 70% of copper requirements

(<https://www.iea.org/reports/global-critical-minerals-outlook-2024>) in the APS.

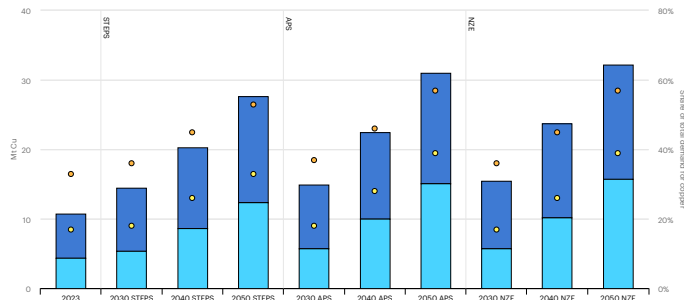
Increasing copper recycling is one of the most critical actions needed to ensure that the shift towards a more electrified and renewables-rich energy system is not held up by a bottleneck in supplies.

Opportunities to boost secondary copper supply are rising as scrap volumes surge from around 2030. Copper scrap availability is expected to grow alongside consumption until 2030, then outpace demand growth. In the APS, scrap volumes increase from 16 million tonnes (Mt) today to 19 Mt by 2030 and 27 Mt by 2050, theoretically able to cover three-quarters of projected demand. Construction remains the largest source of end-of-life copper scrap, but scrap from EVs and storage is set to grow the fastest, expanding more than 35-fold between 2030 and 2050. Enhancing collection rates and investing in secondary processing capacity are key to fully leverage this potential and ease future supply pressures.

Strong policy actions can further raise the share of secondary copper supply. The historical share of secondary supply in total copper demand has stagnated since 2015, but the anticipated surge in end-of-life scrap post-2030 is set to reverse this trend. A combination of policies – raising collection rates for legacy applications such as construction and cables, mandating recycling, improving sorting systems, and investing in new secondary smelters – can further elevate secondary supply's contribution. Facilitating strategic partnerships between copper scrap supply chain actors such as scrap collectors, pre-processors and secondary smelters can also help optimise capacity utilisation and increase scrap trade efficiency. In the APS, the share of secondary copper supply in total demand (excluding direct use scrap) rises from 17% today to nearly 40% by 2050, underscoring the critical role of copper recycling in easing future supply pressures.

Outlook for recycled copper volumes, 2023-2050

Open ↗



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- Secondary production
- Direct-use scrap
- Share of demand including direct scrap
- Share of demand excluding direct scrap

There is substantial untapped potential for metal recovery from e-waste, mine waste and permanent magnets

Metal recovery from e-waste needs much more attention from industry and policy makers. Despite rising awareness, only a quarter (<https://www.unitar.org/about/news-stories/press/global-e-waste-monitor-2024-electronic-waste-rising-five-times-faster-documented-e-waste-recycling>) of e-waste generated in 2022 was documented as properly collected and recycled. Since 2010, global e-waste generation has risen five times faster than collection and recycling efforts, resulting in a decreasing share of recycled e-waste. In 2022 alone, metals contained in e-waste were valued at around USD 90 billion, with only USD 28 billion recovered and turned into valuable materials. Of the 193 countries assessed in our report, only 80 had e-waste regulations as of June 2023, suggesting ample scope for strengthening policy actions. Stricter regulations and penalties for illegal dumping, enhanced traceability, and improvement in pretreatment processes can significantly boost critical mineral recovery from e-waste.

Rare earth recycling from permanent magnets is limited today but the rise of EVs and wind power brings significant potential to step up efforts. Currently, most rare earth recycling feedstock originates from manufacturing losses, with end-of-life permanent magnet recycling constrained by low collection rates (below 15%) and challenging economics. However, the growing use of permanent magnets in EV motors and wind turbines could drive up collection rates. High collection rates alone, however, may not be enough, as recyclers often prioritise more accessible or higher-value materials such as copper or battery metals. Improving recycling rates in this area is likely to require additional measures such as targeted economic incentives, rare earth recycling mandates and consumer commitments to using recycled content in products. In the APS, secondary rare earth supply triples by 2050, contributing to more secure and diversified rare earth supplies.

Recovering minerals from mine waste offers an opportunity to turn environmental liabilities into valuable resources. Mining generates around 100 billion tonnes (<https://www.mdpi.com/2075-163X/9/5/286>) of waste every year, in addition to the sizeable amount already existing in active, inactive and closed tailings. This waste volume is set to increase by almost 90% over 2020 levels by 2030. Reprocessing mine waste, or tailings, can reduce waste generation and mitigate environmental impacts such as water contamination, safety risks and soil pollution. For closed or abandoned sites, it also presents an opportunity for environmental remediation. Previously, the minerals left in mine waste were considered economically unviable, but declining ore quality and future supply concerns are making reprocessing more appealing. For instance, in Chile, the copper content in mine waste with higher grades than primary sources is poised to rise from 1.6 Mt in 2005 to 5.6 Mt by 2050. Realising this potential will require comprehensive waste resource mapping, supporting research and development (R&D) for new recovery technologies, providing economic incentives, and addressing liability barriers related to mine waste at abandoned sites.

Several cross-cutting issues remains to be addressed

Recycling businesses can be profitable, but innovative pricing schemes and business models are key to improving economic viability. Profits for recycling energy transition minerals may be lower than for bulk materials, but increased policy support and feedstock availability can strengthen the business case. Market-based battery metal recycling is particularly sensitive to material price fluctuations, requiring recyclers to have robust balance sheets and working capital to weather volatility and commodity cycles. New models such as toll-based recycling and revenue-sharing could offer recyclers better economic stability and encourage long-term investments, especially for LFP batteries.

New technologies hold promises for improving recycling efficiency. Current technologies often struggle with the complexity and diversity of products containing critical minerals, resulting in lower recovery rates and material loss. Emerging technologies such as advanced sorting, novel chemical and physical processes, and new quality control methods can help overcome these challenges. Positive trends are evident: lithium-ion battery recycling patents grew at an average annual rate of 56% from 2017 to 2022, and venture capital investment in battery and waste recycling surged between 2022 and 2023. Policy incentives and collaborations between research institutions and industry will be essential to bring these promising technologies to market.

Countries are taking action to regulate scrap trade to reduce unmanaged waste leakage and incentivise domestic recycling capacity. In addition to national regulations, international waste agreements such as the Basel Convention

(<https://www.basel.int/Home/tabid/10035/Default.aspx>) and the Organisation for Economic Co-operation and Development Decision on the Control of Transboundary Movements of Wastes

(<https://www.oecd.org/en/about/news/announcements/2024/06/oecd-countries-update-rules-on-international-shipments-of-electronic-waste.html>) continue to strengthen the control of transboundary waste trade. These measures will help ensure that exported scrap is properly recycled and sustainably treated in importing regions. However, effective and nimble implementation is essential to prevent these regulations from hindering the growth of the global recycling industry. For battery metals, a harmonised international classification of lithium-ion battery waste and black mass would provide much-needed clarity, reducing uncertainties around regulations concerning these emerging waste streams.

Recycling is not free from environmental and social impacts. Poorly managed battery recycling may result in pollution from waste residues, water contaminants and harmful emissions. In many countries, the waste collection stage often involves child labour

(https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@ed_dialogue/@sector/documents/publication/wcms_196105.pdf) or unsafe practices. While various voluntary standards are emerging, there are still significant gaps in social and governance aspects, requiring efforts to strengthen existing recycling standards. Traceability mechanisms can allow stakeholders to verify that materials are sourced and recycled according to best practices. Such mechanisms can also allow consumers to favour recyclers with higher environmental and social performance.

Policy makers need to look beyond recycling to integrate broader circular economy principles. Opportunities beyond recycling include circular product design, repair, refurbishing, reuse and repurposing. Circular design principles reflect the importance of improving products' lifetime and facilitating easier recycling at the end of life. Increasing repairability via modular designs that make disassembly easier (https://environment.ec.europa.eu/news/sustainable-smartphones-modular-design-promotes-do-it-yourself-repair-extend-device-life-2023-02-15_en) is a strategy that can be used in EVs and electronics. Repurposing and reusing also offer significant waste reduction opportunities. By adopting a holistic approach that considers the entire product life cycle, policy makers, industry stakeholders and consumers can create more sustainable pathways for the use of critical minerals.

Key actions for policy makers

his report distils a set of key actions for policy makers to scale up critical minerals recycling.

1. **Develop detailed long-term policy roadmaps:** set clear targets and intermediate milestones to provide clarity on policy directions and greater certainty for investors.
2. **Harmonise waste management and recycling policies to develop efficient secondary markets:** facilitate international co-operation to reduce trade barriers and minimise unmanaged leakages.
3. **Strengthen domestic infrastructure with incentives and mandates:** encourage investment in recycling capacity at national and regional levels with economic incentives.
4. **Encourage traceability, standards and certifications to boost the consumption of recycled materials:** the uptake of recycling industries is enabled by transparency and international best practices.
5. **Provide targeted financial support for technology innovation, R&D and workforce training:** ensure continued support for more efficient processes, scaling proven technologies and training a workforce ready for the new energy economy.
6. **Strengthen recycling systems in emerging and developing economies:** introduce new technical and financial instruments to support investment in regions most vulnerable to the effects of improper waste management.
7. **Tackle data and information gaps:** access to reliable and granular data is pivotal for efficient policy and investment choices.
8. **Embrace a holistic approach beyond recycling:** product design, reuse, repair and refurbishment can play a major role in ensuring sustainable mineral value chains.
9. **Tackle environmental, social and governance (ESG) issues for recyclers:** ESG impacts must be identified, minimised and mitigated to contribute to sustainable and responsible supply chains.



Full length article

Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review

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ABSTRACT

The market for electric vehicles (EVs) has grown exponentially over the past decade, largely driven by ambitious sales targets in regions around the world. At end-of-life (EoL), these batteries must be managed properly to maximize reuse and recycling, which requires an efficient and safe collection and transportation system; however, the logistics of transporting EoL batteries are rarely examined in depth in scholarly research. In this paper, we conduct a critical review of the peer-reviewed literature on EV traction battery reuse and recycling to assess how transportation is represented. We find that among 60 studies identified, 70% mentioned collection and transportation as a challenge to battery reuse or recycling, and 63% identified a need for policy or further research related to collection and transportation. Among 17 papers that focus on cost, estimates for transportation costs vary widely among studies, from more than five dollars per kg to less than 30 cents, representing, on average, 41% of the total cost of recycling. Studies that examined the environmental impact of EoL transportation suggest it contributes 1–3.5% of life cycle GHG emissions for a recycled battery. In response to the limited and highly variable treatment of battery EoL transportation, the literature review is followed by contextual information about the United States, including the regulatory framework and existing network for EoL batteries. Recommendations for future study include place-specific research on optimal facility siting that considers both existing and projected infrastructure, and which reflects costs and environmental and social impacts at local scales.

1. Introduction

Recent advancements in lithium-ion batteries (LIBs) have enabled electric vehicles (EVs) to achieve driving ranges that can compete with fuel-powered cars (Fletcher, 2013). The market has grown exponentially over the past decade, and EVs are now a critical component of greenhouse gas (GHG) mitigation targets at state, federal, and international scales (CARB, 2021; IEA, 2020). While EVs represent a promising means of decarbonizing transportation, the material demand associated with LIB production engenders concern about supply chain sustainability and end-of-life (EoL) management. Key value chain inputs such as lithium, cobalt, nickel, and graphite are considered critical or near-critical materials and have negative social and environmental impacts (Banza Lubaba Nkulu et al., 2018; Dunn et al., 2015; Mayyas et al., 2019). At EoL, LIBs must be managed properly to avert environmental damages and to capture the residual value via second-life applications and material recovery. Considering the rapid increase in demand for EV LIBs

and the deluge of retired EV LIBs that will occur in the coming decade, there is a growing body of research on the need for circular economy strategies to reduce dependence on mining and refining for battery materials and to manage retired batteries effectively (IEA, 2020); (Rajaeifar et al., 2020); (Skeete et al., 2020).

On the supply and production side, researchers have forecasted expected material demand (Ambrose and Kendall, 2019a; Olivetti et al., 2017) and analyzed the life cycle impact of EV batteries, often highlighting the impact of cathode materials and battery assembly (Ambrose and Kendall, 2019b; Dai et al., 2019; Dunn et al., 2015; Kelly et al., 2019). Studies focusing on EoL have forecasted the volume of the future waste stream (Ai et al., 2019; Baars et al., 2020; J. Dunn et al., 2021; Kirti Richa et al., 2014), discussed the potential impact of reusing batteries in stationary storage applications (Leila Ahmadi et al., 2017; Bobba et al., 2018; Casals et al., 2019; Cusenza et al., 2019), reviewed the status of recycling (Harper et al., 2019; Heelan et al., 2016; Lv et al., 2017; Mossali et al., 2020; Zhang et al., 2018a,b); and compared the

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environmental and economic implications of different recycling pathways (Ciez & Whitacre, 2019; Hendrickson et al., 2015; Richa et al., 2017).

However, before reuse or recycling is possible, LIBs must be removed from the vehicle, potentially stored until enough batteries accumulate for a cost-effective shipment, and be transported to the appropriate facility. Transporting EoL batteries is a critical aspect of the collection phase, and has been identified as a potential barrier to achieving the high collection rates that are necessary for robust reuse and recycling systems (Ahmadi et al., 2014; Hua et al., 2020; Larouche et al., 2020; Thompson et al., 2020; Wang & Yu, 2021). Despite this, the practical logistics of how batteries will get from the point of vehicle retirement to facilities where they will be refurbished, repurposed, or recycled have received far less attention in scholarly research compared to scientific and technical aspects of reuse or recycling (Fan et al., 2020; Melin, 2019; Nordelöf et al., 2019).

This article seeks to understand how transporting used batteries influences the sustainability and cost of EoL management, identify solutions to reduce the impact of the transportation phase, and provide suggestions for accurately representing transportation in future research. First, we present a literature review of peer-reviewed articles about the cost and environmental impact of lithium-ion battery end-of-life, focusing on how, if at all, authors account for collection and transportation. The literature review is then complemented with contextual information about EoL battery transportation, including the regulatory framework and existing network, to identify key areas of concern and make recommendations for future research. While the scope of the papers reviewed is global, the contextual discussion is focused on the United States, as the specific context of collection and transportation varies by region.

2. Methods

Peer-reviewed articles, reviews, conference proceedings, and book chapters were identified through Scopus and Web of Science using the following title, abstract, and keyword search terms:

- 1 To identify studies on environmental impact: ["lithium-ion batter*" AND "electric vehicle"] AND ["recycl*" OR end-of-life" OR "circular economy"] AND ["sustainab*" OR "environment*" OR "impact" OR "life cycle assessment" OR "LCA"]. This yielded 238 results in Scopus and 107 in Web of Science.
- 2 To identify studies on cost and/or economic analysis: ["lithium-ion batter*" AND "electric vehicle"] AND ["recycl*" OR end-of-life" OR "circular economy"] AND ["sustainab*" OR "environment*" OR "impact" OR "life cycle assessment" OR "LCA"]. This yielded 21 results on Scopus and five on Web of Science, most of which overlapped with articles captured in the first search.

Next, we searched within these results for ["transport*" OR "reverse logistics"], which yielded 127 document results for environmental search terms, and 17 for economic. All results were published after 2011. Each article was then individually reviewed for exclusion based on the following criteria:

- Where "transport" referred only to the transportation sector or transport of lithium ions within a battery cell
- Where "transport" referred only to the transportation of materials or batteries during production, but not EoL
- When EoL transport is mentioned only to state that it is excluded from the analysis
- When the article is not about batteries for passenger EVs
- When the article is a technical paper about a specific recycling method

In total, 46 articles mentioning EoL transportation were selected

through this process from Scopus and an additional eight from Web of Science. Six more were identified by following in-text citations for a total of 60 documents.¹ Among these, 70% ($n = 42$) mentioned collection and transportation as a challenge to battery reuse and/or recycling, and 63% ($n = 37$) identified a need for policy or further research related to collection and transportation (Fig. 1). 17 papers included EoL transportation in cost analysis, and nine in environmental analysis. These articles were then analyzed to determine how, if at all, authors reported the impact of transportation or specified their assumptions. Finally, we looked at whether the authors explain how batteries are transported, reflect the existing network and infrastructure, or provide suggestions for reducing the burden of transportation.

To provide more insight into the factors influencing the impact of transportation, we also reviewed the relevant regulations and industry landscape in the United States. This section was partially guided by interviews with stakeholders who work in battery transportation and storage.

3. Results

3.1. Economics

Of the 60 articles reviewed, 17 include transportation in an analysis of the cost or economics of recycling (Alfaro-Algaba and Ramirez, 2020; Choubey et al., 2017; Fan et al., 2020; Foster et al., 2014; Hendrickson et al., 2015; Idjis and da Costa, 2016; Li et al., 2018; Ma et al., 2018; Sato and Nakata, 2020, 2021; Sun et al., 2020; Tang et al., 2018; L. Wang et al., 2020a; Wang and Yu, 2021; Wang et al., 2014; Zhang et al., 2018a, b). Of these 17, 11 report the disaggregated transportation cost used in their analysis (Table 1). The average estimated cost of transportation is \$1.54/kg, with values varying widely between studies from \$0.24/kg (Hoyer et al., 2015) to \$5.51/kg (Foster et al., 2014). Six studies reported the cost of transportation as a percent of total recycling cost (or provided sufficient data to conduct this calculation), resulting in an average contribution to total recycling cost of 41%. Fig. 2

The variability in cost estimates and assumptions may be partially attributable to regional differences, as transportation costs will vary based on local fuel and labor costs. However, the majority of articles do not justify or even state key assumptions such as distance traveled or mode of transport, even when transportation is reported to be a significant cost with decisive effects on the economics of recycling (e.g. Idjis and Da Costa, 2016). This makes it impossible to determine the contribution of different cost drivers and the cause of such high variability

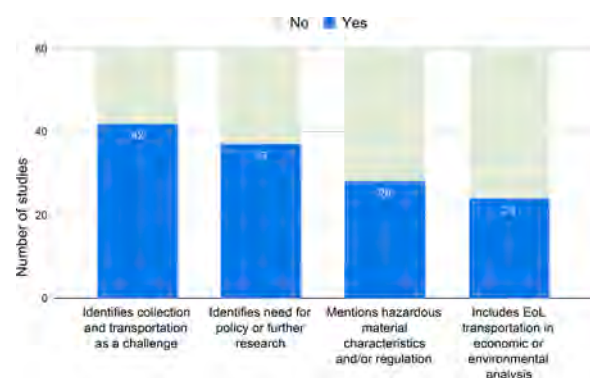


Fig. 1. Breakdown of how transportation is addressed in articles selected for analysis.

¹ The complete list of articles reviewed and corresponding information is included as a spreadsheet in the supplementary materials.

Table 1
Studies that specify a disaggregated transportation cost.

Study	Location	Transport cost	Normalized cost (\$/kg)	% of total cost	Additional Assumptions
(Foster et al., 2014)	United States	\$2.50/ lb.	\$5.51	46%	Transport of a Chevrolet Volt battery (500 lbs) from Detroit to Lancaster, OH. Cost (\$2.50/lb.) is quoted from USPS large freight and hazardous materials division.
(X. Wang et al., 2014)	North America	\$1120/ton	\$1.12	40%	Transportation is assumed to be 40% of variable costs for recycling, which also include collection and processing. Variable costs are \$2800, which is the mean of data taken from a variety of older references about the overall cost of battery recycling.
(Hoyer et al., 2015)	Germany	\$215.25/ BEV-eq. (330 kg)	\$0.71		Cost level assuming one collection facility.
		\$72.12/ BEV-eq. (330 kg)	\$0.24		Cost level assuming 25 collection facilities.
(Idjis and da Costa, 2016)	European Union	\$1660.36/ ton	\$1.66		Not stated.
Choubey et al (Li et al., 2018)	Unspecified	\$3039.50/ ton	\$3.04	53%	Not stated.
(Ma et al., 2018)	Unspecified	\$8.00/ battery-km	NA		Not stated.
	Shenzhen	\$302.62/ ton	\$0.30		Transport cost is obtained from a market investigation in Shenzhen, China, and includes fuel fees and tolls. Cost is estimated at full load circumstances.
(Zhang et al., 2018b)	Unspecified	\$411.00/ ton	\$0.41	63%	Not stated.
(Alfaro-Algaba & Ramirez, 2020)	Spain	\$1096.32/ truckload	NA		Authors estimate the total cost for transporting and handling 500 batteries to be €11,520, which implies that roughly 42 hybrid batteries are shipped per truckload. The weight and capacity of batteries are not specified.
(Dai et al., 2019)	United States	\$2.09/ kg	\$2.09	38%	Battery travels 50 miles to collection, 50 miles from collection to disassembly, 1000 miles from disassembly to recycler. All transportation is via truck; all materials prior to the recycling process are hazardous, and the shipping cost is estimated to be \$1.93/ ton-mile.
(Sun et al., 2020)	China	\$36,209.84 (Units unspecified)	NA		Not stated; transportation is included as a component of the initial investment, but the authors do not justify the value of the assumed cost.
(Wang et al., 2020)	China	\$158.00/ battery (365 kg)	\$0.43	4.8%	Assumes a straight-line distance between the coordinates of collection and recycling facilities in the existing network of a Chinese manufacturer (Chang'an).
(Wang and Wu, 2017)	China	\$0.07/ton-km	NA		Based on the average transportation fee for waste LIBs in China.

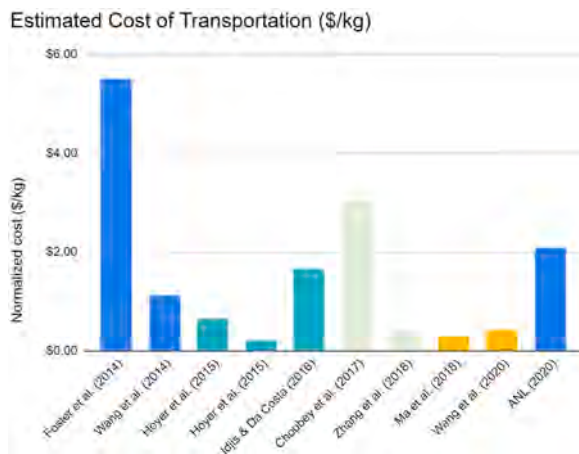


Fig. 2. Cost estimates for EoL transportation. The euro-to-dollar conversion rate is based on the year of publication, using exchange rates from OECD Data. The yuan-to-dollar conversion rate for the publication year was obtained from the US Federal Reserve.

among studies.

Foster et al. (2014), Ma et al. (2018), and Alfaro-Algaba & Ramirez (2020) provide the most detailed explanations behind their assumed cost. Foster et al. specify the battery type and weight (500 lb. Chevrolet Volt battery), estimate the distance traveled based on real-world locations, and obtain a price quote from a specific carrier (the US Postal Service). Notably, their estimated cost is significantly higher than any other study. Ma et al. and Alfaro-Algaba & Ramirez both appear to calculate the cost based on a full truckload, which is important to specify since full truckload shipments are more cost-effective on a per-battery basis. However, to take advantage of the benefits presented by full truckload service, the batteries must be consolidated at a collection

point before shipment. For example, achieving the cost presented by Alfaro-Algaba & Ramirez requires 42 hybrid batteries to be shipped per truckload.

More detailed assumptions regarding transportation are also included in the most recent version of EverBatt, a recycling cost and LCA modeling tool from Argonne National Laboratory (Dai et al., 2019). The model uses a shipping cost of \$1.93 per ton-mile, which includes a hazardous material insurance premium, based on operational cost data for freight trucking from the American Transportation Research Institute (ATRI). Under the default distance assumptions, this translates to \$2.09/kg. The cost difference between EverBatt and Foster et al. may be partially due to EverBatt using operational cost data for motor carriers, while Foster et al. use prices quoted from the US Postal Service.

Several articles include transportation in their analysis, but do not report the cost separately. Fan et al. (2020) state that economic and environmental analysis should include collection and transportation costs and report the results of other studies related to transport. However, they exclude the cost of collection and transportation from the results of their own analysis. Sato & Nakata assume a cost of \$94–141 (10,000–15,000 yen) per unit of hybrid vehicle battery for processing and transportation, but processing and transport are not reported separately.

Finally, several studies discuss transportation cost in the context of system optimization. Wang et al. (2020) find that optimizing the recycling network of Chang'an, a Chinese manufacturer, would reduce transportation costs by 22.9%. Interestingly, this study presents by far the lowest value of transportation as a percentage of overall recycling cost: 4.8% as a baseline, or 4% with optimization. These numbers only account for transportation from the collection center to the recycling facility and do not include the initial transportation to the collection center. Hendrickson et al. (2015) use an optimization model to identify the optimal infrastructure siting scenario for battery recycling in California, considering both transportation and capital cost, although they do not specify the value of their assumed transportation cost. Assuming

pyrometallurgical recycling, they use sensitivity analysis to examine the tradeoff between transportation cost savings and capital cost expenditures, finding an optimal facility size of 7000 tons per year and associated marginal cost of \$37/ton, which includes both capital and transportation costs. To minimize the ton-kilometers traveled between collection and recycling, the authors conclude that the most efficient system is to have two collection points near San Francisco and Los Angeles, with one recycling facility in between.

3.2. Environmental impact

Ten articles accounted for EoL transportation in an assessment of the environmental impact of lithium-ion battery reuse (Mathur et al., 2019; Richa et al., 2017) or recycling (Accardo et al., 2021; Cerdas et al., 2018; Ciez and Whitacre, 2019; Hendrickson et al., 2015; Rahman et al., 2017; Wang et al., 2020; Wang and Yu, 2021; Xiong et al., 2019a). However, only five discuss or report the results separately. These can be generally categorized as studies that report the relative contribution of EoL transport as a percentage of overall emissions (Accardo et al., 2021; Ciez & Whitacre, 2019; Xiong et al., 2019; Hendrickson et al., 2015), and studies that calculate the potential to reduce EoL transportation emissions, either through reuse (Mathur et al., 2019), recycling (Rahman et al., 2017), or system optimization (Hendrickson et al., 2015; Wang et al., 2020).

Where studies report the relative GHG impact of transportation, it is minor, ranging from less than 1% (Accardo et al., 2021) to 3.5% (Ciez & Whitacre, 2019). However, these estimates are relative to the entire life cycle impact of batteries from recycled vs. virgin materials, including production. For example, Ciez & Whitacre use LCA to estimate the greenhouse gas (GHG) emissions and energy inputs associated with batteries produced from recycled materials, comparing pyrometallurgical, hydrometallurgical, and direct physical recycling of different battery chemistries and formats. They include a parametric analysis of transportation impacts, assuming batteries are transported 2500 miles by truck. The authors find that transportation makes a minimal contribution (3.5–4%) to the life-cycle greenhouse gas emissions of batteries made from recycled materials. By contrast, Hendrickson et al. focus on EoL and examine life cycle impacts beyond GHG emissions, highlighting the impact of transportation on local air quality. Under their baseline scenario, freight trucking is found to contribute 99% of human health damages from particulate matter (PM), 54% of SO₂ damages, and 62% of total volatile organic compound (VOC) damages. While the authors assume all transportation will be handled by truck, they find that using rail instead could lower the GHG emissions from transportation by 45%.

Mathur et al. and Rahman et al. assess the environmental benefits of reuse and recycling, respectively. Mathur et al. find that reuse reduces emissions from transportation compared to sending batteries directly to recycling, while Rahman et al. find that recycling avoids emissions compared to sending batteries to a landfill. However, in both cases the authors assume that the reuse or recycling facility is co-located with the dismantling facility, which is unrealistic. Wang et al. (2020) assess the benefits of optimizing collection and recycling infrastructure siting, which they find can reduce carbon emissions by 21.8%, mainly due to reduced transportation.

3.3. Hazardous material regulations and producer responsibility

Nearly half ($n = 28$) of the articles reviewed mention the safety hazard associated with transporting LIBs and corresponding regulations. Several papers point out that the complexity of hazardous material transportation regulations is an added cost that complicates battery recycling (e.g. Harper et al., 2019; Thompson et al., 2020; Ahuja et al., 2020) (Skeete et al., 2020)). Moore et al. (2020) spatially model a second-life deployment scenario in Berlin and identify transport routes that minimize distance to ensure safety compliance, rather than reduce cost. The risk of fire hazard was also mentioned by (Reinhardt et al.,

2019) as a motivating factor towards clear legislation allocating liability for second-life batteries.

The other key policy issue is allocating responsibility for collection and transportation (Gaines et al., 2018; Kellner and Goosey, 2020). Under the EU battery directive, the producer is obligated to ensure that batteries placed on the market are properly recycled and set up take-back systems that facilitate collection at no cost to the owner either directly or through a third party acting on their behalf (Hoyer et al., 2015; Kellner and Goosey, 2020; Richa et al., 2017). Car manufacturers or importers are also responsible for the collection, sorting, storage, and transportation of batteries in China under the Provisional Regulation on the Recycling and Reuse of Traction Batteries from New Energy Vehicles (NEV) (Gaines et al., 2018). Clarifying producer responsibility in cases where the battery is repurposed for stationary storage by a third party is identified as a policy need (Richa et al., 2017).

4. Gaps: safety, cost structure, and existing network

To inform future research, the following sub-sections contain detail on the context of how batteries are typically shipped in the United States, including the regulatory framework and required safety protocols, operational cost and pricing, and the existing network of battery recyclers and collectors. The purpose of this section is to provide context-specific parameters that can be used by researchers who are analyzing the situation in North America. Similar information about other regions of interest would be a valuable area for additional study.

4.1. Regulatory framework and safety protocols

In the United States, LIB shipments are regulated by the Department of Transportation (DOT) as a Class 9 (“Miscellaneous”) hazardous material. Shipping requirements for LIBs are specified under the DOT Code of Federal Regulations (CFR) §173.185. Batteries that are shipped for disposal are exempted from certain classification and packaging requirements but must be packaged in a manner to prevent short circuits, damage caused by movement or placement within the package, and accidental activation of the equipment (Pipeline and Hazardous Materials Safety Administration, Paragraph (B) (1)). Packages containing LIBs must also meet hazard communication requirements by displaying a lithium battery mark. However, there are no specific placarding requirements for the vehicle transporting them beyond the Class 9 Miscellaneous Waste symbol. This reduces the cost of shipping but also means if there is an accident on the road that leads to a fire, the fact that it is a battery fire requiring special protocol will not be obvious to first responders until they look at the paperwork or package labels.

Damaged or defective batteries are subject to more stringent regulations; they are classified as Packaging Group 1 in the United Nations (UN) Manual of Tests and Criteria, indicating highest danger, and must be shipped in a UN-certified container (Huo et al., 2017). Given that the shape and size of EV batteries vary by make and model, such containers currently must be custom ordered from dangerous goods manufacturers at great expense.

Shipping is typically handled by third-party logistics companies, often through large commonly recognized carriers who have their own guidelines that comply with both federal and international regulations (Huo et al., 2017). However, the responsibility for packaging, marking, labeling, and completing documentation for dangerous goods regulations falls to the party who is holding and wants to ship the battery, not the carrier (FedEx, 2021). The complexity of navigating regulations and following proper safety protocol suggests that shippers with knowledge and experience will be necessary actors in a functioning circular EV EoL system (Kellner and Goosey, 2020).

The United States does not have an extended producer requirement for electric vehicle batteries, so the party responsible for paying the cost of transportation is contract-specific rather than being dictated by policy. This may present an issue in the future as out-of-warranty batteries

Table 2
Studies that report the environmental impact of transportation.

Authors	EOL stage(s)	Geographic focus	Results
(Accardo et al., 2021)	Recycling	European Union	Does not specify the value of EoL transportation impact but states that "transport of batteries contributes less than 1% to all the examined categories."
(Ciez & Whitacre, 2019)	Recycling	United States	Transportation contributes 3.5% of GHG emissions of batteries produced from recycled materials. The study assumes batteries travel 4023 km (2500) miles by truck to reach their destination.
(T.P. Hendrickson et al., 2015)	Recycling	California	Freight trucking contributes 99% of human health damages from particulate matter (PM), 54% of SO ₂ damages, and 62% of total volatile organic compound (VOC) damages.
(Rahman et al., 2017)	Recycling	Global/ Unspecified	Transportation emissions are 572 g CO ₂ if the battery is not recycled vs 110 g CO ₂ with recycling. The impact is based on the fuel consumption (121 L/km) of a diesel pickup with a 500 kg payload. Assumes battery exchange workshop and recycling facility are co-located, distance from exchange workshop to landfill is 20 km, and distance from recycling facility to landfill is 8 km.
(Xiong et al., 2019b)	Recycling	China	Transportation accounts for 2.5% of vehicle cycle energy consumption. EoL transportation is modeled from production plant to service shop (1600 km).
(Mathur et al., 2019)	Reuse, Recycling	United States	Reuse avoids 17.78 kg of CO ₂ emissions from transportation compared to direct recycling, assuming that dealership, diagnostic center, and PV industry are co-located. Transport is modeled assuming a light commercial diesel truck using Southwest US transport fuel mix.
(Wang et al., 2020)	Recycling	China	Optimizing the system reduced carbon emissions by 21.8%, mainly due to the reduced need for transportation. Baseline emissions from transportation not reported.

may be dismantled by small auto dismantlers, scrap metal recyclers, or private repair facilities for whom the cost of shipping could be a burden that discourages optimal disposal or dissuades them from acquiring the vehicle in the first place.

4.2. Cost structure

The operational cost of freight transport is dependent on a variety of vehicle-based and driver-based costs. Vehicle-based costs include fuel, vehicle lease or purchase payments, repair and maintenance, insurance, permits and special licenses, and tolls. Driver-based costs are wages and benefits. The operational cost varies by the size and service provided by the motor carrier, as well as by region due to differences in fuel cost, tolls, and labor cost for drivers and repair and maintenance (Williams and Murray, 2020). The cost of shipping is also dependent on the transportation corridor; if the destination is in a remote location, the carrier may not be able to generate revenue through a backhaul shipment and will charge a higher price.

Batteries may be shipped using less-than-truckload (LTL) or full truckload (FTL or TL) services. LTL, which is generally used for shipments up to 15,000 lbs., means the shipper reserves a certain amount of space in a container that is also carrying additional products, and is often charged by weight (Redwood, 2021). FTL means the shipment is transported on a dedicated freight truck and is charged by distance. The operational cost of freight trucking is higher for companies that specialize in LTL (Table 2), and the higher price means the per-unit cost to ship a small quantity of batteries could theoretically exceed the cost of sending an FTL shipment a longer distance in some cases. Furthermore, LTL shipments may be cross-docked, meaning the product is transferred at a terminal from its original truck or rail car to a different outbound vehicle. If this occurs overnight and the terminal is closed, the facility will need to be equipped to properly store dangerous goods and may need approval from the local fire department to store the batteries (Haltrecht, 2020).

This highlights the link and tradeoff between transportation and storage; consolidating batteries at specified collection points may make reverse logistics more efficient as truckload size and volume will affect the cost of shipping. However, storing batteries is costly and associated with its own safety hazards, which could make the prospect of accumulating batteries less attractive depending on the required amount of time. Table 3

4.3. Existing network

Transportation assumptions can be better informed by considering

existing infrastructure when assessing recycling pathways. In this sense, it is important to keep track of industry developments, which is not always easy given the fast pace at which the private sector is advancing. Multiple new recycling companies have been announced in the past several years and are now in the pilot phase, most of them using a hydrometallurgical process (Fig. 3). This challenges a common assertion that pyrometallurgical recycling will continue to be the most likely fate for retired LIBs in the United States, which manifests in previous studies' assumptions that batteries will be shipped to a centralized facility in Lancaster, Ohio.

Additional facilities are planned in Gilbert, Arizona; Sonora, Mexico; and Endicott, NY, although the facility in Endicott has been delayed due to local opposition (Kumagai, 2021; NewsChannel, 2021).

5. Discussion

We find that while transportation of EoL batteries is mentioned as an important contributing factor to recycling costs and environmental impacts, it is rarely assessed in detail or with dedicated research. Among papers that do address transportation, important parameters including truckload size, safety precautions, and in some cases even distance are not specified, although all are important to understand and affect the economics and environmental performance of recycling. Conclusive findings on the relative importance of transport to the environmental impact of reuse or recycling are unclear, especially contributions to GHG emissions. Nonetheless, (Hendrickson et al., 2015) demonstrated that transport contributes significantly to human health damages from criteria pollutants, which illustrates the importance of addressing local impacts as well as GHGs. Notably, all articles reviewed (both economic and environmental) assume that batteries will be transported by truck, although rail transport would have a significantly lower environmental impact. While transport via freight truck is the standard practice today, it is not required by law in the United States.

Table 3

Average marginal cost for freight trucking operations in the United States. Marginal cost does not include insurance premium or other added cost from dangerous goods precautions. Source: ATRI, 2020.

Average Marginal Cost (\$/km)			
By Sector		By Region	
LTL	1.15	Midwest	1.05
Specialized	1.15	Northeast	1.15
TL	0.96	Southeast	0.97
Average	1.03	Southwest	0.96
		West	1.01



Fig. 3. Lithium-ion battery recycling facilities that are operational, at least at a pilot scale, in North America.

Where it is analyzed in papers discussing cost, transportation significantly affects the economics of recycling, contributing over 40% of recycling cost on average and potentially determining whether or not recycling will be a profitable pursuit. This indicates that the motivation for reducing the burden of transport may be driven by improving the economics of recycling, rather than reducing its corresponding GHG emissions. The relatively minor GHG impact was cited by one study as the basis for excluding EoL transport from environmental analysis ((Ahmadi et al., 2017), and may explain why it was more commonly included in economically focused articles. The insight on cost and spatial impacts demonstrated by Hendrickson et al. (2015), Hoyer et al. (2015), and Wang et al. (2020) points to optimized system design as a promising area for future research. When considering the siting for new facilities, researchers should ensure that the current state of the industry is reflected by seeking out and incorporating knowledge of the existing network.

Strategic facility siting that minimizes distance is the most common suggestion to reduce the cost of transportation or make it more efficient (Gaines et al., 2018; Thompson et al., 2020; Wang et al., 2020; (Kellner and Goosey, 2020); Li et al., 2018). Minimizing transport distance is also preferable from a safety perspective (Kellner and Goosey, 2020; Moore et al., 2020). (Larouche et al., 2020) suggest that companies design smaller local process plants or distributed crushing facilities to shorten transport distance, noting that transporting only black mass to central processing plants would neutralize safety concerns. Facilitating access to accurate information about the battery's state of health (SOH) early on in the chain of custody would also reduce the burden of transportation by ensuring batteries are sent to the appropriate facility (i.e. only batteries with a high SOH are sent for reuse or repurposing) and avoiding unnecessary shipments. This would also lower the cost and environmental impact of repurposing by reducing the number of modules that must be tested onsite (Neubauer et al., 2015; K. Richa et al., 2017).

The regional differences in operational transportation costs indicate that optimization research on infrastructure siting can more effectively inform policy by using place-specific parameters. This would allow for a more accurate estimation of the transportation, capital, and operational expenditures among areas with varying property, energy, fuel, and labor costs, as well as differences in environmental impact due to grid mix or local pollution standards. Researchers should also incorporate qualitative information about areas of interest, in addition to seeking a quantitatively optimal solution. The regulatory environment and cost of operation are likely to affect the feasibility of building a recycling facility in a given location, which should be taken into account when evaluating alternatives. For example, in the United States, the stringency of environmental regulations governing hazardous waste management may vary by state under the Resource Recovery Act, (US EPA, n.d.). This is likely to make certain states more favorable for recycling operations than others.

It is also important to account for the local social and political context and evaluate potential developments with an environmental justice lens. For example, the negative air quality impacts reported by Hendrickson et al. from freight trucking are concentrated in communities surrounding transportation corridors, many of which are known to be environmental justice communities that are disproportionately Black and Latinx (Morello-Frosch et al., 2002). The facilities themselves, while potentially a source of employment and economic benefits, also risk perpetuating historic harm and inequality if local impacts are not accounted for and mitigated. The case of the contested SungeEel facility in Endicott, NY exemplifies this tension; in press releases, the company emphasized the economic benefit, while a local activist group (NoBurnBroome) strongly opposed the project due to concerns over the impact of its incineration process on public health (NewsChannel, 2021). Both the environmental impact and the history of the community contributed to the ensuing conflict; NoBurnBroome issued a statement that "SungeEel seems oblivious of the assault on the health of the citizens of Endicott by previous industrial operations," referring to a previous IBM facility in the same location (Connnett et al., 2020).

6. Conclusion

To avoid burden-shifting from greenhouse gas emissions to local impacts from mining, refining, and potentially recycling, climate mitigation strategies must include provisions to ensure that vehicle electrification is consistent with the three pillars of sustainability – social, environmental, and economic. As it relates to EoL management, this means batteries should be transported to a facility that incurs the lowest environmental impact and maximum social benefit, in addition to being economically efficient. Identifying the socially, economically, and environmentally optimal EoL system will require knowledge of the transportation path and associated emissions (including local pollutants), as well as the impact of the recycling process and characteristics of the surrounding communities. Analyzing the economic feasibility will require accurately accounting for all potential costs, including collection and transportation. On a practical level, the qualitative intricacies of transportation logistics must be examined in detail to identify opportunities to reduce cost and promote worker safety.

The literature review conducted in this article revealed that while in research about lithium-ion battery recycling, it is common practice to state assumptions related to battery chemistry and material recovery, most papers are less specific regarding collection and transportation, or in many cases omit this phase entirely. This is because most studies focus on the recycling or repurposing process, without discussing the pathway from retirement to treatment facility. Where it is included, the large proportion of transportation costs, substantial cost variance between literature, and lack of detail in the calculations demonstrate there is a crucial information gap in the literature. To address this issue, we recommend that researchers studying battery EoL be deliberate about including transportation and state the reasoning behind their cost assumptions; for example, by using a regionally-specific industry average; specifying the mode of transport, distance, fuel cost, and truckload size; and/or by referring to a quoted price from a specific carrier. The detailed options provided in the latest version of EverBatt can also be used to facilitate future analysis that incorporates transportation in both economic and environmental analysis. Another promising opportunity for future research is regionally optimized system design that identifies preferable facility siting while considering cost, GHG emissions, and local environmental and social impacts.

Finally, given the complexity of safely transporting batteries in compliance with regulations and the economic advantages of shipping batteries in bulk, facilities that collect and store batteries will be a critical component of the EoL ecosystem. The safety, cost, and regulatory considerations of storing batteries would be a valuable area for future study, as would further exploration of the actual pathway between retirement and collection. For example, while Hendrickson et al.

assume batteries will be collected at dealerships, they may also be exported, sold at insurance auctions, purchased, and resold by auto dismantlers, or even used by do-it-yourself enthusiasts in off-grid homes. The details of how this unfolds and who is involved must be understood to craft policy that effectively brings the batteries back into the collection points and recycling facilities of a circular LIB EoL system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

- Accardo, A., Dotelli, G., Musa, M.L., Spessa, E., 2021. Life cycle assessment of an NMC battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery. *Appl. Sci. (Switz.)* 11 (3), 1–32. <https://doi.org/10.3390/app11031160>.
- Ahmadi, L., Yip, A., Fowler, M., Young, S.B., Fraser, R.A., 2014. Environmental feasibility of re-use of electric vehicle batteries. *Sustain. Energy Technol. Assess.* 6, 64–74. <https://doi.org/10.1016/j.seta.2014.01.006>.
- Ahmadi, L., Young, S.B., Fowler, M., Fraser, R.A., Achachlouei, M.A., 2017. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* 22 (1), 111–124. <https://doi.org/10.1007/s11367-015-0959-7>.
- Ahuja, Jyoti, Dawson, L., Lee, R., 2020. A circular economy for electric vehicle batteries: driving the change. *Journal of Property, Planning and Environmental Law* 12 (3). <https://doi.org/10.1108/JPEEL-02-2020-0011>. In press.
- Ai, N., Zheng, J., Chen, W.Q., 2019. U.S. end-of-life electric vehicle batteries: dynamic inventory modeling and spatial analysis for regional solutions. *Resour. Conserv. Recycl.* 145, 208–219. <https://doi.org/10.1016/j.resconrec.2019.01.021>.
- Alfaro-Algaba, M., Ramirez, F.J., 2020. Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing. *Resour. Conserv. Recycl.* 154 <https://doi.org/10.1016/j.resconrec.2019.104461>.
- Ambrose, H., Kendall, A., 2019a. Understanding the future of lithium: part 1, resource model. *J. Ind. Ecol.* <https://doi.org/10.1111/jiec.12949>.
- Ambrose, H., Kendall, A., 2019b. Understanding the future of lithium: part 2, temporally and spatially resolved life-cycle assessment modeling. *J. Ind. Ecol.* <https://doi.org/10.1111/jiec.12942>.
- Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2020. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nat. Sustain.* 4 (1), 71–79. <https://doi.org/10.1038/s41893-020-00607-0>.
- Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. *Nat. Sustain.* 1 (9), 495–504. <https://doi.org/10.1038/s41893-018-0139-4>.
- Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A., Pfirang, A., 2018. Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. *J. Energy Storage* 19, 213–225. <https://doi.org/10.1016/j.est.2018.07.008>.
- Redwood Logistics. (2021). LTL (Less than Truckload) vs. FTL (Full Truckload) Shipping Rates. Redwood Logistics. Retrieved from <https://www.redwoodlogistics.com/ltl-less-than-truckload-vs-ftl-full-truckload-shipping-rates/> Date accessed: 4 February 2021.
- 2021 CARB. (2021). Zero-Emission Vehicle Program. California Air Resources Board. Retrieved from <https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program>. Date accessed: 25 January 2021.
- Dai, Q., Spangenberg, J., Ahmed, S., Gaines, L., Kelly, J. C., & Wang, M. (2019). EverBatt: A closed-loop battery recycling cost and environmental impacts model. Argonne National Laboratory. Retrieved from <https://publications.anl.gov/anlpubs/2019/07/153050.pdf> Date accessed: 1 July 2021.
- Casals, L.C., Amante García, B., & Canal, C. (2019). Second life batteries lifespan: rest of useful life and environmental analysis. *J. Environ. Manage.* 10.1016/j.jenvman.2018.11.046.
- Cerdas, F., Andrew, S., Thiede, S., Herrmann, C., 2018. Environmental aspects of the recycling of lithium-ion traction batteries. *Sustain. Product. Life Cycle Eng. Manag.* https://doi.org/10.1007/978-3-319-70572-9_16.
- Choubey, P.K., Chung, K.S., Kim, seuk, M., Lee chun, J., Srivastava, R.R., 2017. Advance review on the exploitation of the prominent energy-storage element Lithium. Part II: from sea water and spent lithium ion batteries (LIBs). *Miner. Eng.* 110, 104–121. <https://doi.org/10.1016/j.mineng.2017.04.008>.
- Ciez, R.E., Whitacre, J.F., 2019. Examining different recycling processes for lithium-ion batteries. *Nat. Sustain.* 2 (2), 148–156. <https://doi.org/10.1038/s41893-019-0222-5>.
- Connett, P., Chm, J.R., Connett, E., Fiedler, G., & Kowalski, M.A. (2020). NoBurnBroome Position Paper On the SungEel project Proposed For Endicott (Updated).
- Cusenza, M.A., Guarino, F., Longo, S., Ferraro, M., Cellura, M., 2019. Energy and environmental benefits of circular economy strategies: the case study of reusing used batteries from electric vehicles. *J. Energy Storage* 25. <https://doi.org/10.1016/j.est.2019.100845>.
- Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life cycle analysis of lithium-ion batteries for automotive applications. *Batteries*, 5 (2), 48. <https://doi.org/10.3390/batteries5020048>.
- Dunn, J.B., Gaines, L., Kelly, J.C., James, C., Gallagher, K.G., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ Sci* 8 (1), 158–168. <https://doi.org/10.1039/C4EE03029J>.
- Dunn, J., Slattery, M., Kendall, A., Ambrose, H., & Shen, S. (2021). Circularity of lithium-ion battery materials in electric vehicles. *Environ. Sci. Technol.* 10.1021/acs.est.0c07030.
- Fan, E., Li, L., Wang, Z., Lin, J., Huang, Y., Yao, Y., Chen, R., Wu, F., 2020. Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects. *Chem. Rev.* 120 (14), 7020–7063. <https://doi.org/10.1021/acs.chemrev.9b00535>.
- FedEx. (2021). How to Ship Batteries. Retrieved from <https://www.fedex.com/en-us/shipping/how-to-ship-batteries.html> Date accessed: April 2, 2021.
- Fletcher, S. (2013). Bottled lightning: superbatteries, electric cars, and the new lithium economy. *Choice Rev.Online.* 10.5860/choice.49-1488.
- Foster, M., Isely, P., Standridge, C.R., Hasan, M.M., 2014. Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. *J. Ind. Eng. Manag.* 7 (3), 698–715. <https://doi.org/10.3926/jiem.939>.
- Gaines, L., Richa, K., Spangenberg, J., 2018. Key issues for Li-ion battery recycling. *MRS Energy Sustain.* 5 (1) <https://doi.org/10.1557/mre.2018.13>.
- Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. *Nature* 575 (7781), 75–86. <https://doi.org/10.1038/s41586-019-1682-5>.
- Heelan, J., Gratz, E., Zheng, Z., Wang, Q., Chen, M., Apelian, D., Wang, Y., 2016. Current and prospective Li-ion battery recycling and recovery processes. *JOM* 68 (10), 2632–2638. <https://doi.org/10.1007/s11837-016-1994-y>.
- Hendrickson, T.P., Kavvada, O., Shah, N., Sathre, R., D Scown, C., 2015. Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California. *Environ. Res. Lett.* 10 (1) <https://doi.org/10.1088/1748-9326/10/1/014011>.
- Hoyer, C., Kieckhäfer, K., Spengler, T.S., 2015. Technology and capacity planning for the recycling of lithium-ion electric vehicle batteries in Germany. *J. Bus. Econ.* 85 (5), 505–544. <https://doi.org/10.1007/s11573-014-0744-2>.
- Hua, Y., Zhou, S., Huang, Y., Liu, X., Ling, H., Zhou, X., Zhang, C., Yang, S., 2020. Sustainable value chain of retired lithium-ion batteries for electric vehicles. *J. Power Source* 478 <https://doi.org/10.1016/j.jpowsour.2020.228753>.
- Huo, H., Xing, Y., Pecht, M., Züger, B.J., Khare, N., & Vezzini, A. (2017). Safety requirements for transportation of lithium batteries. *Energies* 10.3390/en10060793.
- Idjis, H., da Costa, P., 2016. Is electric vehicles battery recovery a source of cost or profit? *The Automobile Revolution: Towards a New Electro-Mobility Paradigm*. Springer International Publishing, pp. 117–134. https://doi.org/10.1007/978-3-319-45838-0_8.
- IEA. (2020). Global EV Outlook 2020. <https://www.iea.org/reports/global-ev-outlook-2020>.
- Kellner, R., Goosey, E., 2020. Chapter 9: the recycling of lithium-ion batteries: current and potential approaches. *Issue. Environ. Sci. Technol.* 49 <https://doi.org/10.1039/9781788018784-00246>.
- Kelly, J.C., Dai, Q., & Wang, M. (2019). Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitigation and Adaptation Strategies For Global Change. 10.1007/s11027-019-09869-2.
- Kumagai, J. (2021, January 5). Lithium-ion battery recycling finally takes off in North America and Europe - IEEE spectrum. *IEEE Spectr.* <https://spectrum.ieee.org/>

- energy/batteries-storage/lithiumion-battery-recycling-finally-takes-off-in-north-am-eric-and-europe.
- Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G.P., Zaghib, K., 2020. Progress and status of hydrometallurgical and direct recycling of Li-Ion batteries and beyond. *Materials* 13 (3). <https://doi.org/10.3390/ma13030801>.
- Li, L., Dababneh, F., Zhao, J., 2018. Cost-effective supply chain for electric vehicle battery remanufacturing. *Appl. Energy* 226, 277–286. <https://doi.org/10.1016/j.apenergy.2018.05.115>.
- Lv, W., Wang, Z., Cao, H., Sun, Y., Zhang, Y., & Sun, Z. (2017). A Critical Review and Analysis on the Recycling of Spent Lithium-Ion Batteries. *ACS Sustainable Chem. and Eng.* (Vol. 6, Issue 2, 1504–1521). 10.1021/acssuschemeng.7b03811.
- Ma, X., Ma, Y., Zhou, J., Xiong, S., 2018. The recycling of spent power battery: economic benefits and policy suggestions. *IOP Confer. Ser.* 159 (1), 12017. <https://doi.org/10.1088/1755-1315/159/1/012017>.
- Mathur, N., Deng, S., Singh, S., Yih, Y., Sutherland, J.W., 2019. Evaluating the environmental benefits of implementing Industrial Symbiosis to used electric vehicle batteries. *Procedia CIRP* 80, 661–666. <https://doi.org/10.1016/j.procir.2019.01.074>.
- Mayyas, A., Steward, D., Mann, M., 2019. The case for recycling: overview and challenges in the material supply chain for automotive li-ion batteries. *Sustain. Mater. Technol.* 19. <https://doi.org/10.1016/j.susmat.2018.e00087>.
- Melin, H.E. (2019). State of the art in reuse and recycling of lithium-ion batteries-A research review. Report commissioned by the Swedish Energy Agency. Retrieved from <https://www.energimyndigheten.se/globalassets/forskning-innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf>. Date accessed: 25 January 2021.
- Moore, E.A., Russell, J.D., Babbitt, C.W., Tomaszewski, B., Clark, S.S., 2020. Spatial modeling of a second-use strategy for electric vehicle batteries to improve disaster resilience and circular economy. *Resour. Conserv. Recycl.* 160. <https://doi.org/10.1016/j.resconrec.2020.104889>.
- Morello-Frosch, R., Pastor, M., Porras, C., Sadd, J., 2002. Environmental justice and regional inequality in Southern California: implications for future research. *Environ. Health Perspect.* 110 (SUPPL. 2), 149–154. <https://doi.org/10.1289/ehp.02110s2149>.
- Mossali, E., Picone, N., Gentilini, L., Rodríguez, O., Pérez, J.M., Colledani, M., 2020. Lithium-ion batteries towards circular economy: a literature review of opportunities and issues of recycling treatments. *J. Environ. Manage.* 264, 110500. <https://doi.org/10.1016/j.jenvman.2020.110500>.
- Neubauer, J.S., Wood, E., Pesaran, A., 2015. A Second life for electric vehicle batteries: answering questions on battery degradation and value. *SAE Int. J. Mater. Manuf.* 8 (2). <https://doi.org/10.4271/2015-01-1306>.
- Nordelöf, A., Poulidikou, S., Chordia, M., Bitencourt de Oliveira, F., Tivander, J., Arvidsson, R., 2019. Methodological approaches to end-of-life modelling in life cycle assessments of lithium-ion batteries. *Batteries* 5 (3), 51. <https://doi.org/10.3390/batteries5030051>.
- Olivetti, E.A., Ceder, G., Gaustad, G.G., Fu, X., 2017. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule* 1 (2), 229–243. <https://doi.org/10.1016/j.joule.2017.08.019>.
- NewsChannel 34. (2021). Update on Endicott battery recycling project. Binghamton Homepage. Retrieved from <https://www.binghamtonhomepage.com/news/update-on-endicott-battery-recycling-project/> Date accessed: 25 January 2021.
- Pipeline and Hazardous Materials Safety Administration. (2021). Electronic Code of Federal Regulations (eCFR). Retrieved from <https://www.ecfr.gov/cgi-bin/text-idx?SID=463e264d43ab547a929f96e66f1636d&mc=true&node=se49.2.173.1185&rgn=div8> Date accessed: 7 February 2021.
- Rahman, A., Afroz, R., Safrin, M., 2017. Recycling and disposal of lithium batteries: an economical and environmental approach. *IJUM Eng. J.* 18 (2), 238–252. <https://doi.org/10.31436/ijumej.v18i2.773>.
- Rajaifar, M., Heidrich, O., Ghadimi, P., Rauei, M., Wu, Y., 2020. Sustainable supply and value chains of electric vehicle batteries. *Resources, Conservation, & Recycling* 161. <https://doi.org/10.1016/j.resconrec.2020.104905>.
- Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., Amante García, B., 2019. Towards sustainable business models for electric vehicle battery second use: a critical review. *J. Environ. Manage.* 245, 432–446. <https://doi.org/10.1016/j.jenvman.2019.05.095>.
- Richa, K., Babbitt, C.W., Gaustad, G., 2017a. Eco-efficiency analysis of a lithium-ion battery waste hierarchy inspired by circular economy. *J. Ind. Ecol.* 21 (3), 715–730. <https://doi.org/10.1111/jiec.12607>.
- Richa, K., Babbitt, C.W., Nenadic, N.G., Gaustad, G., 2017b. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int. J. Life Cycle Assess.* 22 (1), 66–81. <https://doi.org/10.1007/s11367-015-0942-3>.
- Richa, Kirti, Babbitt, C.W., Gaustad, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour. Conserv. Recycl.* 83, 63–76. <https://doi.org/10.1016/j.resconrec.2013.11.008>.
- Sato, F.E.K., Nakata, T., 2020. Recoverability analysis of critical materials from electric vehicle lithium-ion batteries through a dynamic fleet-based approach for Japan. *Sustain. (Switz.)* 12 (1). <https://doi.org/10.3390/SU12010147>.
- Sato, F.E.K., Nakata, T., 2021. Analysis of electric vehicle batteries recoverability through a dynamic fleet based approach. *Sustain. Prod. Life Cycle Eng. Manag.* https://doi.org/10.1007/978-981-15-6779-7_22.
- Skeete, Jean-Paul, Wells, Peter, Dong, Xue, Heidrich, Oliver, Harper, Gavin, 2020. Beyond the Event horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. *Energy Research & Social Science* 69. <https://doi.org/10.1016/j.erss.2020.101581>. In press.
- Sun, B., Su, X., Wang, D., Zhang, L., Liu, Y., Yang, Y., Liang, H., Gong, M., Zhang, W., Jiang, J., 2020. Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China. *J. Clean. Prod.* 276. <https://doi.org/10.1016/j.jclepro.2020.123327>.
- Tang, Y., Zhang, Q., Li, Y., Wang, G., Li, Y., 2018. Recycling mechanisms and policy suggestions for spent electric vehicles' power battery -A case of Beijing. *J. Clean. Prod.* 186, 388–406. <https://doi.org/10.1016/j.jclepro.2018.03.043>.
- Thompson, D.L., Hartley, J.M., Lambert, S.M., Shiref, M., Harper, G.D.J., Kendrick, E., Anderson, P., Ryder, K.S., Gaines, L., & Abbott, A.P. (2020). The importance of design in lithium ion battery recycling-a critical review. In *Green Chemistry* (Vol. 22, Issue 22, pp. 7585–7603). Royal Society of Chemistry. 10.1039/d0gc02745f.
- US EPA. (n.d.). State Authorization under the Resource Conservation and Recovery Act (RCRA). EPA.Gov. Retrieved February 4, 2021, from <https://www.epa.gov/rcra/state-authorization-under-resource-conservation-and-recovery-act-rcra>.
- Wang, L., Wang, X., Yang, W., 2020. Optimal design of electric vehicle battery recycling network – From the perspective of electric vehicle manufacturers. *Appl. Energy* 275. <https://doi.org/10.1016/j.apenergy.2020.115328>.
- Wang, S., Yu, J., 2021. A comparative life cycle assessment on lithium-ion battery: case study on electric vehicle battery in China considering battery evolution. *Waste Manage. Res.* 39 (1), 156–164. <https://doi.org/10.1177/0734242X20966637>.
- Wang, W., Wu, Y., 2017. An overview of recycling and treatment of spent LiFePO₄ batteries in China. *Resour. Conserv. Recycl.* 127, 233–243. <https://doi.org/10.1016/j.resconrec.2017.08.019>.
- Wang, X., Gaustad, G., Babbitt, C.W., Richa, K., 2014. Economies of scale for future lithium-ion battery recycling infrastructure. *Resour. Conserv. Recycl.* 83, 53–62. <https://doi.org/10.1016/j.resconrec.2013.11.009>.
- Williams, N., & Murray, D. (2020). An Analysis of the Operational Costs of Trucking: 2020 Update. Report prepared by the American Trucking Research Institution. Retrieved from <https://truckingresearch.org/wp-content/uploads/2020/11/ATRI-Operational-Costs-of-Trucking-2020.pdf> Date accessed: 7 February 2021.
- Xiong, S., Ji, J., Ma, X., 2019a. Comparative life cycle energy and GHG emission analysis for BEVs and PHEVs: a case study in China. *Energies* 12 (5). <https://doi.org/10.3390/en12050834>.
- Zhang, W., Xu, C., He, W., Li, G., Huang, J., 2018a. A review on management of spent lithium ion batteries and strategy for resource recycling of all components from them. In: *Waste Management and Research*, 36. SAGE Publications Ltd, pp. 99–112. <https://doi.org/10.1177/0734242X17744655>.
- Zhang, X., Li, L., Fan, E., Xue, Q., Bian, Y., Wu, F., Chen, R., 2018b. Toward sustainable and systematic recycling of spent rechargeable batteries. *Chem. Soc. Rev.* 47 (19), 7239–7302. <https://doi.org/10.1039/c8cs00297e>.

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Lithium-ion battery recycling: a perspective on key challenges and opportunities



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This paper deals with a critical analysis and perspective of key challenges and opportunities in lithium-ion battery recycling. It examines technical limitations, economic constraints, and regulatory fragmentation, while also identifying opportunities through emerging technologies such as direct recycling, ultrasound-assisted leaching, and bioleaching. It also emphasizes the potential of second-life applications, eco-design integration, and policy innovation to advance a circular, sustainable, and resilient battery value chain.

Lithium-ion batteries (LIBs) are essential in modern energy storage, powering everything from electric vehicles (EVs) and stationary energy systems to portable electronics, relying on critical materials such as lithium, cobalt, nickel, and graphite. However, the latter are not only finite but also heavily concentrated in a limited number of countries, thus raising significant geopolitical and ethical concerns¹. As the world pivots toward clean energy and electric mobility, securing a sustainable supply of critical materials is urgent.

The urgency for efficient LIB recycling is underscored by the exponential growth of the EV market and large-scale renewable energy storage systems. As of 2022, the global EV fleet surpassed 30 million units and is projected to reach about 240 million by 2030². This expansion is expected to drive a corresponding surge in end-of-life (EoL) LIBs in the coming decades. While relatively few EV batteries have reached EoL to date, most current recycling activities process production scrap, estimates suggesting that over 1.2 million EV batteries will be retired annually by 2030, increasing to over 14 million per year by 2040³. Such projections signal the need for immediate action to develop scalable and robust recycling systems that can manage future battery waste volumes and recover high-value materials efficiently.

Crucially, LIB recycling not only supports circularity and environmental goals, but also represents a substantial economic opportunity⁴. The global LIB recycling market is projected to grow from USD 16.23 billion in 2024 to USD 56.87 billion by 2032, as reported by Markets and Markets⁵. Nickel, cobalt, lithium, and copper recovery can reduce the demand for expensive primary materials, enhance price stability in volatile commodity markets, and reduce reliance on politically sensitive supply chains⁴.

Reintroducing recycled materials into the supply chain reduces the carbon footprint associated with the production of new LIB batteries, which also positively impacts lifecycle decarbonization strategies in the automotive and energy sectors. This closed-loop approach, illustrated in Fig. 1, highlights the critical role of material recovery and reintegration in enhancing the sustainability and resilience of the LIB value chain.

Despite these opportunities, the sector remains constrained by significant technical, environmental, economic, and regulatory challenges. In this context, the following sections provide a critical analysis and overview of the key challenges hindering EoL LIB recycling and examine emerging innovations and policy frameworks to overcome them.

Challenges across lithium-ion battery recycling

Design and disassembly bottlenecks

Recycling EoL LIBs poses a complex set of technical, economic, environmental, and regulatory challenges. One of the main technical barriers is that LIBs were not originally designed for easy disassembly and efficient recycling. These batteries exhibit widely varied chemistries and configurations, such as nickel, manganese, cobalt (NMC), lithium iron phosphate (LFP), and lithium cobalt oxide (LCO)⁶, resulting in significant differences in cathode composition, cell design, and material purity. This complexity necessitates developing customized recycling strategies capable of handling mixed chemistries, while ensuring the selective recovery of high-value materials^{7–9}.

Apart from this complexity, the battery pack architecture is typically designed to maximize energy density and structural integrity during

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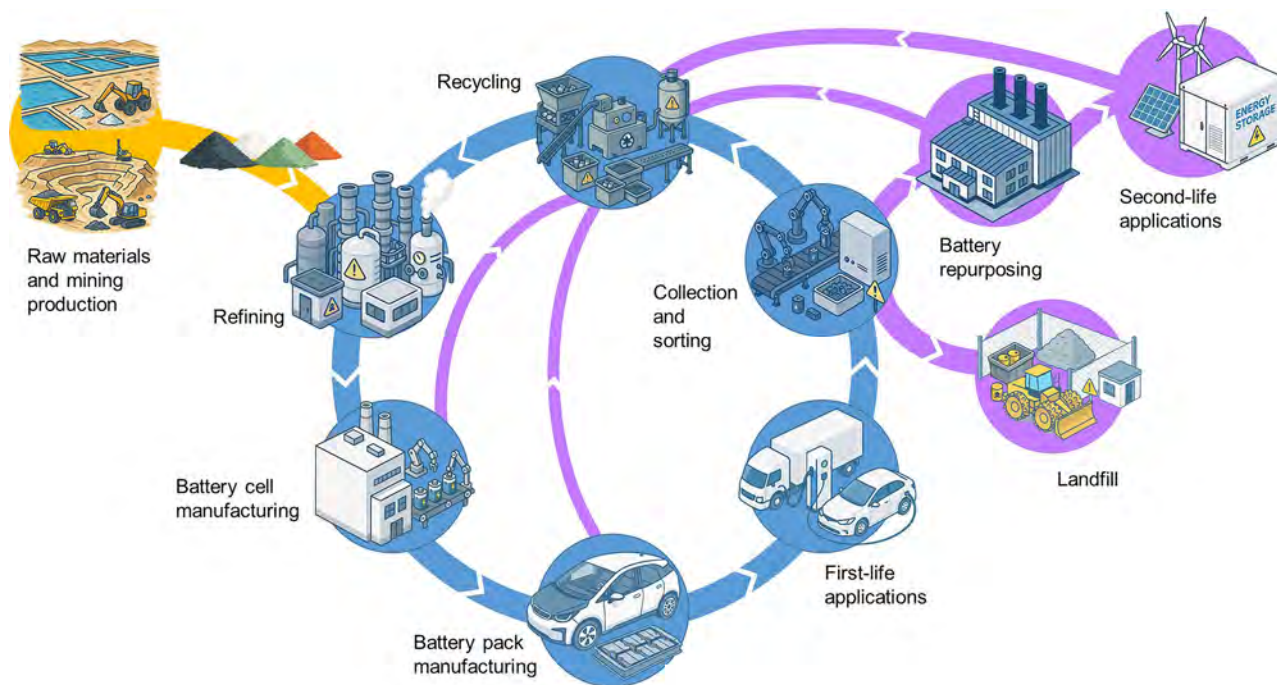


Fig. 1 | Conceptual diagram of the LIB supply chain.

operation, rather than easy disassembly^{10,11}. Cells are embedded in robust modules that incorporate mechanical reinforcements, active thermal management systems, and integrated electronics¹², improving performance but significantly complicating EoL handling. As a result, dismantling battery packs, particularly those used in EVs, is often labor-intensive, time-consuming, and potentially hazardous due to risks such as thermal runaway and fire or toxic exposure^{13–15}. The prevailing battery design approach reveals a persistent misalignment between engineering priorities and sustainability goals, as performance during use is often prioritized at the expense of EoL planning. This underscores the urgent need to embed eco-design principles such as ease of disassembly, modular construction, and material separation into battery architecture, which can reduce disassembly risks and costs, while significantly improving critical material recovery efficiency.

LIB recycling consists of three major stages: collection/sorting, disassembly/separation, and material recovery/regeneration. Each stage poses different challenges; however, recent studies agree on the view that safe disassembly and separation currently represent the most critical bottleneck requiring urgent innovation. This is the stage where technical complexity, safety hazards, and economic inefficiencies intersect most acutely. Battery packs are not designed for EoL handling. They often retain high residual charge, posing risks of short-circuits, thermal runaway, or toxic emissions during dismantling^{16,17}. Furthermore, the heterogeneity of pack designs renders manual disassembly labor-intensive, time-consuming, and costly¹⁸. Automation is still limited due to the absence of standardized pack architectures and the difficulty of designing robots able to adapt to such diverse formats. LIB disassembly is recognized as a critical bottleneck for industrial-scale recycling^{19,20}, underscoring the need for breakthroughs in robotics, automation, and design-for-disassembly approaches^{19,21,22}.

While collection systems and recovery technologies also face significant hurdles, the disassembly bottleneck uniquely constrains overall throughput. Even if 100% batteries are collected and advanced hydrometallurgical or direct recycling methods are available, little progress can be made without scalable, safe, and efficient dismantling.

Complex chemistries and process limitations

A further dimension of complexity arises from the rapid diversification of next-generation chemistries, particularly solid-state (SSBs) and lithium–sulfur (Li–S) batteries. SSBs introduce heterogeneous solid

electrolytes such as oxides, sulfides, halides, and polymers, each demanding specific recycling routes. Oxides are robust but require energy-intensive re-sintering and complex hydrometallurgical treatment under controlled moisture conditions. Sulfides are unstable in ambient environments, releasing toxic H₂S and necessitating inert atmospheres for safe handling. Halides share similarities with sulfides and may enable solvent-based direct resynthesis or reconditioning. Polymers, while safer to manage, face economic and technical barriers due to strong adhesion and low material value^{23,24}. Li–S batteries pose another set of challenges. As a relatively new and innovative system, no dedicated large-scale recycling processes have been established yet²⁵. Moreover, the absence of high-value transition metals such as cobalt or nickel reduces the economic incentive, making lithium recovery the primary focus of recycling efforts²⁶. Sulfur, while abundant, has low market value, underscoring the need for innovative strategies to repurpose or efficiently recycle the sulfur–carbon cathode material. These multifaceted challenges highlight the need for recycling frameworks that are not only flexible but also adaptive, capable of accommodating the distinct material profiles and processing demands of emerging battery chemistries.

Despite growing attention to circularity, the infrastructure supporting EoL LIB collection and reverse logistics remains critically underdeveloped in many regions^{27–29}. Furthermore, the lack of standardized labeling schemes and battery identification protocols complicates sorting LIBs by chemistry and state of health³⁰, while limited public awareness and weak economic incentives for proper disposal further exacerbate collection inefficiencies³¹. These deficiencies not only increase the likelihood of environmental and safety hazards such as uncontrolled thermal events, toxic leakage, or inappropriate hazardous waste landfilling³², but also result in the permanent loss of critical raw materials such as lithium, cobalt, and nickel, which are essential for future battery production and supply chain resilience.

To address these challenges and support a truly circular battery economy, investing not only in improved collection systems but also in the development of regionally distributed and strategically located recycling facilities is essential. Establishing recycling plants near collection centers, ports, or major mining and manufacturing corridors can significantly reduce logistics costs and associated emissions, while improving the resilience and equity of global battery supply chains. Furthermore, fostering international collaboration is essential for harmonizing standards, sharing technological know-how, and coordinating cross-border infrastructure

planning. These coordinated efforts can strengthen regional capacities for recovering strategic materials, reduce dependence on primary resource extraction, and improve the overall economic viability and environmental performance of recycling systems.

Even when batteries reach recycling facilities, technical challenges in treatment processes can significantly limit the recovery efficiency of critical raw materials. Current large-scale industrial recycling is mainly dominated by pyrometallurgical and hydrometallurgical methods, each of which has downsides^{9,33,34}.

Pyrometallurgy is a mature and widely used recycling method that involves heating shredded battery materials to 800–1200 °C under inert or vacuum conditions to recover metals like cobalt, nickel, copper, and iron as mixed alloys^{35,36}. Despite operational speed and technological robustness, pyrometallurgy presents significant limitations, including high energy demand, hazardous gaseous emission release, and the frequent loss of critical elements such as lithium and aluminum to the slag phase^{37,38}. Although partial lithium recovery is possible, pyrometallurgical processes are mainly optimized for high-value transition metals, limiting their circularity and environmental performance compared to the hydrometallurgical method³⁹.

Hydrometallurgical processes involve the chemical dissolution of EoL LIB components through leaching, typically using strong inorganic acids such as sulfuric (H_2SO_4), hydrochloric (HCl), or nitric (HNO_3) acid^{40,41}. This approach facilitates the extraction of transition metals, primarily cobalt, nickel, and manganese, from cathode materials, along with lithium, which remains in the aqueous phase as soluble salts⁴². The leachate is subsequently subjected to sequential purification steps, including solvent extraction, ion exchange, and selective precipitation to separate and recover individual high-purity metal species^{36,43}.

Compared to pyrometallurgical routes, hydrometallurgy offers several advantages, notably operation at lower temperatures, which leads to reduced energy consumption and consequently, lower greenhouse gas emissions⁴⁴. However, this process also poses significant challenges, particularly the generation of large volumes of acidic and metal-rich liquid waste requiring neutralization and, in many cases, further treatment. Therefore, careful management is essential to prevent secondary environmental impacts⁴⁵. The use of large volumes of chemical reagents increases environmental footprint and operational costs⁴⁶, raising concerns about the sustainability and economic viability of this process.

Both pyrometallurgical and hydrometallurgical processes are predominantly optimized for the selective recovery of high-value transition metals. On the other hand, a significant portion of non-metallic components present in EoL LIBs remains neglected by these conventional approaches. Graphitic carbon from anodes, fluorinated salts, and organic solvents from electrolytes, binders, and various casing materials are typically incinerated during thermal treatments or discarded during preprocessing steps^{15,47,48}. This results in the loss of materials that, while individually less valuable, collectively represent a substantial portion of the whole battery composition and its embedded environmental footprint.

Economic and regulatory constraints

Moreover, the rapid evolution of LIB chemistries poses a significant challenge for recyclers, introducing operational and economic uncertainty. As manufacturers progressively reduce or eliminate cobalt content through the transition from conventional cathode compositions such as LCO and NMC111 to high-nickel variants such as NMC811 or toward cobalt-free alternatives like LFP, the elemental composition and value distribution of EoL batteries change notoriously⁴⁹. Simultaneously, cell architecture innovations, including variations in form factors such as pouch, prismatic, and cylindrical cells, as well as the emergence of solid-state technologies, further complicate the recycling process²⁰.

Recycling processes optimized for specific chemistries, such as cobalt-rich NMC, may exhibit significantly lower recovery efficiencies or unfavorable economics when applied to low-value or compositionally distinct chemistries like LFP. This misalignment between static process design and dynamic feedstock variability may render existing recycling infrastructure

obsolete or financially unsustainable. This scenario highlights a critical challenge for ensuring that recycling infrastructure remains both technically and economically viable, given the rapid and unpredictable evolution of battery chemistries and architectures. LIB recycling systems must be capable of maintaining high recovery yields and material purity across a diverse and evolving portfolio of LIB waste.

These technical complexities are further compounded by economic constraints. Recycling profitability depends on complex and dynamic factors such as recoverable metal content, process efficiency, and metal market prices^{50,51}. High-value elements such as cobalt and nickel can often justify a recycling economy, cobalt particularly serving as a key driver due to its scarcity and high market price⁵². In contrast, lithium is relatively inexpensive on a per-weight basis and more technically challenging to extract from spent cells, making recovery less economically attractive under current conditions. Similarly, manganese and graphite hold low market value as commodities⁵³, i.e., their recovery may not be economically viable unless driven by regulatory requirements or significant shifts in market prices. Reported costs indicate that hydrometallurgy operates at about 1.3 USD per kilogram of processed battery, pyrometallurgy at 2.4 USD per kilogram due to its higher energy intensity⁵⁴. Profitability analyses reveal wide variation. Margins range from 0.4 to 3.3 USD per kilogram for hydrometallurgy, and 0.5 to 4.0 USD per kilogram for pyrometallurgy, depending on process conditions and recovered products⁵⁵. Break-even thresholds further highlight these contrasts, with hydrometallurgy viable at 7000 tons per year and pyrometallurgy at 17,000 tons per year⁵⁶.

Raw material price volatility introduces additional risks. When virgin nickel or lithium prices decrease due to oversupply or new mine opening, recycled materials may lose market competitiveness⁵⁷. Recent market trends highlight the economic fragility of lithium recycling and its sensitivity to fluctuations in primary material costs. The rapid expansion of new lithium mining projects, along with a temporary oversupply of lithium compounds, triggers a notable lithium price decline. However, this situation may prove transitory, as the accelerating demand for lithium is expected to rebalance the market, as noted by Xia & Du⁵⁸. These unfavorable market dynamics can erode the profit margins of recycling operations and act as a disincentive for further investment in the sector.

Additionally, in the current nascent stage of the industry, economies of scale are only just being realized. Many facilities are operating below capacity due to the still limited volume of EoL EV batteries^{15,59}, as most EVs sold over the past decade are only now reaching the end of their service life. Recycling companies expanded their capacity in anticipation of increasing volumes of EoL batteries. According to the International Energy Agency, LIB global recycling capacity currently stands at approximately 2 million metric tons per year⁶⁰. By 2030, more than half of EoL LIBs are projected to originate from EVs, contributing to an estimated 1.6 million tons of total LIB waste⁶¹. Consequently, in the short term, a significant portion of this recycling capacity will remain underutilized. Operating below design throughput not only increases per-unit processing costs but also undermines the economic viability of recycling operations.

To enhance recycling efficiency, numerous countries and regions implemented new policies and regulations, underscoring a growing global commitment to sustainable resource management and environmental protection⁶². Leading economies such as the European Union and China implemented increasingly comprehensive and enforceable regulatory frameworks for battery recycling, including Extended Producer Responsibility (EPR) schemes, minimum material recovery targets, and traceability mechanisms^{62,63}. In contrast, many other regions are nonexistent or still in early developmental stages, lacking mandatory targets, formalized infrastructure, or clear accountability mechanisms, thus contributing to a fragmented and uneven global regulatory landscape. Furthermore, legal definition divergences, particularly EoL LIB classification as hazardous waste, significantly avoid establishing efficient international recycling supply chains^{62,64}, as such classifications often subject batteries to stringent cross-border transport regulations, creating administrative and

Fig. 2 | Key challenges and opportunities in lithium-ion battery recycling.



logistical barriers that may delay shipments, increase costs, and ultimately discourage multinational investment in centralized or large-scale recycling hubs⁶⁵.

The combined impact of technical complexity, limited economic viability, and regulatory fragmentation continues to constrain the effective recovery of critical materials from EoL LIBs. Current recycling efforts tend to prioritize high-value metals under favorable market conditions, but often neglect lower-value components due to process limitations or cost inefficiencies. As a result, only a small proportion of LIBs are recycled through formal channels, while the majority are stockpiled, landfilled, or processed in informal sectors with little environmental oversight. These challenges are synthesized in Fig. 2, which highlights the main technical, economic, social, and regulatory bottlenecks hindering LIB recycling.

Based on experiences from informal e-waste recycling in developing countries, where rudimentary methods such as manual dismantling, acid leaching, and open burning are performed under uncontrolled conditions, similar challenges are expected for EoL LIBs^{27,32,66}. Similar risks could emerge in the context of LIB recycling if EoL batteries are processed outside formal and regulated systems. Moreover, informal e-waste hubs often develop near residential areas, raising community concerns over environmental contamination, air quality, and water pollution⁶⁷. These cases highlight the need for early community engagement and transparent governance when siting LIB recycling facilities^{67–69}. Finally, experiences from e-waste also show that transitioning informal workers into safer and formalized recycling systems requires substantial investment in reskilling and upskilling programs and social safety nets. Without these, marginalized labor forces risk exclusion from the value chain, undermining the principles of a just transition.

This fragmented and suboptimal recovery landscape undermines not only the sustainability narrative of battery-based technologies but also the long-term viability of electromobility and renewable energy systems depending on a secure and circular supply of critical materials. The inability to effectively recover and reintegrate key elements such as lithium, cobalt, and nickel threatens to exacerbate resource scarcity, increase dependence on primary extraction, and ultimately compromise the environmental and economic benefits that EVs and clean energy technologies are meant to deliver.

Addressing these bottlenecks requires not only advances in recycling technologies capable of handling mixed chemistries and evolving battery designs, but also robust policy interventions to harmonize EoL management standards, incentivize circular practices, and ensure traceability across the battery value chain. Without systemic reform and coordinated innovation, the goal of closing the materials loop remains largely aspirational.

Opportunities through innovation and policy

Emerging recycling technologies and second-life pathways

In addition to conventional pyrometallurgical and hydrometallurgical routes, various emerging technologies are being explored to improve recovery efficiency and reduce the environmental footprint of LIB recycling processes (Fig. 3). For instance, direct recycling approaches are designed to preserve and refurbish active materials inside batteries, particularly cathode powders, without fully decomposing them into their elemental constituents. Rather than extracting metals in pure forms, these methods aim to restore the electrochemical functionality of cathode materials, enabling direct reuse in new LIB fabrication^{70,71}. Such a method avoids the need for high-temperature or acid-intensive processes, which are typical in pyrometallurgical and hydrometallurgical methods, thereby minimizing secondary waste and greenhouse gas emissions. Another key advantage lies in the potential cost savings and resource efficiency, as bypassing the full re-synthesis of cathode materials allows direct recycling to reduce the demand for virgin raw materials such as lithium, cobalt, and nickel, which is particularly relevant in the context of growing supply chain vulnerabilities and critical material shortages. Nonetheless, direct recycling is critically constrained by feedstock heterogeneity since variations in chemistry, as well as different cell form factors, require chemistry-specific regeneration pathways and additives complicating both standardization and process economics^{72,73}. Another key challenge is the difficulty of selective delamination, where recovering intact cathode powder without contamination from current collectors, PVDF binders, or electrolyte residues remains unresolved at scale, even by using greener solvents, thereby affecting purity and electrochemical performance^{71,74}. Reproducible relithiation and the restoration of stoichiometry, crystallinity, morphology, and particle size distribution are necessary to achieve commercial-grade performance; however, this requires precise reactivation control and robust re-qualification protocols still under development^{75,76}. Overall, despite promising laboratory demonstrations, direct recycling remains at an early to intermediate TRL.

Considerable efforts are also devoted to advancing hydrometallurgical processes for LIB recycling. Among these innovations, ultrasound-assisted leaching gained increasing attention as a promising technique to enhance metal recovery from spent cathode materials. The application of power ultrasound induces cavitation phenomena that produce localized high temperatures and pressures, generating physical effects such as microjets and shock waves, disrupting particle agglomerates and enhancing solid–liquid interactions. According to Tong et al., ultrasound not only accelerates leaching kinetics and improves metal extraction efficiency, but also reduces reaction times and activation energy⁷⁷. Recent studies show that acoustic cavitation significantly accelerates Li, Co, and Ni dissolution and allows using milder organic acids, reducing reaction times by more than

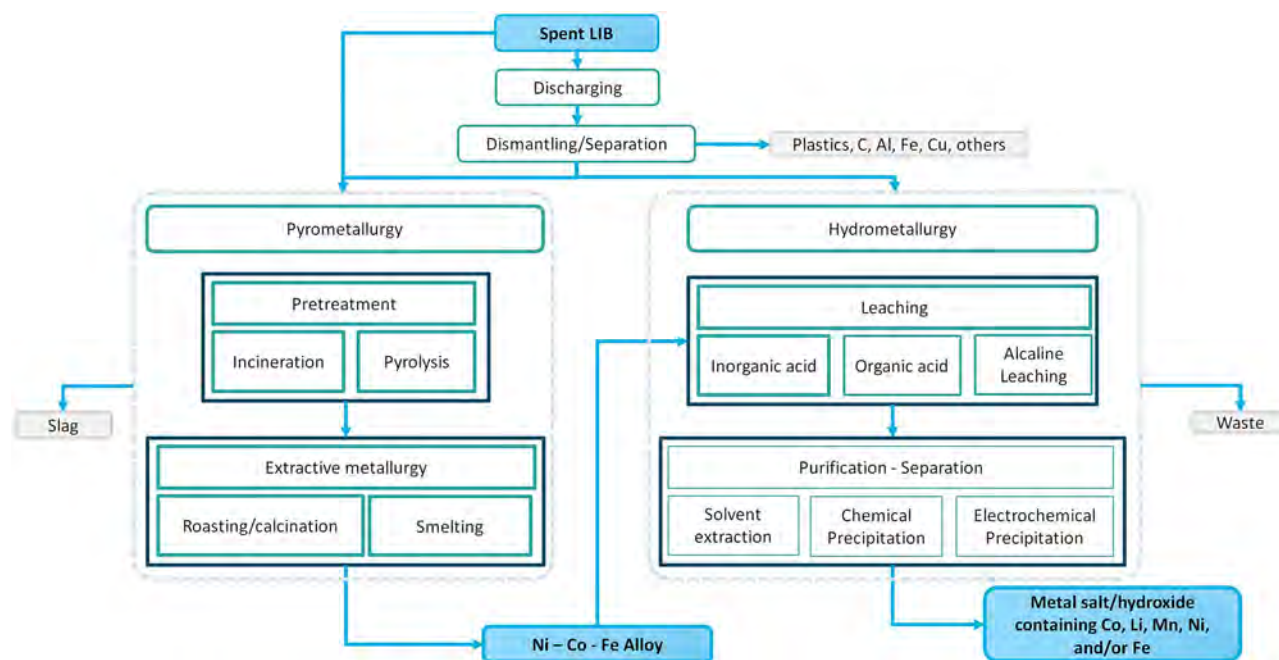


Fig. 3 | Emerging technologies for critical materials recovery via spent-LIB recycling processes (Milián et al.⁹).

50%^{77,78}. However, the main bottleneck is scale-up: delivering homogeneous ultrasonic energy in large reactors, managing cavitation erosion, and demonstrating a positive energy balance compared to conventional agitation^{79,80}. Reported applications remain confined to experimental settings, reflecting an early stage of technological maturity and the absence of commercial deployments.

Organic acids in hydrometallurgical recycling processes offer another promising approach to improve the sustainability and environmental performance of LIB recycling. Organic acids such as citric, malic, and ascorbic acid offer several advantages over traditional inorganic acids, including lower corrosivity, biodegradability, and reduced generation of hazardous byproducts^{81,82}. These acids can act as both leaching and complexing agents, enabling efficient dissolution of valuable metals like lithium, cobalt, and nickel under milder conditions. Importantly, the use of organic acids helps reduce the overall carbon footprint of the recycling process, as it avoids intensive energy demands and greenhouse gas emissions typically associated with the production and use of strong inorganic acids such as sulfuric or hydrochloric acid. Furthermore, many organic acids can be sourced from renewable biomass, adding a circular bioeconomic dimension that enhances resource sustainability and supports the integration of LIB recycling into low-carbon industrial systems. This approach aligns with the broader adoption of environmentally benign solvent systems such as ionic liquids, deep eutectic solvents, and supercritical fluids, which are being increasingly explored for the recovery of cathode materials from EoL LIBs in efficient and sustainable ways^{83–85}.

An alternative approach involves the development of acid-free salt-leaching methods, which further expand the toolkit of environmentally friendly recycling technologies. Dai et al. demonstrated that the use of ferrous sulfate as a leaching agent and ferric sulfate as a precipitating agent enables the efficient recovery of metals from spent NMC cathodes, achieving recovery rates above 96% without the need for any organic or inorganic acid⁸⁶. This method not only simplifies chemical input requirements but also mitigates common operational challenges such as equipment corrosion and toxic gas release associated with acid-based systems. As such, acid-free salt-leaching makes up a cleaner and potentially safer alternative, reinforcing the transition toward more sustainable and less hazardous LIB recycling processes.

Electrodialysis (ED) is emerging as a promising electrochemical technique for the selective recovery of lithium and other critical metals from

complex leachates produced during LIB recycling. For example, González et al. designed and evaluated a sequential ED process that enables the stepwise removal of divalent cations such as Mg^{2+} and Ca^{2+} , followed by the selective isolation of Li^+ , Na^+ , and K^+ ⁸⁷. These approaches underscore the potential of ED as a low-reagent, low-emission separation technology. It reduces chemical inputs and can yield high-purity lithium carbonate; however, membrane fouling, high investment costs, and selectivity limitations in mixed-metal streams remain significant barriers^{87,88}. Despite these challenges, ED benefits from modularity and industrial precedents in other sectors, placing it closer to pilot demonstration than most emerging alternatives.

Bioleaching emerged as a promising alternative employing specific microorganisms or their metabolic byproducts to solubilize metal ions from shredded battery waste^{89,90}. Unlike conventional leaching methods requiring high temperatures and concentrated acids, bioleaching operates under ambient conditions and can substantially decrease hazardous chemical consumption, offering a more sustainable and selective approach to metal extraction^{91,92}. Despite these advantages, bioleaching faces significant challenges, including very slow kinetics and the instability of microbial consortia exposed to high metal concentrations^{93,94}. Low pulp densities, which translate into high liquid volumes and low throughput, are often required, making large-scale adoption difficult^{94,95}. While laboratory studies show >90% Li and Co extraction, the TRL remains low, and industrial feasibility depends on advances in microbial engineering and bioreactor design^{76,95}.

Apart from bioleaching, other complementary microbial strategies are explored to further enhance the recycling process's sustainability. These include biosorption and bioaccumulation for capturing dissolved metals from leachates, bioprecipitation for recovering metals in solid form, bioelectrolysis for electrochemical recovery, and even the biofabrication of electrode materials for new battery production⁹⁶, collectively pointing to a future where biologically integrated systems could close the LIB recycling loop.

While a growing body of research demonstrates the technical feasibility and promise of emerging recycling processes such as bioleaching and direct cathode regeneration, their transition to industrial-scale deployment remains markedly slow. This perspective argues that accelerating the maturation of these innovations requires coordinated and proactive measures. The latter includes reducing scale-up risks, securing sustained public and private funding for pilot and demonstration projects, and fostering

stronger collaboration between academia, industry, and regulatory bodies. Crucially, policy frameworks must evolve in parallel with technological developments, anticipating innovation rather than reacting to it, so as to enable timely and effective commercialization.

It must be recognized that the development of emerging battery recycling technologies cannot be confined to proof-of-concept validation and technical optimization alone. While laboratory-scale successes are necessary milestones, they offer a limited view of the real-world feasibility and sustainability of these processes. A comprehensive evaluation framework integrating environmental assessments through life cycle analysis (LCA) is required, alongside techno-economic evaluations to determine scalability and market competitiveness. Equally important is the inclusion of social impact assessments to address issues such as labor conditions, health and safety, and equitable access to technological benefits. The absence of such multidimensional scrutiny puts at a significant risk seemingly promising solutions that may prove to be environmentally detrimental, economically unsustainable, or socially inequitable when deployed at scale.

Another opportunity lies in battery second-life applications, which, while not recycling per se, form a complementary strategy in the circular economy^{89,97}. Before a battery is recycled for materials, it can often be reused or repurposed once it is no longer fit for high-performance use in vehicles. For instance, many EV batteries still retain 70–80% of their capacity after their automotive life^{14,98,99}. These batteries can be aggregated and redeployed for less demanding applications such as stationary energy storage, including renewable solar or wind energy storage, backup power provision, or electricity grid stabilization^{99–101}. Utilizing retired EV packs as stationary storage defers their entry into the recycling stream by several years and extracts additional value from the manufactured battery, thereby extending the overall lifecycle of battery materials^{99,102}. This relieves some immediate pressure on recycling facilities and reduces the need for new storage batteries to be manufactured.

Second-life batteries face their own challenges, including uncertainties about their remaining lifespan, the absence of standardized evaluation protocols, and safety concerns^{27,103}. Each battery retired from a vehicle has a unique usage history and state of health, and testing them for reuse may be time-consuming¹⁰⁴. However, as frameworks for assessing and certifying used batteries continue to evolve, second-life applications are expected to expand. Importantly, second-life use is not the final stage; after serving their secondary purpose, these batteries still need to be recycled. Therefore, investments in second-life strategies do not replace recycling but rather complement it by maximizing the overall value throughout the battery lifecycle. These technological advances and second-life strategies, together with the challenges they address, are synthesized in Fig. 2.

Policy and regional opportunities

Another critical area of opportunity lies in policy and regulatory support, which has accelerated in recent years, as highlighted by the International Energy Agency¹⁰⁵. For instance, the EU has taken a leading role through Battery Regulation (EU) 2023/1542, a binding framework that standardizes targets across member states. It promotes sustainability by mandating minimum levels of recycled content, setting ambitious recovery targets for key materials such as lithium, cobalt, nickel, and copper, while introducing digital battery passports to enhance traceability and accountability throughout the battery lifecycle⁶².

In China, the world's largest EV market, early fragmented efforts evolved into a comprehensive regulatory system centered on EPR, digital traceability, and standardized recycling practices. Key milestones include the 2018 Interim Measures for battery take-back, and more recently, the 2023 draft regulation aiming to formalize full lifecycle management, with clearer role allocation and stronger enforcement mechanisms^{62,106}.

The United States, while lacking a single federal policy, made substantial progress through a mix of national legislation and state-level initiatives. Laws such as the Infrastructure Investment and Jobs Act (2021) and the Inflation Reduction Act (2022) provide significant funding to scale domestic recycling infrastructure and foster innovation. States like

California implemented EPR frameworks, requiring manufacturers to take responsibility for EoL battery collection and processing⁶². Despite ongoing regulatory fragmentation, these combined actions reflect a growing commitment to enable a circular battery economy and secure access to critical raw materials.

Although no universally accepted framework has yet been established for second-life applications, notable progress has been achieved in recent years. The International Electrotechnical Commission (IEC) published IEC 63330-1:2024 and IEC 63338:2024, setting out general requirements and guidance for evaluating second-life batteries, while the IEEE Standards Association recently approved IEEE 2993–2025, addressing their integration into stationary storage applications. In the United States, UL 1974 provides voluntary guidelines for assessing the safety and performance of second-life battery systems to determine their suitability for repurposing. In parallel, the EU Battery Regulation 2023/1542 mandates that batteries retired from EVs or other uses must be evaluated before deployment in second-life applications. This regulation includes specific requirements for state-of-health (SoH) and safety assessments. Since 2027, batteries with capacities over 2 kWh will be required to carry a battery digital passport documenting their history, condition, and recycled content, thereby enhancing reuse and traceability. China has gone further by introducing mandatory certification schemes and national standards (e.g., GB 40165–2021). China has also advanced a comprehensive regulatory approach, introducing a national battery management platform to ensure full lifecycle traceability and publishing standards such as GB/T 34013–2017 and GB/T 34014–2017, establishing strict technical specifications and coding systems for EV batteries. These measures, complemented by industry-led guidelines from organizations like China Electricity Council (CEC) and China Energy Storage Alliance (CNESA), promote standardization, safe reuse, and integration of second-life batteries into energy storage systems¹⁰⁷.

The emergence of robust regulatory frameworks in key economies represents a foundational shift toward institutionalizing circularity in the battery sector. These developments also reveal persistent asymmetries in global regulatory readiness, coordination, and enforcement capacity. While ambitious policies in the EU, China, and the US provide a roadmap for circular battery governance, their impact will depend on harmonizing standards across jurisdictions, addressing transboundary waste regulations, and fostering compliance in less-regulated markets. A particularly promising tool is the digital battery passport, which can serve as a universal data carrier for composition, lifecycle emissions, and state-of-health, ensuring interoperability and transparency across borders¹⁰⁸. Developing standardized metrics for carbon accounting, recovery efficiency, and traceability is not only essential for consistent benchmarking across markets, but it also represents a necessary step toward building a transparent and credible global LIB recycling system. Furthermore, the global diffusion of best practices, such as extended producer responsibility and eco-design for recyclability, would help align responsibilities across producers while minimizing the risk of exporting EoL batteries to less regulated regions. In addition, international collaboration and capacity-building initiatives are necessary to address asymmetries between highly regulated economies and emerging markets, ensuring that the minimum baseline of environmental and social performance is upheld worldwide. Ultimately, global harmonization should be seen not only as regulatory convergence but also as a strategic enabler of technological innovation, resilient supply chains, and sustainable circularity in the battery sector.

In Latin America, the accelerating deployment of EVs and renewable energy infrastructure creates a critical window of opportunity to establish regionally integrated LIB recycling ecosystems. Despite holding a substantial share of the world's lithium reserves, countries such as Chile, Argentina, and Bolivia remain largely peripheral to the high-value stages of the battery value chain, including recycling and materials recovery. This disconnection underscores a broader geographic and economic asymmetry limiting regional value capture and exacerbating dependency on external supply chains. To close this gap, it is essential to strengthen regulatory frameworks, develop financial and institutional incentives, and invest in

infrastructure supporting both formal collection systems and advanced recycling technologies. Without targeted policy action, the region risks replicating extractive models that externalize environmental burdens while forgoing strategic opportunities for industrial diversification and technological upgrading. Advancing LIB recycling in Latin America is therefore not only an environmental imperative but also a pathway to enhance economic resilience, regional autonomy, and equitable participation in the global energy transition.

Substantial opportunities that can help close the loop for LIB materials are on the horizon. Stronger policies are creating a favorable environment for recycling investments and ensuring that economic signals align with sustainability goals. The rapid expansion of industrial capacity and expertise means that the practical know-how for large-scale recycling is growing and that interim solutions like second-life usage extend the utility of batteries, improving the economy of the overall lifecycle. These trends, coupled with the expected influx of EoL batteries, underscore that we are at a tipping point. With continued innovation and supportive policy, the vision of a closed-loop battery economy, where critical materials are continually reclaimed and reused, is increasingly within closer reach.

Concluding remarks

Transition to circular economy in batteries is critical from an environmental perspective and also a strategic necessity to secure critical raw materials such as lithium, cobalt, and nickel, which are necessary to support electromobility. As EV adoption accelerates and energy storage needs expand, the volume of EoL LIBs will increase dramatically, requiring robust recycling systems. However, current processes are still being optimized for specific chemistries and market conditions, limiting their adaptability and scalability. To avoid resource bottlenecks and environmental setbacks, aligning improved process circularity from battery design, improving recycling technology sustainability, and implementing supply chain strategies following circularity principles are essential.

Emerging technologies, such as direct recycling and new approaches to hydrometallurgical processes, represent a promising shift toward cleaner, more efficient, and selective recycling processes. While still at early stages, these innovations offer the potential to overcome the limitations of conventional pyrometallurgy and hydrometallurgy. Yet, their large-scale implementation will depend on breakthroughs in scalability, integration with upstream and downstream processes, and favorable economic conditions supported by public and private investment. Ensuring their sustainable deployment will also require comprehensive evaluations, including life cycle assessments to quantify environmental impacts, alongside techno-economic and social impact analyses.

Policy frameworks will play a pivotal role in shaping the future of LIB recycling. Regulatory leadership from the EU, China, and the US is setting valuable precedents, but global harmonization remains fragmented. To fully realize the benefits of a closed-loop system, international coordination is needed to standardize definitions, ensure traceability, and support infrastructure development. Ultimately, only through synchronized efforts across technology, policy, and industry can a truly sustainable and resilient battery value chain be established.

Data availability

No datasets were generated or analyzed during the current study.

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References

- Pol, V. G. Lithium-ion battery critical materials sustainability. *ACS Energy Lett.* **10**, 2553–2558 (2025).
- International Energy Agency. *Global EV Outlook 2023: Catching up with climate ambitions*. www.iea.org (2023).
- Tankou, A., Bieker, G. & Hall, D. Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches. in *Proc. ICCT* 1–138 (2023).
- Zhang, B. et al. Lithium-ion battery recycling relieves the threat to material scarcity amid China's electric vehicle ambitions. *Nat. Commun.* **16**, 6661 (2025).
- Markets and Markets. Lithium-ion Battery Recycling Market. [https://www.marketsandmarkets.com/Market-Reports/lithium-ion-battery-recycling-market-153488928.html#:~:text=The global lithium-ion battery,%2C power%2C and other sources \(2024\).](https://www.marketsandmarkets.com/Market-Reports/lithium-ion-battery-recycling-market-153488928.html#:~:text=The global lithium-ion battery,%2C power%2C and other sources (2024).)
- Dash, R., Kommu, P. & Bhattacharyya, A. S. Electrode Materials in Lithium-Ion Batteries. in *Energy Materials: Structure, Properties and Applications* 77–89 (Springer, 2023).
- Sharmili, N., Nagi, R. & Wang, P. A review of research in the Li-ion battery production and reverse supply chains. *J. Energy Storage* **68**, 107622 (2023).
- Miao, Y., Liu, L., Zhang, Y., Tan, Q. & Li, J. An overview of global power lithium-ion batteries and associated critical metal recycling. *J. Hazard. Mater.* **425**, 127900 (2022).
- Milian, Y. E., Jamett, N., Cruz, C., Herrera-León, S. & Chacana-Olivares, J. A comprehensive review of emerging technologies for recycling spent lithium-ion batteries. *Sci. Total Environ.* **910**, 168543 (2024).
- Lander, L. et al. Breaking it down: a techno-economic assessment of the impact of battery pack design on disassembly costs. *Appl. Energy* **331**, 120437 (2023).
- Quarti, M., Bayer, A. & Bessler, W. G. Trade-off between energy density and fast-charge capability of lithium-ion batteries: a model-based design study of cells with thick electrodes. *Electrochem. Sci. Adv.* **3**, e2100161 (2023).
- Osmani, K. et al. Recent progress in the thermal management of lithium-ion batteries. *J. Clean. Prod.* **389**, 136024 (2023).
- Choux, M., Pripp, S. W., Kvalnes, F. & Hellström, M. To shred or to disassemble—a techno-economic assessment of automated disassembly vs. shredding in lithium-ion battery module recycling. *Resour. Conserv. Recycl.* **203**, 107430 (2024).
- Zhu, J. et al. Global regulations for sustainable battery recycling: challenges and opportunities. *Sustainability* **2**, 3045 (2021).
- Tembo, P. M. et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **16**, 43 (2025).
- Garg, N. et al. Advancements of lithium-ion battery Recycling: Transitioning from traditional methods to AI and machine learning techniques. *Front. Robot. AI* **11**, 1179296 (2024).
- Maghsoudi, R. et al. Advantages, Limitations, and Industrial Applications of Lithium-Ion batteries. *Nanostruct. Mater. Energy Storage* **2**, 793–820 (2024).
- Beghi, M., Braghin, F. & Roveda, L. Enhancing disassembly practices for electric vehicle battery packs: a narrative comprehensive review. *Designs* **7**, 109 (2023).
- Meng, K., Xu, G., Peng, X., Youcef-Toumi, K. & Li, J. Intelligent disassembly of electric-vehicle batteries: a forward-looking overview. *Resour. Conserv. Recycl.* **182**, 106207 (2022).
- Rehman, S., Al-Greer, M., Burn, A. S., Short, M. & Cui, X. High-volume battery recycling: technical review of challenges and future directions. *Batteries* **11**, 94 (2025).
- Hathaway, J. et al. Towards reuse and recycling of lithium-ion batteries: tele-robotics for disassembly of electric vehicle batteries. *Front. Robot. AI* **10**, 1179296 (2023).
- Korde, V. B. et al. Advancements of lithium-ion battery recycling: transitioning from traditional methods to AI and machine learning techniques. *Renew. Sustain. Energy Rev.* **225**, 116180 (2026).
- Ahuis, M. et al. Recycling of solid-state batteries. *Nat. Energy* **9**, 373–385 (2024).

24. Jacob, M., Wissel, K. & Clemens, O. Recycling of solid-state batteries—challenge and opportunity for a circular economy?. *Mater. Futur.* **3**, 12101 (2024).
25. Faraji, F., Khanlarian, M., Roshanfar, M., Alvial-Hein, G. & Mahandra, H. Recyclability and recycling technologies for lithium–sulfur batteries. *Lithium-Sulfur Batter.* 627–651. <https://doi.org/10.1016/B978-0-323-91934-0.00014-4> (2022).
26. Schwich, L., Sabarny, P. & Friedrich, B. Recycling potential of lithium–sulfur batteries—a first concept using thermal and hydrometallurgical methods. *Metals* **10**, 1513 (2020).
27. Chen, Z., Yildizbasi, A., Wang, Y. & Sarkis, J. Safety concerns for the management of end-of-life lithium-ion batteries. *Glob. Chall.* **6**, 2200049 (2022).
28. Wang, H. et al. China’s electric vehicle and climate ambitions jeopardized by surging critical material prices. *Nat. Commun.* **14**, 1246 (2023).
29. Ali, A., Shoaib, A., Tasbirul, I. M., Qadir, S. A. & Shahid, M. Sustainable recycling of end-of-life electric vehicle batteries: ev battery recycling frameworks in China and the USA. *Recycling* **10**, 68 (2025).
30. Zorn, M. et al. An approach for automated disassembly of lithium-ion battery packs and high-quality recycling using computer vision, labeling, and material characterization. *Recycling* **7**, 48 (2022).
31. Zeng, J. & Liu, S. Research on recycling benefits of spent lithium batteries with parameter uncertain: application to adjust incentive policy. *J. Energy Storage* **74**, 109314 (2023).
32. Mrozik, W., Rajaeifar, M. A., Heidrich, O. & Christensen, P. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy Environ. Sci.* **14**, 6099–6121 (2021).
33. Reinhart, L. et al. Pyrometallurgical recycling of different lithium-ion battery cell systems: Economic and technical analysis. *J. Clean. Prod.* **416**, 137834 (2023).
34. Ma, X. et al. The evolution of lithium-ion battery recycling. *Nat. Rev. Clean. Technol.* **1**, 75–94 (2025).
35. Baum, Z. J., Bird, R. E., Yu, X. & Ma, J. Lithium-ion battery recycling—overview of techniques and trends. *ACS Energy Lett.* **7**, 712–719 (2022).
36. Lim, J. et al. Hydrometallurgical process of spent lithium-ion battery recycling Part. 2 recovery of valuable metals from the cathode active material leachates: review and cost analysis. *Hydrometallurgy* <https://doi.org/10.1016/j.hydromet.2025.106516> (2025).
37. Chen, M. et al. Recycling end-of-life electric vehicle lithium-ion batteries. *Joule* **3**, 2622–2646 (2019).
38. Zhou, L.-F., Yang, D., Du, T., Gong, H. & Luo, W.-B. The current process for the recycling of spent lithium ion batteries. *Front. Chem.* **8**, 578044 (2020).
39. Windisch-Kern, S., Holzer, A., Ponak, C. & Raupenstrauch, H. Pyrometallurgical lithium-ion-battery recycling: approach to limiting lithium slagging with the InduRed reactor concept. *Processes* **9**, 84 (2021).
40. Wang, J. & Guo, Z. Hydrometallurgically recycling spent lithium-ion batteries. in *Recycling of Spent Lithium-Ion Batteries: Processing Methods and Environmental Impacts* 27–55 (Springer, 2019).
41. Wu, J. et al. Recent advancements in hydrometallurgical recycling technologies of spent lithium-ion battery cathode materials. *Rare Met.* **43**, 879–899 (2024).
42. Chan, K. H., Anawati, J., Malik, M. & Azimi, G. Closed-loop recycling of lithium, cobalt, nickel, and manganese from waste lithium-ion batteries of electric vehicles. *ACS Sustain. Chem. Eng.* **9**, 4398–4410 (2021).
43. Shih, Y.-J., Chien, S.-K., Jhang, S.-R. & Lin, Y.-C. Chemical leaching, precipitation and solvent extraction for sequential separation of valuable metals in cathode material of spent lithium ion batteries. *J. Taiwan Inst. Chem. Eng.* **100**, 151–159 (2019).
44. Brückner, L., Frank, J. & Elwert, T. Industrial recycling of lithium-ion batteries—a critical review of metallurgical process routes. *Metals* **10**, 1107 (2020).
45. Bhattacharyya, S., Vidal, R., Alhashim, S. H., Chen, X. & Ajayan, P. M. Comparative assessment & environmental impacts of lixiviants for hydrometallurgical lithium-ion battery recycling. *Adv. Energy Mater.* <https://doi.org/10.1002/aenm.202405348> (2025).
46. Chen, Q. et al. Comparative environmental impacts of different hydrometallurgical recycling and remanufacturing technologies of lithium-ion batteries considering multi-recycling-approach and temporal-geographical scenarios in China. *Sep. Purif. Technol.* **324**, 124642 (2023).
47. Badenhurst, C. et al. Recovery of graphite from spent lithium-ion batteries. *Recycling* **8**, 79 (2023).
48. Lo Sardo, C., Cacciatore, G., Cappuccino, G., Aiello, D. & Napoli, A. Spent lithium battery recycling: traditional and innovative approaches. *Processes* **13**, 950 (2025).
49. Zeng, A. et al. Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nat. Commun.* **13**, 1341 (2022).
50. Yu, X. et al. Current challenges in efficient lithium-ion batteries’ recycling: a perspective. *Glob. Chall.* **6**, 2200099 (2022).
51. Almahri, R. & An, H. Evaluating economic and environmental viability of recycling lithium-ion battery for electric vehicles in the middle east: a case study in the UAE. *Humanit. Soc. Sci. Commun.* **12**, 1–11 (2025).
52. Gourley, S. W. D., Or, T. & Chen, Z. Breaking free from cobalt reliance in lithium-ion batteries. *Iscience* **23**, 101505 (2020).
53. Gong, S. et al. Sustainable upcycling of spent graphite anodes via concentrated sulfuric acid. *Small* <https://doi.org/10.1002/smll.202503988> (2025).
54. Vinayak, A. K., Xu, Z., Li, G. & Wang, X. Current trends in sourcing, recycling, and regeneration of spent lithium-ion batteries—a review. *Renewables* **1**, 294–315 (2023).
55. Schlott, L., Gutsch, M. & Leker, J. Cost modelling and key drivers in lithium-ion battery recycling. *Nat. Rev. Clean Technol.* **1**, 656 (2025).
56. Lander, L. et al. Financial viability of electric vehicle lithium-ion battery recycling. *Iscience* **24**, 102787 (2021).
57. Gutsch, M. & Leker, J. Costs, carbon footprint, and environmental impacts of lithium-ion batteries—from cathode active material synthesis to cell manufacturing and recycling. *Appl. Energy* **353**, 122132 (2024).
58. Xia, Q., Månberger, A. & Du, D. Long on expectations, short on supply: regional lithium imbalances and the effects of trade allocations by China, the EU, and the USA. *Cell Rep. Sustain.* **2**, 100404 (2025).
59. Harper, G. et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **575**, 75–86 (2019).
60. International Energy Agency. *Batteries and Secure Energy Transitions*. IEA <https://www.iea.org/reports/batteries-and-secure-energy-transitions> (2024).
61. Moisé, E. & Rubínová, S. *Trade policies to promote the circular economy: A Case Study of Lithium-Ion Batteries*. <https://doi.org/10.1787/d75a7f46-en> (2023).
62. Su, D., Mei, Y., Liu, T. & Amine, K. Global regulations for sustainable battery recycling: challenges and opportunities. *Sustainability* **17**, 3045 (2025).
63. Yang, J., Jiang, Q. & Zhang, J. Bridging the regulatory gap: a policy review of extended producer responsibility for power battery recycling in China. *Energy Sustain. Dev.* **86**, 101697 (2025).
64. Bird, R., Baum, Z. J., Yu, X. & Ma, J. The regulatory environment for lithium-ion battery recycling. *ACS Energy Lett.* **7**, 736 (2022).
65. Schlehuber, S., Hemmelder, A. & von Delft, S. Uncovering collaboration and knowledge areas in lithium-ion battery recycling. *EES Batter* <https://doi.org/10.1039/d5eb00056d> (2025).
66. Cesaro, A. et al. A relative risk assessment of the open burning of WEEE. *Environ. Sci. Pollut. Res.* **26**, 11042–11052 (2019).
67. Baldé, C. P. et al. Global e-waste monitor 2024. (2024).

68. Risse, M. Human rights and artificial intelligence: an urgently needed agenda. *Hum. Rights Q.* **41**, 1–16 (2019).
69. Li, B. & Li, J. Public participation in governance of e-waste recycling: a tripartite evolutionary game analysis. *Sustain. Futur.* **8**, 100323 (2024).
70. Lin, J., Li, W. & Chen, Z. Scaling direct recycling of lithium-ion batteries toward industrialization: challenges and opportunities. *ACS Energy Lett.* **10**, 947–957 (2025).
71. Hayagan, N. et al. Challenges and perspectives for direct recycling of electrode scraps and end-of-life lithium-ion batteries. *Batter. Supercaps* **7**, e202400120 (2024).
72. Chu, G., Huang, Y., Hawker, W., Wang, L. & Zhu, X. Direct recycling of degraded Ni-rich cathodes: recent advances in regeneration and upcycling. *J. Mater. Chem. A* **13**, 28749 (2025).
73. Pražanová, A., Plachý, Z., Kočí, J., Fridrich, M. & Knap, V. Direct recycling technology for spent lithium-ion batteries: limitations of current implementation. *Batteries* **10**, 81 (2024).
74. Roy, J. J. et al. Direct recycling of Li-ion batteries from cell to pack level: challenges and prospects on technology, scalability, sustainability, and economics. *Carbon Energy* **6**, e492 (2024).
75. Gnutzmann, M. M. et al. Direct recycling at the material level: unravelling challenges and opportunities through a case study on spent Ni-rich layered oxide-based cathodes. *Adv. Energy Mater.* **14**, 2400840 (2024).
76. Huang, M. et al. Direct regeneration of spent lithium-ion battery cathodes: from theoretical study to production practice. *Nano-Micro Lett.* **16**, 207 (2024).
77. Tong, Z., Ren, X., Ni, M., Bu, X. & Dong, L. Review of ultrasound-assisted recycling and utilization of cathode materials from spent lithium-ion batteries: state-of-the-art and outlook. *Energy Fuels* **37**, 14574–14588 (2023).
78. Xiao, X. et al. Ultrasound-assisted extraction of metals from Lithium-ion batteries using natural organic acids. *Green. Chem.* **23**, 8519–8532 (2021).
79. Tong, Z. et al. Advancements in acoustic cavitation modelling: progress, challenges, and future directions in sonochemical reactor design. *Coatings* **112**, 1288 (2021).
80. Mohammadzadeh, S., Dalfré Filho, J. G., Sampaio Descovi, C., Genovez, A. I. B. & Teixeira Buttignol, T. E. Experimental analysis of cavitation erosion: parameter sensitivity and testing protocols. *Coatings* **14**, 1288 (2024).
81. Wang, J. et al. A green process for recycling and synthesis of cathode materials LiMn_2O_4 from spent lithium-ion batteries using citric acid (2022).
82. Martins, L. S., Rovani, S., Botelho Junior, A. B. & Romano Espinosa, D. C. Sustainable approach for critical metals recovery through hydrometallurgical processing of spent batteries using organic acids. *Ind. Eng. Chem. Res.* **62**, 18672–18682 (2023).
83. Morina, R., Merli, D., Mustarelli, P. & Ferrara, C. Lithium and cobalt recovery from lithium-ion battery waste via functional ionic liquid extraction for effective battery recycling. *ChemElectroChem* **10**, e202201059 (2023).
84. Tran, M. K., Rodrigues, M.-T. F., Kato, K., Babu, G. & Ajayan, P. M. Deep eutectic solvents for cathode recycling of Li-ion batteries. *Nat. Energy* **4**, 339–345 (2019).
85. Cattaneo, P., D'Aprile, F., Kapelyushko, V., Mustarelli, P. & Quartarone, E. Supercritical CO_2 technology for the treatment of end-of-life lithium-ion batteries. *RSC Sustain.* **2**, 1692–1707 (2024).
86. Dai, Y. et al. Acid-free leaching nickel, cobalt, manganese, and lithium from spent lithium-ion batteries using Fe (II) and Fe (III) solution. *J. Sustain. Metall.* **8**, 863–871 (2022).
87. Cerrillo-Gonzalez, M. et al. Li_2CO_3 recovery through a carbon-negative electrodialysis of lithium-ion battery leachates. *Processes* **10**, 1485 (2022).
88. González, A., Choque, G., Grágeda, M. & Ushak, S. The development and analysis of a preliminary electrodialysis process for the purification of complex lithium solutions for the production of Li_2CO_3 and LiOH . *Membranes (Basel)* **15**, 50 (2025).
89. Ferrara, C., Ruffo, R., Quartarone, E. & Mustarelli, P. Circular economy and the fate of lithium batteries: second life and recycling. *Adv. Energy Sustain. Res.* **2**, 2100047 (2021).
90. Biswal, B. K. & Balasubramanian, R. Recovery of valuable metals from spent lithium-ion batteries using microbial agents for bioleaching: a review. *Front. Microbiol.* **14**, 1197081 (2023).
91. Abdollahi, H. et al. Biotechnological applications in spent lithium-ion battery processing. in *Biotechnological Innovations in the Mineral-Metal Industry* 79–109 (Springer, 2024).
92. Gu, J. et al. Efficient bioleaching of Li from waste lithium–iron phosphate batteries by acidophilic bacterial consortium: enrichment condition, Li recovery, and brief carbon footprint analysis. *Chem. Eng. J.* **509**, 161450 (2025).
93. Kim, J., Nwe, H. H. & Yoon, C. S. Enhanced bioleaching of spent Li-ion batteries using *A. ferrooxidans* by application of external magnetic field. *J. Environ. Manag.* **367**, 122012 (2024).
94. Huang, Z. et al. A novel closed-loop biotechnology for recovery of cobalt from a lithium-ion battery active cathode material. *J. Environ. Manag.* **15**, 1475 (2024).
95. Lalropuia, L. et al. Metal recovery from spent lithium-ion batteries via two-step bioleaching using adapted chemolithotrophs from an acidic mine pit lake. *Front. Microbiol.* **15**, 1347072 (2024).
96. Roy, J. J., Zaiden, N., Do, M. P., Cao, B. & Srinivasan, M. Microbial recycling of lithium-ion batteries: challenges and outlook. *Joule* **7**, 450–456 (2023).
97. Kapiloff, D. et al. *Emerging Policies and Best Practices to Promote Lithium-Ion Battery Second-Life Applications in the United States Applications in the United States* (2024).
98. Iqbal, H., Sarwar, S., Kirli, D., Shek, J. K. H. & Kiprakis, A. E. A survey of second-life batteries based on techno-economic perspective and applications-based analysis. *Carbon Neutrality* **2**, 8 (2023).
99. Patel, A. N. et al. Lithium-ion battery second life: pathways, challenges and outlook. *Front. Chem.* **12**, 1358417 (2024).
100. Kebede, A. A. et al. Optimal sizing and lifetime investigation of second life lithium-ion battery for grid-scale stationary application. *J. Energy Storage* **72**, 108541 (2023).
101. Aguilar Lopez, F., Lauinger, D., Vuille, F. & Müller, D. B. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. *Nat. Commun.* **15**, 4179 (2024).
102. Vullum-Bruer, F., Galteland, O., Gouis, M., McDougall, N. & Tenhunen-Lunkka, A. Existing and upcoming challenges for extending electric vehicle battery lifetime through 2nd life applications. *J. Circ. Econ.* **2**, 1 (2024).
103. Kampker, A. et al. Identification of challenges for second-life battery systems—a literature review. *World Electr. Veh. J.* **14**, 80 (2023).
104. Azizighalehsari, S., Venugopal, P., Pratap Singh, D., Batista Soeiro, T. & Rietveld, G. Empowering electric vehicles batteries: a comprehensive look at the application and challenges of second-life batteries. *Batteries* **10**, 161 (2024).
105. International Energy Agency. Recycling of Critical Minerals Strategies to scale up recycling and urban mining A World Energy Outlook Special Report. *IEA* (2024).
106. Li, J., Wang, Z., Li, H. & Jiao, J. Which policy can effectively promote the formal recycling of power batteries in China?. *Energy* **299**, 131445 (2024).
107. Rufino Júnior, C. A. et al. Towards to battery digital passport: reviewing regulations and standards for second-life batteries. *Batteries* **10**, 115 (2024).
108. Berger, K., Schöggel, J.-P. & Baumgartner, R. J. Digital battery passports to enable circular and sustainable value chains: conceptualization and use cases. *J. Clean. Prod.* **353**, 131492 (2022).

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J.C.-O. Conceptualization, Writing-original draft, review & editing. B.P., M.G., C.C., and L.R.: Discussion, Writing-review & editing. B.C.: Discussion, Writing—review & editing.

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The authors declare no competing interests.

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Review

A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective

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Abstract: Lithium-ion batteries (LIBs) are currently one of the most important electrochemical energy storage devices, powering electronic mobile devices and electric vehicles alike. However, there is a remarkable difference between their rate of production and rate of recycling. At the end of their lifecycle, only a limited number of LIBs undergo any recycling treatment, with the majority go to landfills or being hoarded in households. Further losses of LIB components occur because the the state-of-the-art LIB recycling processes are limited to components with high economic value, e.g., Co, Cu, Fe, and Al. With the increasing popularity of concepts such as “circular economy” (CE), new LIB recycling systems have been proposed that target a wider spectrum of compounds, thus reducing the environmental impact associated with LIB production. This review work presents a discussion of the current practices and some of the most promising emerging technologies for recycling LIBs. While other authoritative reviews have focused on the description of recycling processes, the aim of the present was is to offer an analysis of recycling technologies from a CE perspective. Consequently, the discussion is based on the ability of each technology to recover every component in LIBs. The gathered data depicted a direct relationship between process complexity and the variety and usability of the recovered fractions. Indeed, only processes employing a combination of mechanical processing, and hydro- and pyrometallurgical steps seemed able to obtain materials suitable for LIB (re)manufacture. On the other hand, processes relying on pyrometallurgical steps are robust, but only capable of recovering metallic components.

Keywords: circular economy; recycling processes; lithium-ion battery

1. Introduction: The Societal and Economic Importance of Lithium-Ion Batteries

A secondary lithium-ion battery (LIB) is a rechargeable electrochemical energy storage device. Since their development in the 1970s, and because of their unique characteristics of high energy capacity and long lifespan, LIBs have become important in the field of portable electronic goods [1,2]. Compared to other types of batteries (e.g., NiMH and Pb-acid), LIBs present lower environmental risks, longer life-span, compact design, better resistance to self-discharge, higher resistance to elevated temperatures, and higher voltage output (e.g., 3.7 V for a LIB vs. 1.2 V for a Pb-acid battery) [3,4]. These technical advantages make them attractive for urban or industrial mobility applications [2,5–7] (e.g., the Tesla S car is powered by 7104 LIB cells [8]). In addition, as electrical vehicles are being

pushed forward due to government and societal awareness of climate change, LIBs have become a promising option for the reduction CO₂ emissions. The importance of LIBs as power sources is reflected by their constant increase in production rate and their continuously growing share of the market. In 2011, nearly 4500 million LIB cells were produced, an estimated increase of 43% compared to 2008 [9]. In 2015, at least 5600 million LIB cells were sold worldwide [10], and the LIB market size is forecasted to increase by another 10.6% from 2016 to 2024, reaching a market value of USD \$56 billion by 2024 [11]. In addition, the electric power supplied by LIBs has presented unprecedented growth, shifting from approximately 100,000 MWh in 2016 to approximately 125,000 MWh in 2017, for example [12]. Notably, the 2019 Nobel Prize in Chemistry was awarded to the developers of LIBs, attesting to the importance of these energy storage devices in our modern society.

Consequently, there has been a direct increase in the exploitation required of mineral deposits to provide the raw materials needed by the LIB market [12–14]. Natural mineral deposits, however, are reaching critical grades of valuable metals. This has resulted in an increased environmental footprint associated with metals extraction, in direct conflict with the pursuit of climate change alleviation via electrically powered goods, in particular EVs. Furthermore, it has been estimated that 95% of the LIBs produced globally remain untreated in households [15]. Another typical pathway for end-of-life (EoL) LIBs is their exportation to emerging economies, where they can be treated at low cost [16]. In Europe alone, the LIB market reported a total of 65,500 tons of LIB consumed between the years 2013–2014 [5], while only about 1900 tons were recycled in the same period. The low recycling rates for LIBs can be presently attributed to several factors, ranging from deficient legislation, inefficient collection systems, and the lack of feasible recycling technologies for the rapidly changing stream of LIB waste.

The gap between recycling and production currently represents an untapped source of valuable materials. Apart from representing a direct economic loss and an environmental hazard, this gap results in a growing need for virgin raw materials, with their associated environmental footprint [15,17,18]. For example, an EV battery with an energy density of approximately 78 kWh/kg produces an estimated 172–196 kg of CO₂ eq per kWh from raw material extraction, cell manufacturing, and assembly [19,20]. Ellingsen et al. (2013) [21] also demonstrated that a significant environmental footprint is incurred during production of the cathode paste and current collector.

Recycling processes thus represent a viable option for the reintroduction of LIB compounds into the economic cycle, reducing the need for primary raw materials [22–26]. Recycling processes are a fundamental aspect of the circular economy (CE) as they enable internal material flows, reducing the consumption of resources associated with the production of primary raw materials [26–29]. Indeed, the circular economy (CE) is intended to mimic natural process, where no waste is generated. It is worth noting that the stages of the circular economy are highly interdependent. For instance, to accomplish the expected CO₂ reduction from LIB-powered transportation, the energy for their production should ideally come from renewable sources [30]. Evidently, a CE also depends on environmental, political, and financial conditions, turning it into a living and complex organism.

Geissdoerfer [28] presented conceptual means to achieve CE by “long-lasting design, maintenance, repair, re-use, remanufacturing, refurbishing, and recycling” of consumer goods. Van Schalkwyk et al. (2017) [31] described the need to define the CE concept by including thermodynamic losses into the loop.

In a similar fashion, Figure 1 shows a recently proposed CE model that accounts for the losses of material inherent to the production and recovery of materials [32]. In the loops shown in Figure 1, the material moves from the input stage (1) towards the EoL of the product (6), where recovery systems (7) take action and reintroduce elements into the value generation chain. Unlike other models, Figure 1 shows different reintroduction points relative to the recovery process and their energy intensiveness. That is, the further the reinsertion point is from the waste disposal and management (7) point, the more resource-intensive the recovery process will be. It is well known that both economic and technological feasibility are bounded to the market trends, which decide whether LIBs will be processed down to

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level of elements and compounds [33]. Indirectly, these drivers also define the usability of the recovered materials in other advanced materials on the level of elements and compounds. These materials have a potentially broader field of application than those obtained through refurbishment. For example, elemental Li recovered from spent LIBs can be used for electrolyte production, and a constructed LIB recycling. In reality, industrial-scale LIB recycling processes are not as efficient as they need to be in order to be viable. The reason for this is a (so far) unmet challenge: the state-of-the-art (SoA) technology is lagging behind by approximately four years compared to the physical and chemical properties of the materials. Currently, only Al, Fe, and Cu compounds are recovered, while only Al, Fe, and Cu are currently targeted by LIB recycling processes as their separation and refinement is technically simple and economically feasible, while other compounds such as graphite and Li are lost.

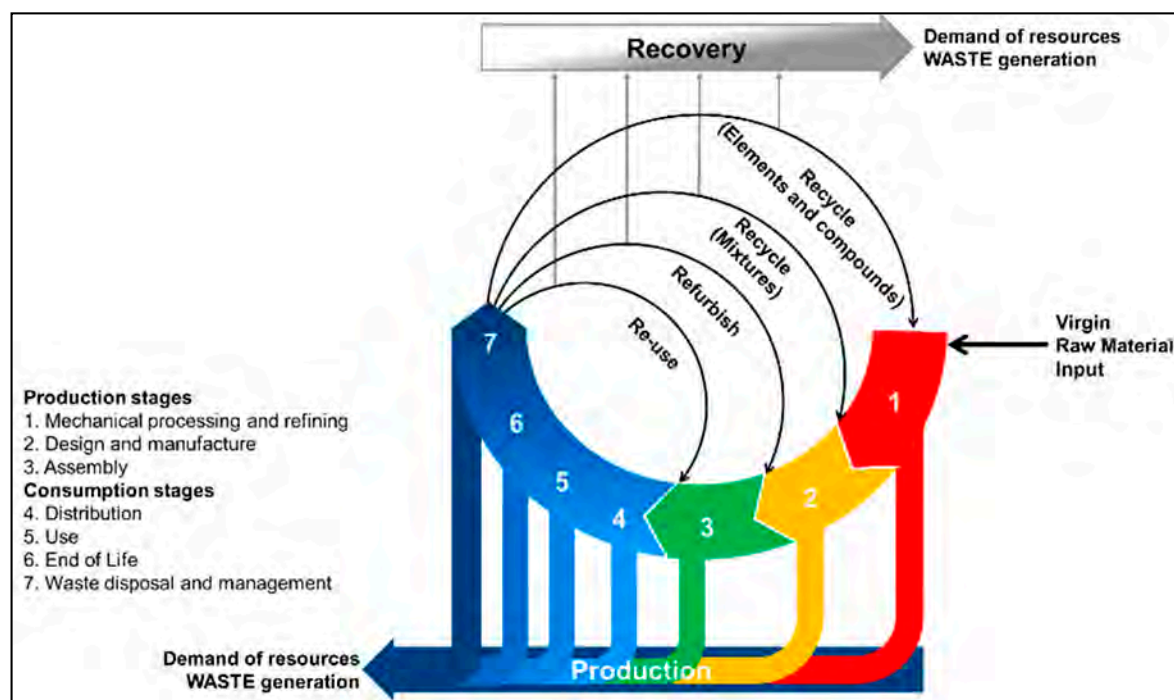


Figure 1: Circular economy model from a material-centric perspective based on Martínez et al. (2019) [32].

This critical review offers an analysis of the the SoA and emerging technologies for Bredt's ring from a GEM perspective by considering during the spectrum of recovered compounds and the inequality. This is a unique progress process going to be a "closed loop" of special interest results should be noted that in that, in this materials materials for a put pose other than the primary production has been a considerable following the the definition of the ideal CE loop.

Methodology and Scope

This review utilized as baseline the previous works of Xu et al. (2008), Espinosa et al. (2004), Bernardes et al. (2004), Farella et al. (2008), Ruffino et al. (2011), Ordoñez et al. (2016), Sayilgan et al. (2009), Vezzini (2014), and Zeng et al. (2014) [22,27,35–41] regarding battery recycling at industrial and laboratory scales. Other references were collected from scientific literature databases such as Scopus, Google Scholar, ResearchGate, ScienceDirect, and Google Patents. The search included original scientific articles, edited books, online available presentations, and battery organizations' webpages, employing keywords as "lithium-ion battery recycling" and "LiB recycling" with additional strings of "mechanical processing", "separations", company names, and owner patents. From all the data gathered regarding primary (disposable) and secondary (rechargeable) LiB recycling, the focus was narrowed down to processes targeting secondary LiBs, either as a single feed stream or as the major feed fraction. In addition, the processes were required to be in accordance with the European Union Directive 2006/66/EC and to recover a minimum of 50% by mass. The different processes thus identified and included in this review can be classified as follows:

Council Directive 2006/66/EC and to recover a minimum of 50% by mass. The different processes thus identified and included in this review can be classified as follows:

1. Established industrial processes with LIBs as the major or unique feed;
2. Emerging technologies designed for LIB recycling;
3. Processes which do not use LIBs as either a major or unique fraction of the feed, but accept them as secondary feed.

Due to the broad number of emerging technologies reported in the literature, those chosen include those in pilot plant stages, under permitting procedure, under commercialization, or that have produced several patents. The technologies chosen clearly support towards the CE philosophy by offering a broad range of recovered LIB material components. Hence, this review encompassed the following recycling technologies:

1. Established: Umicore Valéas™ (Umicore, Bruxelles, Belgium), Retrie Technologies (Retriev), Recupyl Valibat (Recupyl), Akkuser, and Sumitomo–Sony (Sumitomo).
2. Emerging: LithoRec, Accurec, Battery Resources, Steven Loop: OnTo Technology (OnTo), Aalto University Process.
3. Other industrial processes accepting LIBs: BatRec, Inmetco, and Glencore.

The so-called “Aalto University Process” is a theoretical process partially based on the developments of Reference [42], applying laboratory-scale results to processing real LIB waste [43]. This process, analyzed by Reference [44], was classified into the “Emerging” category because it recovers all the LIB compounds.

Moreover, the recycling processes were analyzed using the following guidelines:

1. What type of battery feed does the process accept?
2. What are the main recoveries? What is their final quality?
3. Which processes, i.e., hydro- or pyrometallurgy and/or mechanical processing, are used? What are their limitations?
4. What other material inputs does the process require?

This review is divided into five main sections. Section 2 discusses the challenges of LIB recycling processes from a material and process perspective. Section 3 first describes the established processes (Section 3.1), followed by emerging technologies (Section 3.2). Section 4 provides a comparative analysis of all recycling processes from two different perspectives: based on the complexity of the process itself (Section 4.1), and based on the quality of recyclates (Section 4.2). Conclusions are presented in Section 5.

2. Challenges in LIB Recycling

Compound Challenges

In general terms, a LIB is formed of either a single or multiple electrochemical cells connected and enclosed in a metallic or plastic case. Table 1 presents the composition of a typical LIB based on Reference [17,22,45,46].

Table 1. Lithium-Ion Battery (LiB) Constructive Components and Materials.

Battery Component	%w/w	Most Commonly Used Material
Case	~25%	Steel/plastics
Cathode	~27%	LiCoO ₂ , LiNi _x Mn _y Co _z O ₂ , LiMn ₂ O ₄ , LiNiO ₂ , LiFePO ₄
Anode	~17%	Graphite/Li ₄ Ti ₅ O ₁₂
Copper and aluminium foils and current collectors	~13%	Cu/Al
Electrolyte	~10%	Solution of LiPF ₆ , LiBF ₄ , LiClO ₄ , and LiSO ₂ dissolved in propylene carbonate, ethylene carbonate, or dimethyl sulfoxide
Separator	~4%	Microporous polypropylene
Binder	~4%	Polivinyldene Difluoride (PVDF)

A cell, the basic construction unit of all LIBs, is formed of a transition metal compound as the cathode, graphite as the anode, Al and Cu as current collectors, Li salt as electrolyte, a polymeric separator, and a metallic cell casing [1,2,47]. The cathode, usually a lithiated transition metal oxide/phosphate (Table 1), defines the obtainable voltage of the LIB if there are no changes in the anode material [47]. The anode material, most commonly graphite, but also Li₄Ti₅O₁₂ in some stationary applications, should enable the efficient flow of Li ions without excessive structural and volume changes, while being able to conduct electrons [47–49]. The polymeric separator is placed between the electrodes to prevent direct contact and short circuits. Nevertheless, the separator should have enough porosity to allow Li-ion migration [47]. The electrolyte consists of a Li salt dissolved in an organic solvent, its main purpose being to efficiently conduct the Li ions between electrodes [15,50,51]. PVDF binds the cell together and, thus, it should present high mechanical strength and good chemical and environmental endurance [52]. The electric current is carried through Al and Cu foils connected to the cathode and anode, respectively [15]. Finally, the cell components are enclosed in an Al, Fe, or plastic casing [47,48].

The five cathode chemistries displayed in Table 1 are currently dominant in the market. However, in the search of better performance, stability, and/or longer lifespan, an increasing number of cathode chemistries are being explored, potentially resulting in a higher degree of material complexity. For example, LiCoO₂ provides a good specific capacity, but is expensive and presents safety risks at elevated temperatures [47,53]. The specific capacity, measured in mAh/g, describes how much electricity is delivered by a cell [2]. These drawbacks have been reportedly tackled by replacing the Co with Mn, either partially or totally, as LiMn₂O₄ offers a lower economic cost, higher stability at high temperatures, and better tolerance to overcharging [45,48]. Simultaneously, LiMn₂O₄ presents an irreversible loss of capacity during operation due to the dissolution of Mn ions into the electrolyte [45,54]. As LIB chemistries become more specialized, they include a larger amount of elements, increasing the cost of recycling [15,18,55–57]. The wide variety of mixed LIB chemistries reaching recycling streams is already generating further challenges in recycling processes [18]. In addition, consumer electronics powered by LIBs reach an EoL point at between 3 to 4 years, while EV or PHEV applications take 10 years or more, broadening the lag of recycling systems.

As the focus of the LIB recycling processes is driven by market value, Co and metallic fractions are currently their main target [58]. Currently, metallic components are commonly recovered as metallic alloys as a result of pyrometallurgical processes or, in the case of large casing materials, during mechanical dismantling. The remaining materials, e.g., Li compounds, electrolyte, plastics, and organic materials, are lost, except in China and South Korea, where Li is recovered as LiCO₃ [59]. The latter is a useful material, since cathode compounds are manufactured from Li metal oxide/phosphate or Li carbonate/hydroxide [60]. While SoA processes successfully recover metallic fractions, emerging processes are focused on the recovery of cathode salts or their precursors. Co may be recovered in

different chemical forms, either as a pure metal or as part of a chemical compound (e.g., cathode precursor salts).

3. Description of LIB Recycling Processes

The various stages in the recycling process can be broadly classified into pre-processing and mechanical, hydrometallurgical, and pyro-metallurgical methods. Pre-processing is here considered to be any process which does not alter the structure of the LIB cells, e.g., sorting by battery type from mixed waste. Mechanical processing involves the use of different techniques to liberate, classify, and concentrate materials without altering their chemistry. These techniques operate based on relative differences in the physical properties of materials, for instance density, shape, and size, and they generally occur before stages involving chemical reactions [61–64]. After mechanical processing, the material obtained is refined by hydrometallurgy, pyrometallurgy, or a mixture of both. Pyro-metallurgy refers to operations at elevated temperatures where redox reactions are activated to smelt and purify valuable metals [15,22,27]. Hydrometallurgy involves the leaching of valuable elements from a solid from a solid matrix and their subsequent precipitation through modification of the chemistry phase. These techniques are highly resource-intensive and they are strongly influenced by economic constraints [65].

3.1. Established LIB Recycling Processes

3.1.1. Retrieval Technologies

Initially called “Toxco” and developed for primary LIBs, this technology is nowadays also applied to secondary LIBs and offers a capacity of 4500 tons/year. [66–68]. A schematic representation is presented in Figure 2.

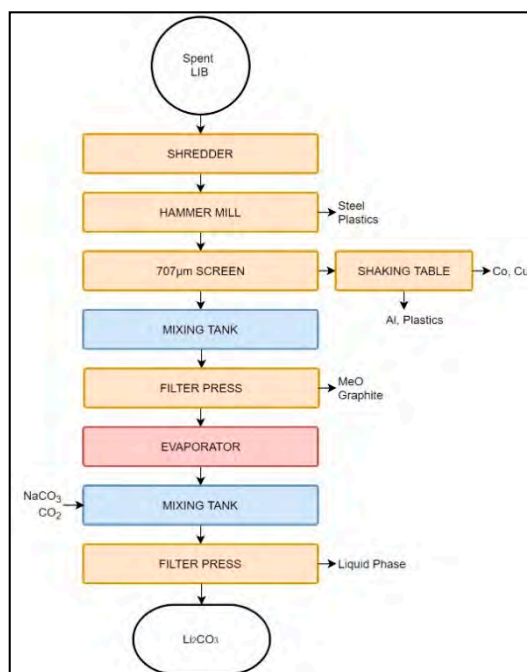


Figure 2. Schematic representation of the Retrieval LIB recycling process.

The Toxco process begins by shredding LIBs submerged in a brine solution to deactivate the cells and prevent fire due to Li oxidation. Large LIB packs undergo preliminary manual disassembly, while small batteries and cells rely on processed access [64,65,69]. Depending on the characteristics (differences) between primary and secondary LIBs, the protective may change from brine to liquid N₂ (cryogenic crushing), the latter being employed when the quantity of primary LIBs is high [40,66,69,70].

After shredding, the slurry is processed with a hammer mill, and the larger particles, containing mainly metallic components, are separated by screening. The resulting Cu–Co-rich overflow is treated with a shaking table to remove Al particles and plastics. The cathode-rich undersize particles are filtered to obtain a cake rich in C and metallic oxides (MeO). The filtered liquid is also rich in Li

liquid N_2 (cryogenic crushing), the latter being employed when the quantity of primary LIBs is high [40,66,69,70].

After shredding, the slurry is processed with a hammer mill, and the larger particles, containing mainly metallic components, are separated by screening. The resulting Cu–Co-rich overflow is treated with a shaking table to remove Al particles and plastics. The cathode-rich undersize particles are filtered to obtain a cake rich in C and metallic oxides (MeO). The filtered liquid is also rich in Li and may be reacted with Na_2CO_3 or CO_2 to produce Li_2CO_3 [66,70]. The metallic oxide and Li_2CO_3 cakes are used in metal industry, and are thus considered downcycled [67,70].

Furthermore, the Retrie Technology company patented a method (Figure 3) to recover and regenerate cathode-grade material from spent LIBs [71]. However, this process is still undergoing commercialization and, at the time of writing this review, no evidence of its productivity was available [69].

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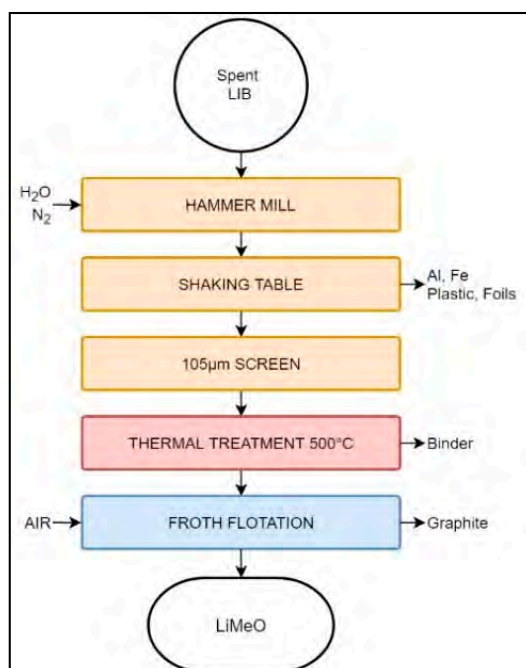


Figure 3. Schematic representation of the Retrie Technology LIB recycling process for cathode-grade material regeneration.

Similarly to the original Retrie process, this modified version starts by shredding the waste LIBs in an artificial atmosphere of N_2 or spray water. Coarser particles of Al and Steel (Fe) are removed from the slurry using a shaking table. The remaining slurry, rich in electrode material, is split with a 105 μm sieve. The undersize fraction is heated at 500 $^{\circ}C$ for two hours, permitting the evaporation of water, pyrolysis of the binder, and structural modification of the carbon, while avoiding the ignition of the latter. The dry, binder-free material is subsequently mixed with distilled water and sent to a flotation process, where the anode and cathode particles are separated via their differences of hydrophobicity. Anode powder reports to the froth phase, while cathode and carbon particles are recovered from the non-floated fraction [71].

The Sony Process, with a capacity of 150 tons/year, was developed by a cooperation between Sony Electronics and Sumitomo Metal Mining Company [68,72]. Although the information regarding this process is scarce, this process was reportedly designed for the recycling of LIBs.

The Sony process starts with a calcination step to remove the electrolyte and other organic materials. The remaining fractions are subdued to a pyrometallurgical transformation, leading to the recovery of a metallic alloy consisting of Co, Ni, and Fe, while the Li is lost to the slag. Co is subsequently extracted from the metallic alloy by a leaching process. The main product of the Sumitomo–Sony process is CoO of sufficient quality that it can be used to manufacture LIBs [72]. Cu and Fe are by-products that are separated mechanically [72,73].

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3.1.3. Recupyl Valibat

The Recupyl process, with a nominal capacity of 110 tons/year, was developed as a low-temperature LIB recycling technology, directly addressing the gas emissions resulting from pyrometallurgy in the above-mentioned processes. Figure 4 presents the Recupyl process.

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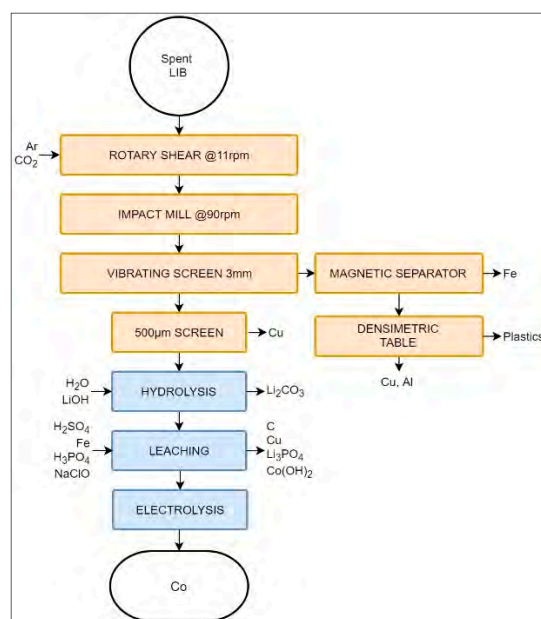


Figure 4. Schematic representation of the Recupyl Valibat recycling process.

The feed in the Recupyl process may be either primary or secondary LIBs [74]. Batteries are then transferred to a two-step comminution. First, LIBs are treated in a low-speed rotary shear (11 rpm) in Ar or CO₂ atmosphere to expose the internal compounds. The inert atmosphere ensures the safe processing of potentially charged batteries. When CO₂ is used, it passivates the metallic Li of the primary LIBs, forming a surface of Li₂CO₃ and reducing fire risks. Secondary grinding is carried out in an impact mill at 90 rpm to reduce particles to a size lower than 3 mm. The target particle size is obtained with the help of a vibrating screen, thus creating over- and undersize fractions.

The oversize fraction is processed using a high-induction magnetic separator to remove ferrous metals. The non-magnetic fraction is then processed with a densimetric table. The relative difference in density creates a high-density fraction (containing C and Al) and a low-density fraction (formed by paper and plastics) [74]. The 3 mm sieve undersize fraction is further classified using sieves with a 500 µm opening size. There, most of the remaining Cu particles are removed, the passing material containing only <0.3% of Cu [40,74]. Cu removal is a crucial step, since this metal is an impurity that will affect subsequent hydrometallurgical steps.

The electrode-rich fine fraction (i.e., <500 µm) is then mixed with water, and its pH is adjusted to 12. This step releases H₂ due to hydrolysis. Li salts are then dissolved into the aqueous phase, leaving MeO and graphite suspended in the solution, to be separated by a filtration process. At this stage, it is possible to recover Li₂CO₃ or LiCoO₂ from the liquid phase by the addition of gaseous CO₂ or by solid/liquid separation [74].

The remaining solid fraction undergoes a series of leaching steps: first being treated by H₂SO₄ at 80–80 °C. C is filtered out from the solution and Cu is then cemented with steel, i.e., reduced to its elemental form. The possible remaining Li can be precipitated at this point as Li₃PO₄ by the addition of H₃PO₄. Finally, Co may be recovered as Co(OH)₂ in the presence of NaClO, or as elemental Co by electrolysis [74].

3.1.4. Akkuser

The Akkuser process employs low-temperature stages aimed at obtaining a metal-enriched fraction suitable for subsequent refining. This process involves only a mechanical pre-processing

of H_3PO_4 . Finally, Co may be recovered as $\text{Co}(\text{OH})_2$ in the presence of NaClO , or as elemental Co by electrolysis [74].

3.1.4. Akkuser

The Akkuser process employs low-temperature stages aimed at obtaining a metal-enriched fraction suitable for subsequent refining. This process involves only a mechanical pre-processing treatment and does not encompass hydro- or pyrometallurgical steps [40,75]. It is reported that Akkuser has a capacity of 4000 tons/year [68]. As this review is focused LIB recycling, the Akkuser process for this type of battery is presented, as depicted in Figure 5.

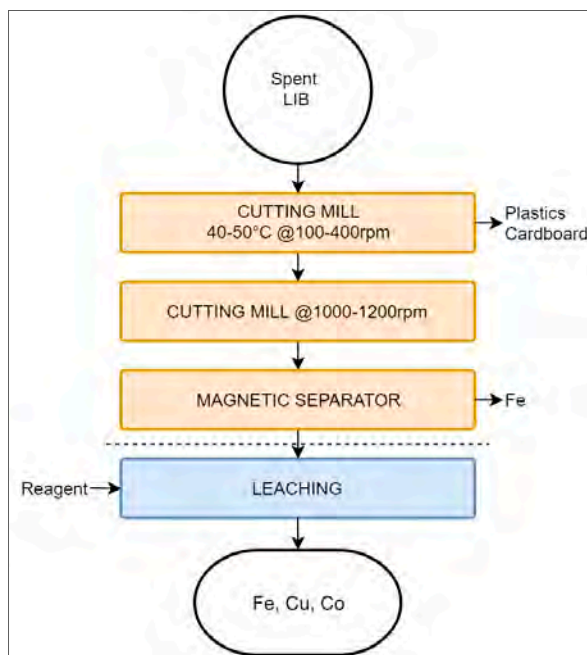


Figure 5. Schematic representation of the Akkuser recycling process.

This process accepts a mixed feed, as the batteries are pre-sorted by type [75]. After sorting, LIBs are processed by two continuous cutting mills. The first mill operates at a temperature range of 40–50 °C, at 100–400 rpm, reducing the battery size in the range of 2.5 to 2.5 cm. There is no mention in the literature of a protective atmosphere during size reduction; however, it may be inferred that fire risks are considered low. Naturally occurring gases, H_2 and O_2 , are extracted and filtered using a cyclonic system. The filtration residues, most being plastic and metal particles, are then processed to recover Ni and Co by leaching. Upon reaching a pristine quality, the exhaust gases are then released into the atmosphere [75].

The shredded material is then transferred through an air-tight cooling tube into a secondary mill operating at 1000–1200 rpm. The secondary cutting mill reduces the material to a fine volume. Volatile particles are captured with a secondary cyclonic air system, from which ferrous metals are recovered employing a magnetic separator. The resulting non-volatile fraction rich in Co and Cu is ready to be refined by either hydro- or pyrometallurgy [75]. The final recovery composition is not detailed in the literature, but is likely a mixture of electrode materials and traces of Al [76].

3.1.5. Umicore Valeas™ (Bruxelles, Belgium)

The Umicore process is focused on the recovery of Co and Ni, primarily from LIBs and NiMH batteries, and it presents the largest capacity of the discussed processes, with 7000 tons/year [68]. It involves a combination of pyro- and hydrometallurgical steps, as presented in Figure 6.

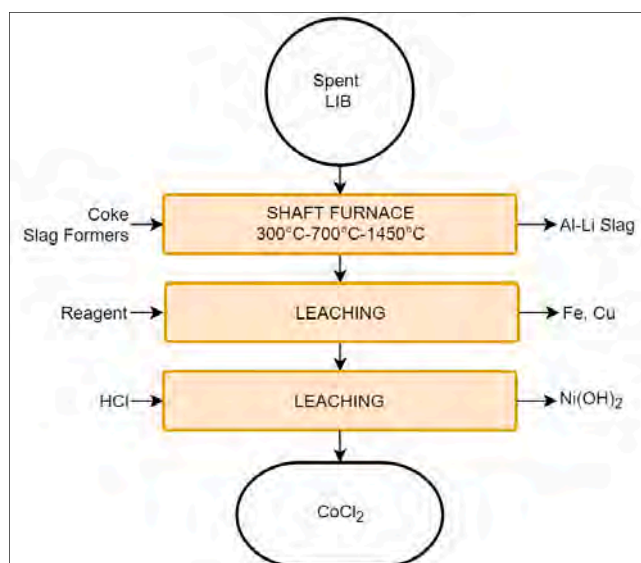


Figure 6. Schematic representation of the Umicore Valéas recycling process.

The batteries undergo preliminary discharging increasing temperature as per material (metaplastic paste) and expansion posing the T helper thus begins by introducing the graphite slabs at a rate of 4 whr, whiles, cast may be divided into three different sections according to temperature low ($\leq 30^\circ\text{C}$), medium (70°C) and high ($120^\circ\text{--}145^\circ\text{C}$). [Each] section performs pyrolysis of different materials and refinement of the rest of the area follows as follows:

1. Low temperature section: evaporation of electrolyte;
2. Medium temperature: plastics pyrolysis;
3. High temperature: smelting and reduction (1200–1450 °C).

Generally Na, Ca, or ZnO are introduced to capture halogens and volatile compounds. In cases where the feed contains alkaline batteries, their ZnO content is considered sufficient for such purposes [40,70]. The metallic product of the shaft contains Cu, Co, Ni, Li, and traces of Fe, while Al, Si, Ca, Fe, Mn, Li, and Rare earth elements (REEs) report to the slag [40,67]. The presence of Al and Fe in the slag is crucial, as they are considered impurities for the subsequent leaching stages [17,77]. The metallic alloy is then processed by hydrometallurgical means. Initially, Fe and Cu are enriched by an undisclosed leaching solution. The remaining fraction is treated with HCl, resulting in a solution of $\text{Ni}(\text{OH})_2$ and CoCl_2 , and the latter may be processed to obtain cathode grade LiCoO_2 [67,70].

The Umicore process pays special attention to the exhaust gases. For example, the mid-section exhaust is recirculated into the low-temperature section, aiding with the electrolyte evaporation and reducing energy consumption. Additionally, the exhaust gases of the high temperature section are cooled down to avoid the formation of dioxins and furans, and are finally filtered [40,77].

3.1.6. Other Industrial Processes Accepting LIBs

3.1.6. Other Industrial Processes Accepting LIBs

Batrec

Batreç

Batrec began battery recycling in the end of the 1980s, processing a mixture of alkaline and Zn-C batteries, focusing on the recycling of Zn and Hg [19,80]. The Batrec process predates capacity fading/fears and is the activation of zinc as per [39,78]. In the Batrec process [35], pH is raised and H_2 is evolved, and CO_2 absorption on the Japanese reaction, where the Zn cathodes are neutralized by acid and [29]. The atmospheric batteries are described as used to store energy, exposed to air, and covered by moist air [79]. The possible subsequent steps were not available in the literature [47,67,79,80]. However, details of the possible subsequent steps were not available in the literature [17,67,79,80].

Inmetco

Inmetco

In the Inmetco process, the batteries and other scrap (possible electric arc furnace fumes) are fed into a rotary hearth furnace along with reducing pellets. The molten material is then refined in an electric arc furnace. In this process, only Co, Ni, and Fe are recovered in the form of an alloy. Other metals are lost to the slag phase and organic materials are burned [17,27]. Inmetco operates with a capacity of 6000 tons/year.

In a similar manner, the Glencore process targets the recovery of Co, Ni, and Cu through pyrometallurgical and hydrometallurgical methods, and presents a capacity of 7000 tons/year. Any other components are consumed in the process, either as a source of energy or reducing agents or being lost to the slag phase [17,81].

3.2. Emerging LIB Recycling Processes

3.2.1. Accurec

The process designed by the German company Accurec GmbH[®] (Krefeld, Germany) was initially designed to treat Ni–Co batteries. Nevertheless, it has broadened its scope to process various types of batteries, including LIBs [27,29,40,82]. At the moment, LIB recycling by this process operates at a batch-industrial scale in Germany [82]. The Accurec process for LIBs, presented in Figure 7, is a combination of mechanical, pyrometallurgical and hydrometallurgical processes aimed at recovering a Li_2CO_3 cathode precursor and a Co–Ni–Mn alloy.

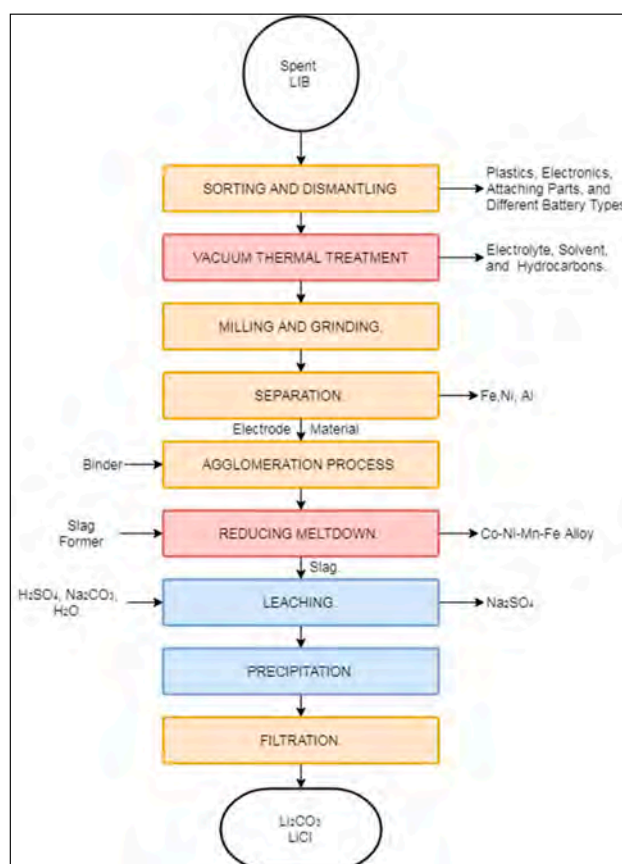


Figure 7. Schematic representation of the Accurec process.

The process begins with the sorting, cleaning, and manual dismantling of spent LIBs from consumer goods and EVs [82]. The dismantled feed is transported to the company's proprietary vacuum thermal treatment, where it is treated at 250 °C under a vacuum to remove electrolytes, solvents, and volatile hydrocarbons [82,83]. The produced fraction is then transported to milling and grinding operations to expose the enclosed constituents. Ground material undergoes a series of mechanical separation steps consisting of a vibrating screen, magnetic separator, and zig-zag classifier ("separation" box in Figure 7), although the exact order of these operations is not specified in the literature. The mechanical separation produces fractions of Fe–Ni, Al, and Al–Cu, from which base metals can be extracted. The remaining fraction is sent to agglomeration and a two-step pyrometallurgical process. The first pyrometallurgical step is carried out in a rotary kiln at 800 °C. The second pyrometallurgical operation is carried out in an electric arc furnace (EAF) ("reducing meltdown" box in Figure 2), where graphite is consumed to enhance the recovery of either Co or Mn, depending on the composition of the previously added slag. As the current market value of Co is higher than that of Mn, the purification of the former is favoured, while the latter is mostly lost in the slag phase [17]. According to Georgi-Maschler et al. (2012), the Co alloy recovered at this stage has commercial value. Similarly to Mn, Li is lost in the slag or volatilized as flue dust during EAF operation.

The concentration of Li in the flue dust and slag has been estimated to be 5 times higher than in the feed, thus offering the possibility of recovery by hydrometallurgical means in the form of the cathode precursor Li_2CO_3 . In such cases, the slag is processed mechanically to obtain a particle size <100 µm, while the flue dust fraction is sent directly to hydrometallurgical treatment. Li is then leached using H_2SO_4 , yielding Na_2SO_4 as a by-product. After extraction, Li is precipitated in the form of Li_2CO_3 . The Accurec process claims to achieve a Li_2CO_3 recovery of 90%; it can then be used either as a cathode precursor or as a raw material for glass manufacturing [17].

3.2.2. Battery Resources "Closed Loop" Process

The Battery Resources process is considered a "closed loop" process by its developers, since it recovers battery components suitable for LIB production [84–86]. According to Heelan et al. (2016) this process is currently in the commercialization phase, with a pilot plant operation ongoing since the summer of 2018 [87–89]. The Battery Resources process uses mostly mechanical and hydrometallurgical operations, with a single sintering step at the end for product refining. The Battery Resources process is designed to treat LIBs with $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$ cathode chemistry. Figure 8 presents a schematic representation of the process.

Initially, spent LIBs undergo a discharging step to reduce the risk of spontaneous explosion during shredding. After discharging, the spent LIBs are shredded with a hammer mill to liberate the constituents and reduce the particle size to <6.3 mm. The shredded mixed material is treated by magnetic separation, producing a magnetic fraction with high content of steel and a cathode-containing non-magnetic fraction. The final destination of the magnetic fraction has not been mentioned in the literature [84,85], but refining could be carried out by a third party company. The non-magnetic fraction is mixed with NaOH in order to extract Al in the form of NaAlO_2 ("dissolving" box in Figure 8). The resulting slurry is then filtered and dried at 60 °C, followed by sieving with an opening size of 250 µm. The coarser fraction is treated by dense media separation (DMS) to obtain a Cu-rich fraction. The fine fraction is sent to a four-step hydrometallurgical process. The first stage removes C, LiFePO_4 , and the remaining plastics in the presence of H_2O_2 and H_2SO_4 at a temperature between 65–70 °C. The remaining solution contains ionic forms of Co, Ni, Mn, Li, Al, and Cu. Adjusting the pH to 6.5 with the addition of NaOH promotes the precipitation of the remaining Al, Fe, and Cu ("2. Leaching and Precipitation" in Figure 8). At this stage, N_2 gas is also added to prevent the oxidation of Mn^{2+} ions [86]. In the third leaching stage, different amounts of MnSO_4 , NiSO_4 , and CoSO_4 are added ("3. Leaching and Precipitation" in Figure 8), to obtain a ratio of 1:1:1 of Co, Mn, and Ni in the solution. There were no details available in the literature about the origins of the Ni, Mn, and Co salts added [84]. Increasing the pH of the solution to 11 with additional NaOH promotes the precipitation

of solid $\text{Co}(\text{OH})_2$, $\text{Mn}(\text{OH})_2$, and $\text{Ni}(\text{OH})_2$. During the final hydrometallurgical step (“4. Leaching and Precipitation” in Figure 8), Na_2CO_3 is added at a temperature of 40°C to precipitate Li_2CO_3 from the remaining solution. The previously extracted $\text{Co}(\text{OH})_2$, $\text{Mn}(\text{OH})_2$, and $\text{Ni}(\text{OH})_2$ are mixed with the precipitated Li_2CO_3 and some additional virgin Li_2CO_3 to synthesize battery-grade cathode material through compression into pellets and sintering at 900°C .

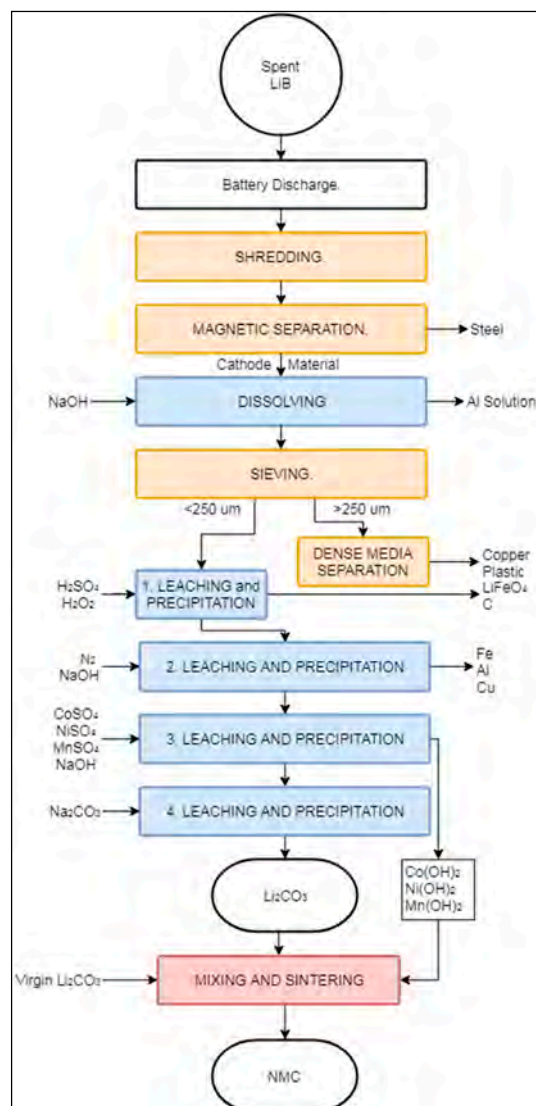


Figure 8. Schematic representation of the Battery Resources recycling process.

3.2.3. LithoRec

Initially, spent LIBs undergo a discharging step to reduce the risk of spontaneous explosion during shredding. After discharging, the spent LIBs are shredded with a hammer mill to liberate the constituents and reduce the particle size to $<6.3\text{ mm}$. The shredded mixed material is treated by magnets, e.g., for trucks, EVs, and heavy-duty fraction [97]. It has been reported that this process offers a capacity of 2000 tons/year [88]. The final destination of the magnetic fraction has not been mentioned in the literature [84–85], but refining could be carried out by a third party company. The non-magnetic fraction is mixed with NaOH in order to extract Al in the form of NaAlO_2 (“dissolving”, in Figure 8). The resulting slurry is then filtered and dried at 60°C , followed by sieving with an opening size of $250\text{ }\mu\text{m}$. The coarser fraction is treated by dense media separation (DMS) to obtain a virgin-like cathode material, 5% electric components, 2% steel, and an additional 10% “plastics [98]”. The fine fraction is sent to a four-step hydrometallurgical process. The first stage removes G LiFePO_4 and the remaining plastics in the presence of H_2O_2 and H_2SO_4 at a temperature between $65\text{--}70^\circ\text{C}$. The remaining solution contains ionic forms of Co , Ni , Mn , Li , Al , and Cu . Adjusting the pH to 6.5 with the addition of NaOH promotes the precipitation of the remaining Al , Fe , and Cu (“2. Leaching and Precipitation” in Figure 8). At this stage, N_2 gas is also added to prevent the oxidation of Mn^{2+} ions [86]. In the third leaching stage, different amounts of MnSO_4 , NiSO_4 , and CoSO_4 are added (“3. Leaching and Precipitation” in Figure 8), to obtain a ratio of 1:1:1 of Co , Mn , and Ni in the solution. There were no details available in the literature about the origins of the Ni .

a capacity of 2000 tons/year [68]. Currently, the company Duesenfeld in Germany bases its continuous operation on this process [93]. Compared to an average LIB (Table 1), those used for traction purposes contain 63% cell material, 5% electric components, 21% steel, and an additional 11% plastics [94]. Their comparatively larger plastic content, which aims to reduce the vibration during normal operation of the vehicle, requires a more complex process compared to the recycling of traditional LIBs. As the content of battery cell components in traction LIBs is low, it becomes highly important to achieve proper and efficient separation of casing materials. Hence, the LithoRec relies heavily on mechanical processing and hydrometallurgical pyrometallurgy. A schematic flow sheet of the LithoRec process is displayed in Figure 9.

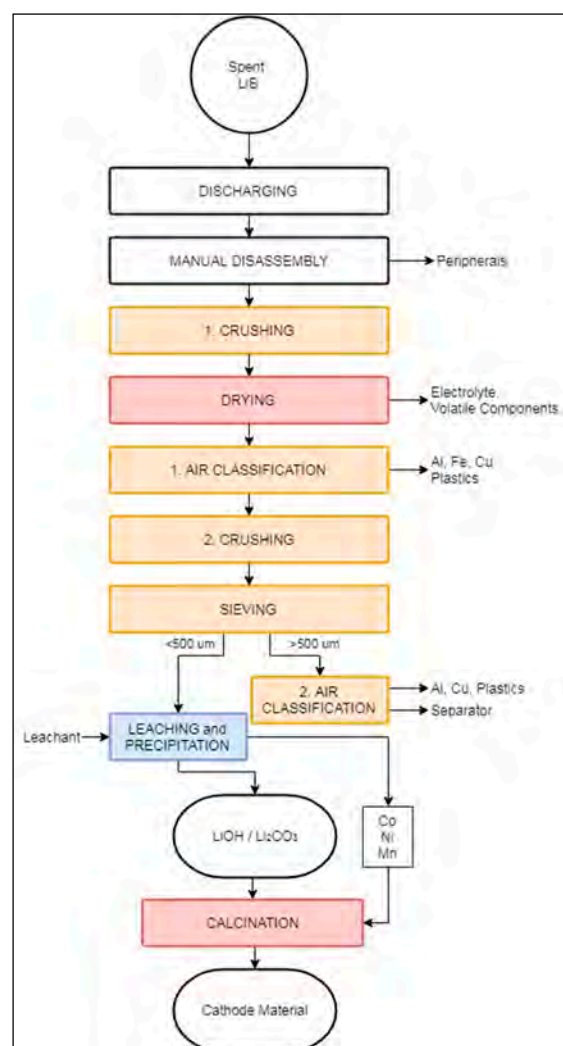


Figure 9. Schematic representation of the LithoRec recycling process.

As the LIBs fed into the LithoRec process are larger than the LIBs used for traditional applications (e.g., mobile phones), the risk of sudden explosion is higher. Thus, the LithoRec process begins with the discharging of batteries [91]. After discharging, the LIB modules are manually disassembled to remove peripherals, i.e., protective case, wiring, plastics, and contaminants (“Peripherals” in Figure 9). The dismantled LIB modules are then crushed with a 20 mm rotary shear crusher between 100–140 °C under an N₂ atmosphere, volatilizing solvents and evaporating the electrolyte. The crushed modules are subsequently sent for initial classification in a zig-zag sifter (“1. Air Classification” in Figure 9), where Al, Fe, Cu, and plastics are separated. The remaining fine solids (a.k.a., black mass) are mostly cathode and anode materials, and are further sent to a secondary crushing stage [91,92]. The crushed black mass is then sieved with a mesh opening size of 500 µm. The overflow is transferred to a second classification step (“2. Air Classification” in Figure 9), where it is split into fractions containing Al–Cu and plastics. The sieved underflow is directed to a leaching phase in the presence of an undisclosed extraction agent.

During leaching, graphite is initially removed from the solution, followed by Co, Ni, and Mn, which are precipitated in oxide form. The Li remaining in solution is then precipitated as LiOH, Li₂CO₃, by crystallization, or as a mixture of LiOH and Li₂CO₃ by electrochemical precipitation (“Leaching and

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3.2.4. OnTo Technology

The OnTo Process (sometimes also referred to as EcoBat) aims to recover a wide range of LIB components, including anode, cathode, and metals, explicitly mentioning polymeric materials as the single loss [97–99]. At present, this process includes several patents and an operation at the laboratory scale [51,100–104]. Figure 10 presents a graphical representation as accurate as the publicly available information allowed.

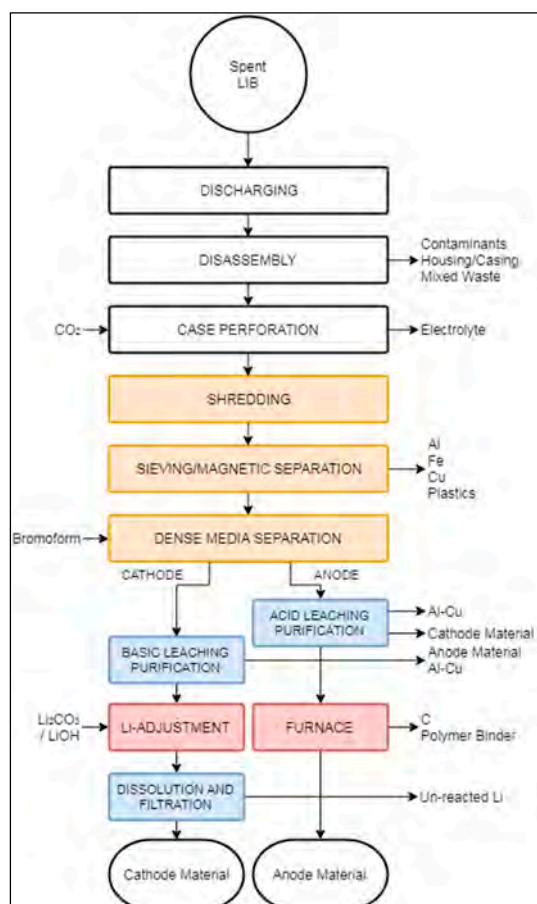


Figure 10. Schematic representation of the OnTo recycling process.

Similarly to the Battery Resources and LithoRec processes, the OnTo process proposes an initial discharging to reduce the risk of explosion, followed by disassembling to remove large components in the feed. The clean, exposed cells undergo a perforation stage to expose the internal components [100]. After perforation, the cells are enclosed in a chamber with CO_2 at supercritical condition (i.e., 74 bars and 31 °C). These conditions reportedly make possible the extraction and recovery of the solvent and electrolyte. The remaining cell, i.e., casing, anode, cathode, and separator, are then stabilized at atmospheric pressure and temperature. Shredding is then carried out, but is not performed under any particular environment, although an atmosphere free of moisture and oxygen has been suggested to avoid contamination of the material [51]. After shredding, Sloop (2010) presents the idea of sorting the elements into the following materials: (i) metal oxides, (ii) propylene, (iii) Li_2CO_3 , (iv) Cu and Al, and (v) graphite. Hailey and Kepler (2015) [97] suggested the metals be separated based on particle

size and magnetic properties, although they did not present the details of these proposed stages (“Sieve/Magnetic Separation” box in Figure 10).

The overflow fraction, rich in Al, Fe, Cu, and propylene, is extracted from the process, which can then be further treated to separate the metallic fractions. The underflow fraction, containing a mixture of electrode material, can be separated using dense media separation (DMS) to refurbish anode (graphitic carbon) and cathode (Li_2CO_3) materials. DMS is carried out in media of about 2.2 to 3.5 g/cm³ [97].

Cathode and anode streams are then directed to parallel hydrometallurgical purification processes. As the DMS process is not 100% efficient, anode particles need to be removed from the cathode fraction and vice versa. Anode purification occurs in two different environments to remove possible impurities: a low-pH treatment removes the remaining cathode particles, then a high-pH environment extracts Al and Cu particles. Cathode purification happens in a basic solution to extract anode particles. Further details about these stages were undisclosed, likely due to intellectual property concerns, but purification was reported to reach a purity of 99% for both anode and cathode materials [97].

Anode and cathode fractions are transferred to a pyrometallurgical stage, where the cathode material is regenerated in a high-energy environment with the addition of pristine Li_2CO_3 or LiOH . Anode regeneration occurs at a high temperature, where moisture, carbon, unreacted Li, and polymer impurities are eliminated. During pyrometallurgical treatment of the anode fraction, no additional input of chemical additives is required. After the regeneration stages, anode and cathode materials are reportedly suitable for LIB production.

3.2.5. Laboratory Process Suggested by Aalto University

The process discussed by References [43,44] encompasses a mixture of mechanical pre-processing stages followed by a pyrometallurgical step and a thorough hydrometallurgical treatment to recover 99% of the LIB materials.

The process, shown in Figure 11, begins with crushing and sieving, resulting in two distinctive fractions: one formed mostly of the electric peripherals, current collectors, and foils, and a second one formed mostly of the electrode materials. As seen in Figure 10, the two fractions obtained mechanically are processed via two parallel paths: a hydrometallurgical and a pyrometallurgical process designed to treat the electrode material and metallic fraction, respectively. The hydrometallurgical treatment consists of a series of 11 steps specifically designed to obtain cobalt oxalate, CoC_2O_4 , while recovering other elements found in the electrode material fraction, including Li, Ni, Fe, and Co. A pyrometallurgical treatment in a rotary kiln has been proposed to recover Al and Cu. Based on laboratory-scale experiments and process simulations, the Aalto University process has been claimed to recover the vast majority of elements contained in LIBs with a high efficiency [44]. That is, the hydrometallurgical stage recovers 99% of Al, 93% of Li, 89% of Co, 97% of Ni, 98% of Cu, 98% of Mn, and 99% of Fe. The pyrometallurgical path produces a molten phase with 74% of Al with 26% of Cu. It should be noted, however, that the hydrometallurgical products are not in their elemental forms, but rather in chemical compounds, which may require further treatment to be considered usable raw materials for the LIB industry.

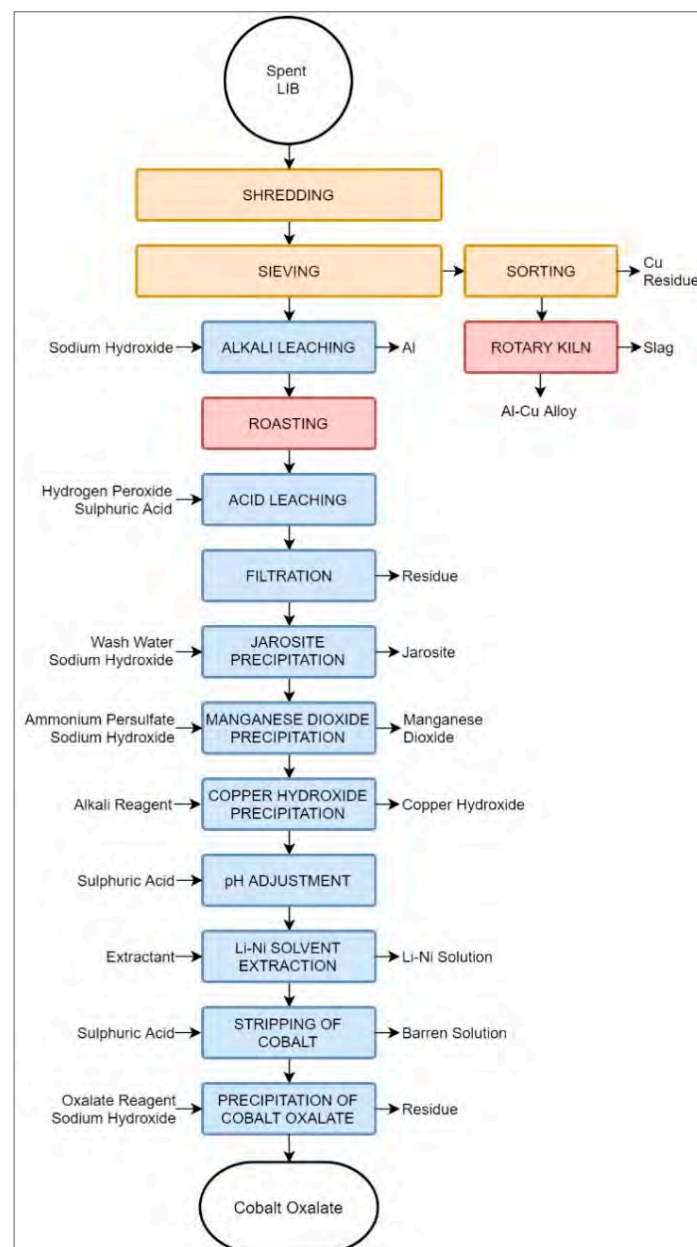


Figure 11. Schematic representation of Aalto University's suggested recycling process.

4. Discussion

4.1. Recycling Processes

In this section, a critical discussion on the suitability of the recycling processes and their viability to support a CE model is presented. Table 2 presents a summary of processing stages, final products and their target use, for all technologies discussed in Section 3.

Table 2. Summary of LiB recycling processes.

Process	Feed	Pre-Processing	Mechanical Processing	Pyro	Hydro	Main Recoveries	Secondary Recoveries	Use of Main Recoveries	Use of Secondary Recoveries	Losses
Umicore ValÉas™	LiB, NiMH	Dismantling	-	Shaft furnace	Leaching solvent extraction	Co, Ni, Cu, Fe CoCl ₂	Slag: Al, Si, Ca, Fe, Li, Mn, REE	Metal industry, cathode production	Construction industry	Electrolyte, plastics, graphite
Sumitomo–Sony	LiB.	Sorting Dismantling	-	Calcination	Hydro	CoO	Co–Ni–Fe alloy Cu, Al, Fe	Battery industry	Metal industry	Electrolyte, plastics, Li, Ni, graphite
Retriev Technologies	LiB Primary Li	Dismantling	Wet comminution, screening, shaking table, filtration,		Precipitation	Li ₂ CO ₃ MeO	Steel Cu, Co, Al	Cathode production, metal industry	Metal industry	Plastic
Recupyl Valibat	LiB Primary Li	-	crushing, vibrating screen, secondary screen, magnetic separator, densimetric table,	-	Hydrolysis leaching	Li ₂ CO ₃ , LiCO ₂ , Li ₃ PO ₄	Steel Cu, Al Cu, MeO, C	Cathode Production.	Metal industry	Cu, graphite
Akkuser	LiB	Sorting	1st cutting, air filtration, cutting, magnetic separator	-	-	Co, Cu powder Fe	Non-ferrous metals	Various including metal industry	Metal industry	Plastic
Accurec	LiB	Sorting Dismantling	Milling, separation, agglomeration, filtration, ambient	Vacuum thermal treatment, reduction	H ₂ SO ₄	Li ₂ CO ₃ Co-Alloy	Metallic alloy	Production of cathode material	Metal recovery	Electrolyte, polymers, graphite
Battery Resources	LiB	Discharge	Shredding, magnetic separation, sieving, dense media; ambient	Sintering	Leaching by: NaOH, H ₂ O ₂ , H ₂ SO ₄ , and Na ₂ CO ₃	Li ₂ CO ₃ NMC(OH) ₂	Ferrous metals	Battery cell production	Metal industry	Electrolyte
LithoRec	LiB	Discharge Manual disassembly	Two-stage crushing, two-stage air classification; inert.	Drying, calcination	Undisclosed leaching agent	Li ₂ CO ₃ metal oxides	Al–Cu, plastic fractions	Battery cell production	Metal industry	Electrolyte
OnTo	LiB Primary Li	Discharge Dismantling	Shredding, sieving dense media separation; supercritical CO ₂	Present (undisclosed).	Leaching purification, dissolution	Refurbished cell cathode powder	Ferrous and non-ferrous metals	Battery cell production	Metal industry	Binder, graphite
Aalto University	LiB	-	Shredding, sieving	Aluminium smelter	Leaching	CoC ₂ O ₄ Al	Jarosite, manganese dioxide, copper hydroxide, Li–Ni solution.	Reprocessing required	Reprocessing required	Graphite, binder plastic, Cu, water

As seen in Table 2, only two of the state-of-the-art recycling processes are specialized for treating LIB, i.e., Sumitomo–Sony and Akkuser. Of the emerging processes, only the OnTo Process is capable of treating primary and secondary LIBs simultaneously. The rest of the processes are specialized for one or the other. Nevertheless, while Umicore and Recupyl processes were not initially designed for the processing of LIB, the increasing presence of these types of battery in waste streams pushed for a redesign to accept LIBs as part of their feed. At the same time, the Umicore and Sumitomo–Sony processes claim that their products can be mixed with virgin materials and used as raw materials for batteries. In this manner, the requirement for pristine material is reduced without sacrificing quality requirements.

In the new process developed by Retrie Technologies (Figure 3), the material is ground to a smaller particle size (105 μm vs. 707 μm) compared to the original process (Figure 2). This change in particle size improves the separation of anode and cathode by froth flotation while removing carbon and binder, the presence of which deteriorates the performance of remanufactured cathode [104,105]. Nevertheless, employing a water-intensive technology such as froth flotation involves environmental risks, as it is well known that some hazardous battery components are water-soluble [51]. On the other hand, the wet-crushing system of the original Retrie Process, Figure 2, is at a disadvantage for carbon–binder separation [106]. This drawback is tackled by thermal treatment at 500 $^{\circ}\text{C}$, where the binder is decomposed.

The Recupyl process is capable of recovering Co-containing cathode powder and LiFePO_4 whenever it is present in the feed. In addition, processing of the electrolyte LiPF_6 is possible, recovering PF_6 and an ammonium salt during a hydrolysis phase (Figure 4) [80].

The high levels of recycling efficiency of the Akkuser process (i.e., >90%) and its low energy consumption (0.3 kWh/kg_{material}) set this process in a privileged position compared to the rest. It is, however, only possible to reach this cost/efficient value because this process is based only on mechanical processing steps, and aims to obtain a black mass for cathode precursor manufacturing by a third party [107,108]. Thus, the stages for refinement are not directly related to Akkuser, and have been left out of this process [75]. Moreover, the Akkuser process reports losses of plastics only during processing. The process was included in this review because it is a real industrial-scale operation [75,108].

There has been a general shift regarding the final aim for materials recovery from the SoA to emerging technologies. While the former focus on metals recovery (or alloys), the latter also aim to recover cathode or cathode precursor material. In addition, the goal of diminishing material losses is more explicitly pursued by the emerging processes. The extensive processing in emerging processes is directly related to the quality of the final recovery. In processes dominated by pyrometallurgy, the only expected product is a metallic alloy. More complex processes entailing hydro- and pyrometallurgy and mechanical processing are able to obtain a wider variety of materials. Additionally, processes using pyrometallurgical operations report larger losses, e.g., Umicore ValéasTM and Sumitomo–Sony processes do not recover electrolyte, plastics, organic material, metals, and graphite. In the case of the Umicore ValéasTM, the slag is not listed as a loss, but as a by-product, because this process explicitly pursues an afterlife for the slag phase as additive for the construction industry [34]. However, using a material in applications with low economic value can be considered a downgrading operation. Nevertheless, as seen in Table 2, methods presenting an initial pyrometallurgical step do not require a discharging step, as is the case for mechanical and hydrometallurgical processes. Discharge in a controlled environment is bound to the mechanical and hydrometallurgical stages, due to the risk of ignition [51,91]. For example, the Akkuser process requires environmental control carried out by a cyclone air system. In the Retrie process, the concentration of O_2 in the environment needs to be adjusted, as it is highly reactive with the pure Li found in primary LIBs.

Other significant differences between SoA technologies and emerging processes is that the main products of the former are not specifically recovered for LIB manufacturing. In comparison, the emerging technologies aim to recover cathode and/or anode precursor materials to satisfy the specific needs of the LIB industry.

Consequently, the emerging technologies require a larger number of mechanical processing stages, in addition to a combination of hydro- and pyrometallurgical stages. Evidently, the higher complexity of the emerging technologies raises questions of their viability compared to simpler process recovering a limited variety of products. For instance, the Battery Resources process requires the consumption of various chemical reagents (e.g., MnSO_4 , NiSO_4 , and CoSO_4) but obtains the most suitable product for use as a cathode material, at least out of the processes analyzed herein. This brings up the need for balance between the total number of stages, the overall process complexity, and the quality of the products [45]. It is well known that a more complex process, of any nature, is associated with a higher possibility of failure, and requires larger quantities of energy and chemical reagent input while not fully eliminating the generation of waste. For instance, the Aalto University process presents a high quality of products, but also demands a large number of reagents in the hydrometallurgical stages and high energy in the pyrometallurgical step, in addition to efficient mechanical pre-processing stages.

Comparing the different operations present in the processes, there is a clear advantage to the use of mechanical processing coupled hydrometallurgical operations from a CE perspective, i.e., an increase in the variety and usability of the recoveries [73]. This can especially be seen in the products of the Toxco and Recupyl processes, where the losses are diminished considerably in comparison to Umicore Valeas™ or Sumitomo–Sony. Even if the main recoveries of the Umicore Valeas™, Toxco, and Recupyl processes are intended to be used for cathode production, only the latter two recover Li_2CO_3 and LiCO_2 in the same operation, which are considered cathode precursors. If a cathode precursor is defined as a material that do not require further processing to be used in cathode manufacture, the CoCl_2 obtained in the Umicore Valeas™ process cannot be considered a cathode precursor, as it requires further chemical treatment for cathode material synthesis [70,97]. Thus, it is possible to say that the Toxco and Recupyl are more in line with the idea of circular economy, in comparison to the rest of the processes.

As seen in Table 2, how close the recovered Li components are from being re-used as cathode material is directly related to the complexity of the process. For example, the Recupyl process recovers a cathode precursor, while Sumitomo–Sony produces CoO . Evidently, there are advantages and drawbacks for recycling processes based on either pyro- or hydrometallurgy. In general, pyrometallurgical processes are more energy intensive and lead to larger material losses, but the metallic components are easily upgraded to a commercially valuable state. On the other hand, processes based on hydrometallurgy can recover materials with chemical characteristics suitable for LIB manufacturing, thus “closing the loop” in a more efficient manner. However, hydrometallurgical processes are bound to mechanical processing operations in order to liberate the valuable elements confined in the LIBs. In addition, hydrometallurgical operations require vast amounts of reagents and strictly controlled chemical environments to perform dilution or precipitation of the target materials. In summary, the technologies presented in Table 2 suggest that processes with a higher degree of complexity are necessary to close the materials cycle for all components of LIBs.

From a CE perspective, the preferred processes should entail multiple layers of closed material loops using the fewest possible external inputs to obtain, for instance, cathode precursors. As described in previous sections, both emerging and state-of-the-art processes achieve to some extent the aims of CE for LIBs, bringing valuable materials back into the economic cycle. However, the recovery of materials is only one aspect of the CE. In a closed loop process, resource inputs should also be minimized. Emerging processes require the consumption of additional reagents to achieve the target recoveries. The internal loops in the Battery Resources and LithoRec processes support reduced consumption of external resources for the pyrometallurgical refining process for cathode precursors, e.g., Li_2CO_3 . In addition, the OnTo process reports the possibility of recovering battery components suitable for LIB manufacturing [100–102].

Even though emerging processes appear to be closer to the ideal of circular economy, they are not without their drawbacks. For instance, they are mostly focused on one type of battery chemistry, reducing the flexibility of the feed compared to SoA technologies. Some of these technologies require chemical reagents considered hazardous, e.g., the bromoform used in the OnTo process to

separate anode and cathode during dense media separation has been associated with kidney and liver injuries [109]. Evidently, there is still room for improvement. For example, the Accurec and LithoRec processes do not recover electrolyte, while the available information on the Battery Resources process does not mention electrolyte recovery whatsoever. The OnTo process is unique in this sense as it allegedly recovers the electrolyte components, i.e., solvent and Li salt [51,100,110]. It has been expressed that the OnTo process is able to recover about 80% of the LIB components, making it an attractive possibility for development at the industrial scale [99]. Interestingly, during a test conducted by Rothermel et al. [111] graphite recovered from the OnTo process outperformed new synthetic graphite in discharge capacity, although it presented a lower discharge capacity compared with non-synthetic graphite. This drawback was attributed to the environment used during the extraction of electrolyte with supercritical CO₂, as it may have damaged the crystalline structure of the graphite [111]. As the emerging processes are still in early stages of development, additional risks may become evident during the scale-up phase [27,29,65,73].

4.2. Recovery of Materials

4.2.1. Cathode Active Material

The cathode active powder is the main target of most of emerging recycling processes because of its high economic value, particularly in formulations containing Co [58,70]. Indeed, Co-containing cathode chemistries (LiCoO₂, LiNi_xMn_yCo_zO₂) have a relatively higher cost than other commercial cathode materials (LiMn₂O₄, LiNiO₂, LiFePO₄).

The recovery of cathodes is, however, a complicated process. As discussed in previous sections, it requires a vast number of preparation and enrichment stages before undergoing final hydrometallurgical refining. Proper purification of the EoL cathode material is crucial because of its high chemical sensibility, where minor contaminants may compromise the quality of the final product. For example, a concentration of Cu above 1.8% slows down the cathode capacity retention compared to pristine chemistries of LiNi_xMn_yCo_zO₂ [86,92], while Al in a concentration higher than 0.6% decreases the capacity from 6–14% within the first 500 cycles [96]. (A cycle is herein defined as the process of full charge and discharge of a battery.) Nevertheless, a concentration up to 0.3% of Al in the recycled cathode material does not result in a significant difference on the cell capacity compared to pristine material [84]. Moreover, the chemical sensibility of the hydrometallurgical steps is affected by the composition of the throughput. For example, during Ni precipitation processes Cu traces are co-precipitated, effectively resulting in Ni losses [85]. Nevertheless, the detrimental effect of impurities should be further researched in order to define tolerable concentrations. It is possible that the materials currently considered impurities could be turned into useful components at the right concentrations. This would make the recycling processes more flexible and, therefore, more suitable for industrial-scale operations. Table 3 presents a summary of the processes from a cathode recovery perspective.

On the other hand, efforts to recycle LiFePO₄ and LiMn₂O₄ cathode chemistries have been limited, mainly due to their relative lower commercial value [67,112]. However, these chemistries cover a larger share of the energy demand in the market, with LiFePO₄ and LiMn₂O₄ representing 22% and 15%, respectively. In comparison, Co-containing chemistries represent only 10% of the market [9]. In addition, between the years 2008 to 2014, the market share for these cathode chemistries increased from 4 to 9% for LiFePO₄ and 11 to 16% for LiMn₂O₄, while the share for LiCoO₂ was reduced from 61% to 40% in the same period [15].

Table 3. Cathode material recovery summary of the recycling processes.

Process	Co Recovery	Quality of Recovery
Umicore	CoCl ₂	Ready for LiCoO ₂ synthesis
Sumitomo–Sony	CoO	Recovery needs pyrometallurgical processes before cathode synthesis
Retriev Technologies	MeO + cake	Elemental cobalt
Recupyl	LCO/Co(OH) ₂ /Co	final product
Akkuser	Co + graphite	Recovery requires hydro- and/or pyrometallurgical processes before cathode synthesis
Accurec	Co alloy	Elemental cobalt
Battery Resources	NMC(OH) ₂	Ready for cathode synthesis
LithoRec	MeO	Ready for cathode synthesis
OnTo	Cathode powder (refurbished)	Final product
Aalto University	CoC ₂ O ₄	Recovery requires processing

The emerging technologies Battery Resources, LithoRec, and OnTo are, however, capable of processing these upcoming chemistries. Although the Battery Resources process is mainly focused on Co-containing chemistries, it is claimed that it is able accept other chemistries. The OnTo and LithoRec processes accept LiFePO₄ and LiNi_xMn_yCo_zO₂ chemistries, respectively. The Battery Resources and LithoRec processes are of special interest from the circular economy perspective as they include an internal loop, where previously recovered materials (i.e., Li, Mn, Ni oxides, Li₂CO₃) are consumed in the final pyrometallurgical stages [84,105]. In both of these processes, the final product, i.e., cathode precursor of pristine quality, is obtained with marginal amounts of additional reagents. Such internal loops may require more complex process control strategies and additional energy for operation. On the other hand, the OnTo process is the only one to address direct use of the cathode material after re-lithiation [98]. The Aalto University process, on the other hand, does not obtain a cathode quality material, rather producing precursors containing Co and Li in solution.

Finally, an economic–energetic analysis conducted by Reference [113] revealed that the process of manufacturing of these cathode chemistries from either primary or secondary sources would surpass economic feasibility. Hence, until the economic panorama changes for LiFePO₄ and LiMn₂O₄, these chemistries will remain secondary priorities for the recycling industry.

4.2.2. Lithium Recovery

Elemental Li is currently not a primary driver for LIB recycling, being mainly recovered as part of the cathode active materials. Other forms of Li (e.g., in electrolyte) are generally lost. Being present in at least two different compounds, the recovery of this element is complicated and not pursued by SoA recycling processes. In addition, Li is not considered to be a critical element by the EU [114–116], and the global reserves of this metal are deemed sufficient [117]. Li recovery is, thus, in a disadvantageous position compared to other LIB components. However, the losses of Li into waste contribute to unnecessary mining operations. Additionally, the importance of this metal may increase moving forward, and its recyclability may be justified by the increasing demand for LIBs [9,18,45,110,118].

As previously mentioned, Li recovery as part of the cathode is chemically demanding and requires carefully controlled environments. Thus, efficient Li recovery methods should be developed [84], or a replacement material found that is easier to recycle. Further complications come in the form of stability of the hydrometallurgical process feed, where Li precipitation is usually the final stage and therefore is highly dependent on the separation efficiency of previous stages. Table 4 summarizes the recycling processes from a lithium recovery standpoint, including recovery method, process efficiency, quality, and potential use of recovery.

Table 4. Lithium recovery summary of the recycling processes.

Process	Li Product	Recovery Method	Efficiency	Recovery Quality	Target Use of Recovery
Umicore	Not recovered	-	-	-	-
Sumitomo–Sony	Not recovered	-	-	-	-
Retriev Technologies	Li ₂ CO ₃	Precipitation with Na ₂ CO ₃ /CO ₂	90%	No data	Metal manufacture
Recupyl	Li ₂ CO ₃ /Li ₃ PO ₄	Precipitation with CO ₂	No Data	No data	Not discussed
Akkuser	Not recovered	-	-	-	-
Accurec	Li ₂ CO ₃	Precipitation	76–90%	>99%	Glass production/cathode synthesis
Battery Resources	Li ₂ CO ₃	Precipitation with Na ₂ CO ₃	67–80%	“High Purity”	Cathode powder synthesis
LithoRec	Li ₂ CO ₃ /LiOH	Precipitation	85–95%	No Data	Cathode powder synthesis
OnTo	Li ₂ CO ₃ /cathode	Undisclosed	Undisclosed	99%	Battery production
Aalto University	Li–Ni solution	Leaching	93–97%	0.1%	Not discussed

As seen in Table 4, the efficiency of the processes varies from 76% to 95% of Li being recovered, reflecting processes with a potentially positive economic impact [17,85,91]. It has been proposed that Li recovery could lead to different possible uses after enrichment, ranging from ceramics and glass to cathode precursors, depending on its purity. Clearly, the quality of recovered Li salt from the emerging processes can be considered suitable for LIB industry and, thus, using them as glassware raw material would be a downgrade of the original material. Indeed, Accurec reports a 99% purity of Li recovery, while Battery Resources reports a “high purity” product. The Li_2CO_3 obtained in the Accurec and Battery Resources recoveries can also be used during Al production as an electrolyte additive [117]. However, the recovery process for Li compounds is a delicate process; for instance, as Li_2CO_3 cannot be precipitated from aqueous solutions, it is easily lost as a by-product [84]. In the Aalto University process, a high recovery of Li can be achieved (up to 93%), although in a highly diluted form. Since the recovery of Li–Ni in solution is, in fact, one of the last hydrometallurgical stages, there can be a high accumulation of liquid solvents. In addition, the extractant may not be highly efficient at separating Li from the cathode, thus requiring large quantities to effectively separate this compound into its elements.

Accurec, Battery Resources, and LithoRec mention active cathode powder manufacturing as the intended use for Li salts, although Accurec also mentions flask production as an alternative option. The OnTo technology recommends its Li compounds for battery production, among other unspecified uses. As the purity requirement for Li_2CO_3 to be reused in cathode production is 99.5% [119], it is likely that the only process able to achieve such quality will involve blending it with virgin materials. This strategy is already followed in some emerging processes. However, the purity requirements may rise up to 99.9% [119], in which case downgrading may be the most suitable afterlife for this element. In fact, Li could be used in the glass and ceramic industries, which represent a market share for Li_2CO_3 of similar size (32%) to batteries (35%) [117]. Other possible uses for Li salts could be as an electrolyte additive during Al production and metal casting [117].

4.2.3. Metals Recovery

The recovery of metals is the major driver for the SoA LIB recycling processes, and remains essential in the emerging processes. In emerging technologies, the extraction of metals entails collateral benefits, as Cu, Al, and Fe act as impurities in the hydrometallurgical cathode recovery process. Table 5 summarizes the recycling processes from a metal enrichment perspective.

Those processes relying on pyrometallurgy as main recycling step present losses of metals in addition to the electrode components. However, the metallic fractions (mostly present in the form of foils) may be recovered by mechanical processing steps during pre-treatment [120]. This shows again that recycling processes employing a more thorough pre-processing may indeed recover the majority of the LIB components.

As seen in Table 5, most of the processes recover Fe and Cu through mechanical processing operations, e.g., Retrie Technologies employing shaking tables, or the recovery of Fe in the Battery Resources process using magnetic separation. Those processes overlooking pre-concentration report further losses, i.e., Al is lost as slag in the Umicore and Sumitomo–Sony processes. Retrie employs shaking tables for metal separation, which is a reasonable choice as the intended application of products is in metals manufacturing, and materials of superior quality are not required. The two-step comminution process used by Recupyl and Akkuser seems to be associated with safe and controlled processing of the active cells. Even though the comminution parameters in the Akkuser process were not discussed in relation to separation efficiency, it is notable that a cutting mill was specifically chosen out of all available comminution options. Thus, there is some indication that cutting stress is associated with good separation results. In the Recupyl process, particular attention is paid to comminution due to the presence of primary Li cells. In the LithoRec, a two-step comminution under mild cutting stress was chosen for improved separation efficiency.

Table 5. Metal recovery summary of the recycling processes.

Process	Fe Casing	Al and Cu Foils	Losses
Umicore	Fe: recovered in alloy	Cu: recovered in alloy	Al, polymer
Sumitomo–Sony	Fe: recovered in alloy	Cu: recovered.in alloy	Al, polymer
Retriev Technologies	Fe, Al, and plastics: recovered in shaking table	Not mentioned.	Not mentioned
Recupyl	Fe: recovered with magnetic separator	Al, Cu, and plastics: recovered with density separation	Not mentioned
Akkuser	Fe: recovered with magnetic separator Plastics: recovered via air filtration	Al and Cu: recovered from fin powder	Fraction of Cu and Al
Accurec	Fe: recovered with magnetic separator	Al and Cu: recovered via air separator	Polymer
Battery Resources	Fe: recovered with magnetic separator	Al: recovered during leaching Cu: recovered via dense media separation and precipitation	Not mentioned
LithoRec	Fe, Al, and plastics: recovered via air separator	Al and Cu: recovered via sieves and zig-zag sifter	Not mentioned
OnTo	Fe, Al, and plastics: recovered	Al and Cu: recovered	Not mentioned
Aalto University	Fe: extracted at pre-processing	Rotary kiln	Cu, graphite.

In the LithoRec and OnTo processes, metallic components such as Cu can be separated by sieving, as they report to specific particle size fractions after shredding [50,111]. However, shredding also delivers fine particles of which recovery may only be possible through leaching during the electrode purification stage, as in the OnTo process. The Accurec process uses an air separator followed by magnetic separation to promote the separation of Fe from the Al and Cu phases. Originally, LithoRec claimed to be able to separate steel without magnetic separation, although this step was added to the process in a follow-up project [50,111]. Detailed information about the exact methods OnTo implements for casing and foil separation was unavailable, but different types of density-based methods are mentioned as suggestions. The Aalto University process, on the other hand, relies on sieving followed by a rotary kiln to recover Al and Cu in alloy form.

As can be seen, casing and foil materials can be recovered by physical means, although they may require further processing to become raw materials suitable for LIB manufacturing. In addition, precipitation may be necessary during the hydrometallurgical steps for cathode recovery in order to further remove finer metallic fractions.

4.2.4. Graphite Recovery

Even though graphite is presently not of major interest for the battery recycling industry [92], promoting its reinsertion into the economic cycle is a valid concern from the CE perspective, as it will decrease the exploitation of mineral deposits and their associated environmental impact. Table 6 presents a summary of the recycling processes based on their corresponding graphite recovery abilities.

Table 6. Graphite recovery summary in emerging processes.

Process	Graphite
Umicore	Used as reducing agent in furnace
Sumitomo–Sony	Lost during calcination
Retriev Technologies	Recovered during filtration as: MeO–graphite cake
Recupyl	Filtered off in leaching step
Akkuser	Remain as fraction of the black mass
Accurec	Used as reduction agent
Battery Resources	Extraction, no use expressed
LithoRec	Extraction, no use expressed
OnTo	Recovered by leaching for LIB purposes
Aalto University	Lost in rotary kiln

As shown in Table 6, details related to graphite recovery are scarce. It is also necessary to emphasize that, in most cases, the real recovery of graphite remains uncertain. Indeed, graphite is extracted from the feed but the subsequent phases are not typically discussed. In processes that use pyrometallurgical methods, like the Umicore, Sony, Accurec, and Aalto University processes, graphite is used as energy source and reducing agent. Retriev technologies recover graphite in an elemental form in a MeO filter cake. The Akkuser process seems to recover graphite as part of the black mass containing cathode material. In Recupyl and LithoRec, graphite is removed from the solution at the beginning of the leaching step. However, it is mentioned that utilizing such recovered graphite is not feasible at the moment [92], even though it has been proven technically possible to produce battery-grade graphite via subcritical CO₂ cleaning combined with thermal treatment [112]. Battery Resources and OnTo state that they recover graphite, but the details of the exact method have not been provided. Nevertheless, the electrolyte recovery step with supercritical CO₂ is capable of removing reactive functional groups from the graphite surface [51,111]. Monadi et al. [121] stated that to separate graphite by hydrometallurgical methods, the anode has to be treated separately from the cathode, pointing out the need for pre-separation of graphite.

As seen, OnTo is the only process in Table 6 that explicitly recovers graphite for LIB anode manufacturing using CO₂ in supercritical conditions followed by thermal treatment [51]. The anode

recovered from the OnTo process has the same physical characteristics (i.e., grain size and morphology) as pristine graphite [97]. However, the OnTo process is particularly complicated, since it requires pH control for the different components embedded in the cathode and anode. The Accurec process explicitly mentions the use of graphite as a reduction agent during the pyrometallurgical process. The Battery Resources and LithoRec processes are able to extract graphite as a by-product during their leaching processes, but they do not mention any particular use for the anode after extraction [92].

Compared to the cathode and metallic components, graphite production constitutes a small share of the total energy consumption of the cell materials during their life cycle [105]. Even though there is proof of the potential use of recycled graphite, further economic studies may be needed to demonstrate their feasibility [111].

5. Conclusions and Recommendations

This review offers a critical analysis of emerging and SoA recycling processes for LIBs, focusing on their potential to contribute to CE. It discussed emerging processes that are more in line with the concept of CE, as they recover a larger variety of components and aim to reduce the waste streams or repurpose the generated by-products. The OnTo process is of particular interest, as it recovers cathode and anode material from spent LIBs to a point where they can be reused directly for LIB manufacturing. Similar processes, like Battery Resources, LithoRec, and Accurec, obtain similar products in line with the CE concept. However, their processes still have flaws, i.e., losses in the form of non-recovered anode material. In addition, the Aalto University process presents a recovery of the vast majority of the LIB compounds; however, the recovered forms still require further processing to be considered usable raw materials. Contrastingly, the SoA technologies result in significant material losses, e.g., electrolyte, graphite, Cu, Ni, Li, etc.

Furthermore, the importance of developing processes that rely on fewer external inputs and lower waste generation was addressed. For instance, the LithoRec process reports a single battery type in the feed, leachant and multiple reagents as part of its regular operation, and output streams of cathode material, metallic fraction, electrolyte, and volatile material, which may be used again for LIB production. In comparison, the OnTo process requires multiple inputs (i.e., bromoform, CO₂, and Li compounds) to recover suitable anode and cathode mixed materials, while also producing mixed waste containing electrolyte, C, and organic material. Thus, an ideal recycling process with a true attachment to the CE concept obtains materials in the same chemical form as those found in the products with a minimum input of external resources and negligible waste streams. From this perspective, the OnTo process may be the technology with a closest attachment to the goals of CE, from the alternatives studied in this review. In other emerging technologies, the recycling products require further chemical transformations before their use in the manufacturing of LIBs is possible. Although these processes still aim to fulfil the ideals of CE, additional processing is inevitably associated with the consumption of additional resources and generation of waste.

Further research on the subject of processing diluted mixtures and the correlation between feed and product quality is therefore advisable. Different authors have approached this challenge by proposing and discussing the use of process simulators, e.g., HSC Sim[®] (Outotec, Pori, Finland), Aspen Plus[®] (Hyprotech, Calgary, AB, Canada), Chemcad[®] (Chemstations, Smithfield, NC, USA), etc., to evaluate the costs of these complex physical and chemical transformations [122–125]. This type of metallurgical process analysis surpasses the capacity of traditional and expensive in situ testing through the calculation of thermodynamic and engineering parameters such as:

1. Energy cost calculations,
2. Plant efficiency.

Moreover, References [32,44] used process simulation to obtain a systemic assessment based on statistical entropy and material flow analysis. Such approaches describe recycling processes based on the material concentrating efficiency of a system, where the material losses (dilutions) have a

measurable impact on the final entropic value. This use of process simulation tools, sometimes referred to as the “digitalization of circular economy”, is a necessity in systems with intricate materials such as LIBs, in order to objectively evaluate their impact on the circular economy.

Furthermore, the diversity of cathode chemistries presents an additional challenge, since they may require diverse conditions for an efficient recycling process. Thus, treating them simultaneously may increase the required resources (e.g., energy and time consumed by a sorting mechanism) or may have a negative impact on the quality of recovered components (e.g., incompatibilities among cathode chemistries or processing conditions). Current developments in battery chemistry may also introduce additional elements in the future. As countermeasure for these drawbacks, it is worth exploring the concentration limits for impurities in secondary raw materials. On the other hand, consensus between battery manufacturers as to the use of a standardized LIB labeling system (e.g., based on the cathode chemistry) might allow automatic sorting operations. In this way, resources would be better used to obtain a suitable feed for efficient processing. This review thus intended also to offer a starting point for serious discussion on the need to design batteries while taking into consideration the technical challenges currently present in recycling processes.

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References

1. Tarascon, J.M.; Armand, M. Issues and challenges facing rechargeable lithium batteries. *Nature* **2001**, *414*, 359–367. [[CrossRef](#)] [[PubMed](#)]
2. Linden, D.; Reddy, B.T. (Eds.) *Linden’s Handbook of Batteries*, 4th ed.; McGraw Hill: New York, NY, USA, 2011.
3. Aditya, J.P.; Ferdowsi, M. Comparison of NiMH and Li-ion batteries in automotive applications. In Proceedings of the 2008 IEEE Vehicle Power and Propulsion Conference, Harbin, China, 3–5 September 2008; pp. 1–6.
4. Hameer, S.; Van Niekerk, J.L. A review of large-scale electrical energy storage. *Int. J. Energy Res.* **2015**, *39*, 1179–1195. [[CrossRef](#)]
5. EBRA. 2012: *Noticeable Growth of the Quantity of Batteries Recycled*; European Battery Recycling Association: Brussels, Belgium, 2012.
6. EUR-Lex. Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. *Off. J. Eur. Union* **2006**, *266*, 1–14.
7. European Commission. *Report on Critical Raw Materials for the EU*; European Commission: Brussels, Belgium, 2014.
8. Roper, L.D. *Tesla Model S*; Virginia Polytechnic Institute and State University: USA, 2019. Available online: <http://www.roperld.com/science/TeslaModelS.htm> (accessed on 13 June 2019).
9. Bernhart, W. The Lithium-Ion Battery Value Chain—Status, Trends and Implications. In *Lithium-Ion Batteries*; Elsevier: Rome, Italy, 2014; pp. 553–565.
10. Pillot, C. The Rechargeable Battery Market and Main Trends 2014–2025. In Proceedings of the Advanced Automotive Battery Conference, Chicago, IL, USA, 21 September 2016.
11. Mohammadi, F. Electric Vehicle Battery Market Analysis: Lithium-Ion. In Proceedings of the 1st International Conference on Modern Approaches in Engineering Science, Tbilisi, Georgia, 21 November 2018.
12. Pillot, C. The Rechargeable Battery Market 2017–2025. *Avicenne Energy* **2018**, *6*, 26–29.

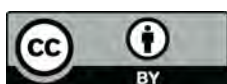
13. HDR. *Human Development Reports*; United Nations Development Programme: New York, NY, USA, 2015.
14. Earle, S.; Panchuk, K. *Physical Geology*, 2nd ed.; BC Campus: Victoria, BC, Canada, 2019.
15. Heelan, J.; Gratz, E.; Zheng, Z.; Wang, Q.; Chen, M.; Apelian, D. Current and Prospective Li-Ion Battery Recycling and Recovery Processes. *JOM* **2016**, *68*, 2632–2638. [[CrossRef](#)]
16. Ledung, G. *State-of-the-Art in Reuse and Recycling of Lithium-ion Batteries-A Research Review by Hans Eric Melin, Circular Energy Storage*; The Swedish Energy Agency: Eskilstuna, Sweden, 2019.
17. Georgi-Maschler, T.; Friedrich, B.; Weyhe, R.; Heegn, H.; Rutz, M. Development of a recycling process for Li-ion batteries. *J. Power Sources* **2012**, *207*, 173–182. [[CrossRef](#)]
18. Wang, X.; Gaustad, G.; Babbitt, C.W.; Richa, K. Economies of scale for future lithium-ion battery recycling infrastructure. *Resour. Conserv. Recycl.* **2014**, *83*, 53–62. [[CrossRef](#)]
19. Cerdas, F.; Titscher, P.; Bogner, N.; Schmich, R.; Winter, M.; Kwade, A.; Herrmann, C. Exploring the Effect of Increased Energy Density on the Environmental Impacts of Traction Batteries: A Comparison of Energy Optimized Lithium-Ion and Lithium-Sulfur Batteries for Mobility Applications. *Energies* **2018**, *11*, 150. [[CrossRef](#)]
20. Kim, H.C.; Wallington, T.J.; Arsenault, R.; Bae, C.; Ahn, S.; Lee, J. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. *Environ. Sci. Technol.* **2016**, *50*, 7715–7722. [[CrossRef](#)]
21. Ellingsen, L.A.W.; Majeau-Bettez, G.; Singh, B.; Srivastava, A.K.; Valøen, L.O.; Strømman, A.H.; Majeau-Bettez, G. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *J. Ind. Ecol.* **2013**, *18*, 113–124. [[CrossRef](#)]
22. Xu, J.; Thomas, H.; Francis, R.W.; Lum, K.R.; Wang, J.; Liang, B. A review of processes and technologies for the recycling of lithium-ion secondary batteries. *J. Power Sources* **2008**, *177*, 512–527. [[CrossRef](#)]
23. Pillot, C. *Future Trends in the Rechargeable Battery Market*; Avicenne Energy: Montreux, Switzerland, 2015.
24. Kivi, J. *Battery Recycling, Metal Recovery and Waste Processing State of the Art*; Metallialan Ympäristö ja Kiertotalous: Espoo, Finland, 2016.
25. He, L.P.; Sun, S.Y.; Song, X.F.; Yu, J.G. Recovery of cathode materials and Al from spent lithium-ion batteries by ultrasonic cleaning. *Waste Manag.* **2015**, *46*, 523–528. [[CrossRef](#)] [[PubMed](#)]
26. Da Costa, A.J.; Matos, J.F.; Bernardes, A.M.; Müller, I.L. Beneficiation of cobalt, copper and aluminum from wasted lithium-ion batteries by mechanical processing. *Int. J. Miner. Process.* **2015**, *145*, 77–82. [[CrossRef](#)]
27. Espinosa, D.C.R.; Bernardes, A.M.; Tenório, J.A.S. An overview on the current processes for the recycling of batteries. *J. Power Sources* **2004**, *135*, 311–319. [[CrossRef](#)]
28. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [[CrossRef](#)]
29. Reuter, M.A.; Worrell, E. *Handbook of Recycling*; Elsevier: Amsterdam, The Netherlands, 2014.
30. Hawkins, T.R.; Singh, B.; Strømman, A.H.; Majeau-Bettez, G.; Majeau-Bettez, G. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* **2012**, *17*, 53–64. [[CrossRef](#)]
31. van Schalkwyk, R.F.; Reuter, M.; Gutzmer, J.; Stelter, M. Challenges of digitalizing the circular economy: Assessment of the state-of-the-art of metallurgical carrier metal platform for lead and its associated technology elements. *J. Clean. Prod.* **2017**, *186*, 585–601. [[CrossRef](#)]
32. Martínez, O.V.; Boogaart, K.V.D.; Lundström, M.; Santasalo-Aarnio, A.; Reuter, M.; Serna-Guerrero, R. Statistical entropy analysis as tool for circular economy: Proof of concept by optimizing a lithium-ion battery waste sieving system. *J. Clean. Prod.* **2019**, *212*, 1568–1579. [[CrossRef](#)]
33. Melin, H.E. *The Lithium-Ion Battery End-of-Life Market—A Baseline Study*; World Economic Forum: Cologny, Switzerland, 2018; pp. 1–11.
34. Pistoia, G. (Ed.) *Lithium-Ion Batteries Advances and Applications*, 1st ed.; Elsevier BV: Oxford, UK, 2014.
35. Bernardes, A.; Espinosa, D.; Tenório, J.; Bernardes, A.; Espinosa, D.C.R. Recycling of batteries: A review of current processes and technologies. *J. Power Sources* **2004**, *130*, 291–298. [[CrossRef](#)]
36. Ferella, F.; De Michelis, I.; Vegliò, F. Process for the recycling of alkaline and zinc–carbon spent batteries. *J. Power Sources* **2008**, *183*, 805–811. [[CrossRef](#)]
37. Ruffino, B.; Zanetti, M.; Marini, P. A mechanical pre-treatment process for the valorization of useful fractions from spent batteries. *Resour. Conserv. Recycl.* **2011**, *55*, 309–315. [[CrossRef](#)]
38. Ordóñez, J.; Gago, E.; Girard, A. Processes and technologies for the recycling and recovery of spent lithium-ion batteries. *Renew. Sustain. Energy Rev.* **2016**, *60*, 195–205. [[CrossRef](#)]

39. Sayilgan, E.; Kukrer, T.; Civelekoglu, G.; Ferella, F.; Akcil, A.; Veglio, F.; Kitis, M. A review of technologies for the recovery of metals from spent alkaline and zinc–carbon batteries. *Hydrometallurgy* **2009**, *97*, 158–166. [CrossRef]
40. Vezzini, A. Manufacturers, Materials and Recycling Technologies. In *Lithium-Ion Batteries*; Elsevier BV: Rome, Italy, 2014; pp. 529–551.
41. Zeng, X.; Li, J.; Singh, N. Recycling of Spent Lithium-Ion Battery: A Critical Review. *Crit. Rev. Environ. Sci. Technol.* **2014**, *44*, 1129–1165. [CrossRef]
42. Chen, L.; Tang, X.; Zhang, Y.; Li, L.; Zeng, Z.; Zhang, Y. Process for the recovery of cobalt oxalate from spent lithium-ion batteries. *Hydrometallurgy* **2011**, *108*, 80–86. [CrossRef]
43. Porvali, A.; Aaltonen, M.; Ojanen, S.; Velazquez-Martinez, O.; Eronen, E.; Liu, F.; Wilson, B.P.; Serna-Guerrero, R.; Lundström, M. Mechanical and hydrometallurgical processes in HCl media for the recycling of valuable metals from Li-ion battery waste. *Resour. Conserv. Recycl.* **2019**, *142*, 257–266. [CrossRef]
44. Martinez, V.; Porvali, A.; Boogaart, V.D.; Aarnio, S.; Lundström, M.; Reuter, M.; Guerrero, S.; Velázquez-Martinez, O.; Boogaart, K.G.V.D.; Santasalo-Aarnio, A.; et al. On the Use of Statistical Entropy Analysis as Assessment Parameter for the Comparison of Lithium-Ion Battery Recycling Processes. *Batteries* **2019**, *5*, 41. [CrossRef]
45. Nishi, Y. Lithium ion secondary batteries; past 10 years and the future. *J. Power Sources* **2001**, *100*, 101–106. [CrossRef]
46. Nitta, N.; Wu, F.; Lee, J.T.; Yushin, G. Li-ion battery materials: Present and future. *Mater. Today* **2015**, *18*, 252–264. [CrossRef]
47. Dahn, J.; Ehrlich, G.M. Lithium-Ion Batteries. In *Linden's Handbook of Batteries*, 4th ed.; Reddy, T.B., Ed.; McGraw Hill: New York, NY, USA, 2011; pp. 1–79.
48. Scrosati, B.; Garche, J. Lithium batteries: Status, prospects and future. *J. Power Sources* **2010**, *195*, 2419–2430. [CrossRef]
49. Blomgren, G.E. The Development and Future of Lithium Ion Batteries. *J. Electrochem. Soc.* **2017**, *164*, A5019–A5025. [CrossRef]
50. Grützke, M.; Mönnighoff, X.; Horsthemke, F.; Kraft, V.; Nowak, S.; Winter, M. Extraction of lithium-ion battery electrolytes with liquid and supercritical carbon dioxide and additional solvents. *RSC Adv.* **2015**, *5*, 43209–43217. [CrossRef]
51. Sloop, S.E. System and Method for Removing and Electrolyte from Energy Storage and/or Conversion Device Using a Supercritical Fluid. U.S. Patent 7,858,216 B2, 28 December 2010.
52. Nanografi. PVDF Binder for Li-ion Battery Electrodes. 2018. Available online: <https://nanografi.com/blog/pvdf-binder-for-liion-battery-electrodes/> (accessed on 18 June 2019).
53. Christmann, P.; Gloaguen, E.; Labbé, J.F.; Melleton, J.; Piantone, P. Global Lithium Resources and Sustainability Issues. In *Lithium Process Chemistry*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 1–40.
54. Broussely, M.; Biensan, P.; Bonhomme, F.; Blanchard, P.; Herreyre, S.; Nechev, K.; Staniewicz, R. Main aging mechanisms in Li ion batteries. *J. Power Sources* **2005**, *146*, 90–96. [CrossRef]
55. Van Beukering, P.; Kuik, O.; Oosterhuis, F. The Economics of Recycling. In *Handbook of Recycling*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 479–489.
56. Li, J.; Wang, G.; Xu, Z. Environmentally-friendly oxygen-free roasting/wet magnetic separation technology for in situ recycling cobalt, lithium carbonate and graphite from spent LiCoO₂/graphite lithium batteries. *J. Hazard. Mater.* **2016**, *302*, 97–104. [CrossRef]
57. Corrigan, D.A.; Masias, A. Batteries for electric and hybrid vehicles. In *Linden's Handbook of Batteries*, 4th ed.; Reddy, T.B., Ed.; McGraw Hill: New York, NY, USA, 2011; pp. 3–48.
58. U.S. Geological Survey. *Mineral Commodity Summaries 2018*; Unites States Geological Survey: Reston, VA, USA, 2018.
59. Pagliaro, M.; Meneguzzo, F. Lithium battery reusing and recycling: A circular economy insight. *Heliyon* **2019**, *5*, e01866. [CrossRef]
60. Dunn, J.B.; James, C.; Gaines, L.; Gallagher, K.; Dai, Q.; Kelly, J.C. *Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries*; Argonne National Laboratory: Chicago, IL, USA, 2015.
61. Wills, B.A.; Finch, J.A.; Wills, B.A.; Finch, J.A. Introduction. In *Wills' Mineral Processing Technology*; Butterworth-Heinemann: Oxford, UK, 2016; pp. 1–27.

62. Kaya, M. Recovery of Metals from Electronic Waste by Physical and Chemical Recycling Processes. *Int. J. Chem. Mol. Nucl. Mater. Metall. Eng.* **2016**, *10*, 232–243. [CrossRef]
63. Schubert, W.; Tomas, J. Chapter 24 Liberation of Valuables Embedded in Particle Compounds and Solid Waste. In *Handbook of Powder Technology*; Elsevier: Amsterdam, The Netherlands, 2007; Volume 12, pp. 989–1018.
64. Clark, J.H.; Farmer, T.J.; Herrero-Davila, L.; Sherwood, J. ChemInform Abstract: Circular Economy Design Considerations for Research and Process Development in the Chemical Sciences. *Green Chem.* **2016**, *18*, 3914–3934. [CrossRef]
65. Wills, B.A.; Napier-Munn, T. *Mineral Processing Technology An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*, 7th ed.; Elsevier Science & Technology Books: Oxford, UK, 2006.
66. McLaughlin, W.; Adams, T.S. Li Reclamation Process. U.S. Patent 5,888,463, 30 March 1999.
67. Commission for Environmental Cooperation. *Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America*; Commission for Environmental Cooperation: Montreal, Canada, 2015.
68. Lv, W.; Wang, Z.; Cao, H.; Sun, Y.; Zhang, Y.; Sun, Z.H. A Critical Review and Analysis on the Recycling of Spent Lithium-Ion Batteries. *ACS Sustain. Chem. Eng.* **2018**, *6*, 1504–1521. [CrossRef]
69. Retrieval Technologies. Lithium-Ion, 2019. Available online: <https://www.retrievaltech.com/lithiumion> (accessed on 19 June 2019).
70. Gaines, L.L.; Dunn, J.B. Lithium-Ion Battery Environmental Impacts. In *Lithium-Ion Batteries*; Elsevier BV: Rome, Italy, 2014; pp. 483–508.
71. Smith, W.N.; Swoffer, S. Process for Recovering and Regenerating Lithium Cathode Material from Lithium-Ion Batteries. U.S. Patent 8,882,007 B1, 11 November 2014.
72. Cardarelli, F.; Dube, J. Method for Recycling Spent Lithium Metal Polymer Rechargeable Batteries and Related Materials. U.S. Patent 7,192,564 B2, 20 March 2007.
73. Al-Thyabat, S.; Nakamura, T.; Shibata, E.; Iizuka, A. Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: Critical review. *Miner. Eng.* **2013**, *45*, 4–17. [CrossRef]
74. Tedjar, F.; Foudraz, J.C. Method for the Mixed Recycling of Lithium-Based Anode Batteries and Cells. U.S. Patent 7,820,317 B2, 26 October 2010.
75. Pudas, J.; Erkkila, A.; Viljamaa, J. Battery Recycling Method. U.S. Patent 8,979,006 B2, 17 March 2015.
76. Zhang, T.; He, Y.; Wang, F.; Ge, L.; Zhu, X.; Li, H. Chemical and process mineralogical characterizations of spent lithium-ion batteries: An approach by multi-analytical techniques. *Waste Manag.* **2014**, *34*, 1051–1058. [CrossRef]
77. Cheret, D.; Santen, S. Battery Recycling. U.S. Patent 7,916,920 B2, 30 January 2007.
78. Batrec, “Batrec”. Available online: <http://www.batrec.ch/en/> (accessed on 20 June 2019).
79. Zenger, T.; Krebs, A.; van Deutekom, H.J.H. Method of and Apparatus for Dismantling and Storage of Objects Comprising Alkali Metals, Such as Alkali Metal Containing Batteries. U.S. Patent 7,833,646 B2, 16 November 2010.
80. Vadenbo, C.O. *Prospective Environmental Assessment of Lithium Recovery in Battery Recycling*; Institute of Environmental Decisions: Zurich, Switzerland, 2009.
81. Rombach, E.; Friedrich, B. Recycling of Rare Metals. In *Handbook of Recycling*; Elsevier: Boston, MA, USA, 2014; pp. 125–150.
82. Accurec Recycling GmbH, “Accurec,” 2019. Available online: <https://accurec.de/lithium> (accessed on 30 October 2019).
83. Meshram, P.; Pandey, B.; Mankhand, T. Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review. *Hydrometallurgy* **2014**, *150*, 192–208. [CrossRef]
84. Gratz, E.; Sa, Q.; Apelian, D.; Wang, Y. A closed loop process for recycling spent lithium ion batteries. *J. Power Sources* **2014**, *262*, 255–262. [CrossRef]
85. Zou, H.; Gratz, E.; Apelian, D.; Wang, Y. A novel method to recycle mixed cathode materials for lithium ion batteries. *Green Chem.* **2013**, *15*, 1183. [CrossRef]
86. Sa, Q.; Gratz, E.; He, M.; Lu, W.; Apelian, D.; Wang, Y. Synthesis of high performance LiNi_{1/3}Mn_{1/3}Co_{1/3}O₂ from lithium ion battery recovery stream. *J. Power Sources* **2015**, *282*, 140–145. [CrossRef]
87. Baron, A. A Battery of Success, 2016. Available online: <https://www.wpi.edu/news/battery-successes> (accessed on 23 August 2019).

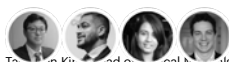
88. National Science Foundation. SBIR Phase II: A Closed Loop Process for the Recycle of End-of-Life Li-Ion Batteries. 2017. Available online: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1738027&HistoricalAw (accessed on 23 August 2019).
89. Battery Resources, “Battery Resources News”. 2019. Available online: <https://www.batteryresources.com/news> (accessed on 23 August 2019).
90. Weyhe, R.; Pan, Q. *High Energy Lithium Sulphur Cells and Batteries*; European Commission: Brussels, Belgium, 2016; pp. 1–30.
91. Diekmann, J.; Hanisch, C.; Loellhoeffel, T.; Schällicke, G.; Kwade, A. Ecologically Friendly Recycling of Lithium-Ion Batteries—The LithoRec-Process. *ECS Trans.* **2016**, *73*, 1–9. [[CrossRef](#)]
92. Diekmann, J.; Hanisch, C.; Frob, L.; Sch, G.; Loellhoeffel, T.; Kwade, A. Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes. *J. Electrochem. Soc.* **2017**, *164*, 6184–6191. [[CrossRef](#)]
93. Duesenfeld. 2019. Available online: https://www.duesenfeld.com/recycling_en.html (accessed on 23 August 2019).
94. Träger, T.; Friedrich, B.; Weyhe, R. Recovery Concept of Value Metals from Automotive Lithium-Ion Batteries. *Chem. Ing. Tech.* **2015**, *87*, 1550–1557. [[CrossRef](#)]
95. Hanisch, C.; Diekmann, J.; Stieger, A.; Haselrieder, W.; Kwade, A. Recycling of Lithium-Ion Batteries. In *Handbook of Clean Energy Systems*; Yan, J., Cabeza, L.F., Sioshansi, R., Eds.; John Wiley & Sons, Ltd.: West Sussex, UK, 2015.
96. Krüger, S.; Hanisch, C.; Kwade, A.; Winter, M.; Nowak, S. Effect of impurities caused by a recycling process on the electrochemical performance of Li[Ni_{0.33}Co_{0.33}Mn_{0.33}]O₂. *J. Electroanal. Chem.* **2014**, *726*, 91–96. [[CrossRef](#)]
97. Hailey, P.; Kepler, K. *Direct Recycling Technology for Plug-In electric Vehicle Lithium-Ion Battery Packs*; Farasis Energy Inc.: Hayward, CA, USA, 2015.
98. Sloop, S.E. *Battery Materials Recycling*; OnTo Technology LLC: Bend, OR, USA, 2015; p. 20.
99. Gaines, L.; Sullivan, J.; Burnham, A.; Belharouak, I. Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries. *Transp. Res. Rec. J. Transp. Res. Board* **2011**, *2252*, 57–65. [[CrossRef](#)]
100. Sloop, S.E.; Parker, R. System and Method for Processing an End-of-Life or Reduced Performance Energy Storage and/or Conversion Device Using a Supercritical Fluid. U.S. Patent 8,067,107 B2, 29 November 2011.
101. Sloop, S.E. Reintroduction of Lithium into Recycled Battery Materials. U.S. Patent 8,846,225 B2, 30 September 2014.
102. Sloop, S.E. Reintroduction of Lithium into Recycled Battery Materials. U.S. Patent 9,287,552 B2, 15 March 2016.
103. Sloop, S.E. Recycling Positive-Electrode Material of a Lithium-Ion Battery. U.S. Patent 2016/004,3450 A1, 11 February 2016.
104. Sloop, S.E.; Bend, M.A. Recycling and Reconditioning of Battery Electrode Materials. U.S. Patent 9,484,606 B1, 1 November 2016.
105. Dunn, J.B.; Gaines, L.; Sullivan, J.; Wang, M.Q. Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. *Environ. Sci. Technol.* **2012**, *46*, 12704–12710. [[CrossRef](#)]
106. Zhang, T.; He, Y.; Ge, L.; Fu, R.; Zhang, X.; Huang, Y. Characteristics of wet and dry crushing methods in the recycling process of spent lithium-ion batteries. *J. Power Sources* **2013**, *240*, 766–771. [[CrossRef](#)]
107. Ekberg, C.; Petranikova, M. (Eds.) *Lithium Process Chemistry*; Elsevier: Amsterdam, The Netherlands, 2015.
108. Pudas, J. *Best Battery Recycling, Dry Technology*; Akkuser: Nivala, Finland, 2009.
109. Agency for Toxic Substances & Disease Registry. ATSDR, 2015. Available online: <https://www.atsdr.cdc.gov/phs/phs.asp?id=711&tid=128> (accessed on 15 August 2019).
110. Dunn, J.; Gaines, L.; Barnes, M.; Wang, M.; Sullivan, J. *Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle*; Argonne National Laboratory: Chicago, IL, USA, 2012.
111. Rothermel, S.; Evertz, M.; Kasnatscheew, J.; Qi, X.; Grütze, M.; Winter, M.; Nowak, S.; Kasnatscheew, J. Graphite Recycling from Spent Lithium-Ion Batteries. *ChemSusChem* **2016**, *9*, 3473–3484. [[CrossRef](#)] [[PubMed](#)]
112. Boyden, A.; Soo, V.K.; Doolan, M. The Environmental Impacts of Recycling Portable Lithium-Ion Batteries. *Procedia CIRP* **2016**, *48*, 188–193. [[CrossRef](#)]

113. Dunn, J.B.; Gaines, L.; Kelly, J.C.; James, C.; Gallagher, K.G. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *J. Ind. Ecol.* **2015**, *19*, 518–519. [[CrossRef](#)]
114. European Commission. *Report on Non-Critical Raw Material Profiles*; European Commission: Brussels, Belgium, 2014.
115. Glöser, S.; Espinoza, L.T.; Gandenberger, C.; Faulstich, M. Raw material criticality in the context of classical risk assessment. *Resour. Policy* **2015**, *44*, 35–46. [[CrossRef](#)]
116. Oliveira, L.; Messagie, M.; Rangaraju, S.; Sanfelix, J.; Rivas, M.H.; Van Mierlo, J. Key issues of lithium-ion batteries—From resource depletion to environmental performance indicators. *J. Clean. Prod.* **2015**, *108*, 354–362. [[CrossRef](#)]
117. Martin, G.; Rentsch, L.; Höck, M.; Bertau, M. Lithium market research—Global supply, future demand and price development. *Energy Storage Mater.* **2017**, *6*, 171–179. [[CrossRef](#)]
118. Reuter, M.A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C. *Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel*; United Nations Environmental Programme: Paris, France, 2013.
119. Tran, T.; Luong, V.T. Lithium Production Processes. In *Lithium Process Chemistry*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 81–124.
120. Hanisch, C.; Haselrieder, W.; Kwade, A. Recovery of Active Materials from Spent Lithium-Ion Electrodes and Electrode Production Rejects. In *Globalized Solutions for Sustainability in Manufacturing*; Springer Science and Business Media LLC: Berlin, Germany, 2011; pp. 85–89.
121. Moradi, B.; Botte, G.G. Recycling of graphite anodes for the next generation of lithium ion batteries. *J. Appl. Electrochem.* **2016**, *46*, 123–148. [[CrossRef](#)]
122. Llamas, A.A.; Delgado, A.V.; Capilla, A.V.; Cuadra, C.T.; Hultgren, M.; Peltomäki, M.; Roine, A.; Stelter, M.; Reuter, M. Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production. *Miner. Eng.* **2019**, *131*, 51–65. [[CrossRef](#)]
123. Michaux, B.; Hannula, J.; Rudolph, M.; Reuter, M.; Boogaart, K.V.D.; Möckel, R.; Kobylin, P.; Hultgren, M.; Peltomäki, M.; Roine, A.; et al. Water-saving strategies in the mining industry—The potential of mineral processing simulators as a tool for their implementation. *J. Environ. Manag.* **2019**, *234*, 546–553. [[CrossRef](#)]
124. Jose-Luis, P.; Abadias, A.; Valero, A.; Valero, A.; Reuter, M. The energy needed to concentrate minerals from common rocks: The case of copper ore. *Energy* **2019**, *181*, 494–503. [[CrossRef](#)]
125. Reuter, M.A.; Van Schaik, A.; Gutzmer, J.; Bartie, N.; Abadías-Llamas, A. Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. *Annu. Rev. Mater. Res.* **2019**, *49*, 253–274. [[CrossRef](#)]



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With new export controls on critical minerals, supply concentration risks become reality



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Commentary — 23 October 2025

Mineral supply chains now face one of the most pressing challenges for energy security and economic stability

In today's tense geopolitical environment, critical minerals have risen rapidly up the policy agenda as a cornerstone of energy and economic security. These minerals are not only crucial for energy technologies but also play a vital role in high-tech industries, aerospace, defence and advanced manufacturing, making them central not only to energy security but also to broader economic resilience.

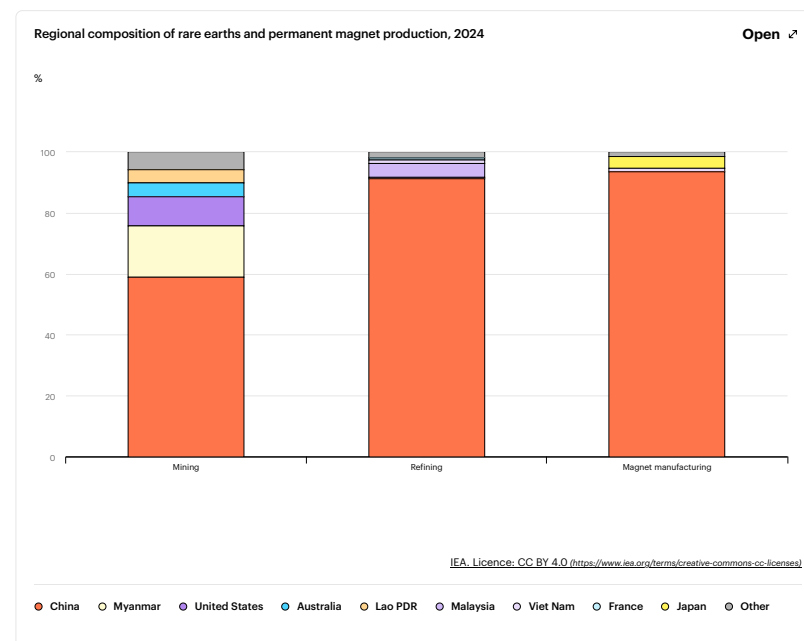
The IEA was the first to highlight the risks of high supply concentration of critical mineral supplies, especially in processing and refining. The Global Critical Minerals Outlook 2025 (<https://www.iea.org/reports/global-critical-minerals-outlook-2025>) showed that, for a remarkable 19 out of 20 important strategic minerals, China is the leading refiner, with an average market share of 70%. Moreover, our analysis shows that this concentration has only intensified in recent years. Reliance on a small number of suppliers increases vulnerability to shocks and disruptions, be it from extreme weather, technical failure or trade disruptions.

This is no longer just a theoretical concern. There has been a proliferation of export controls on key materials and technologies in recent years. New restrictions on rare earth elements and lithium-ion battery supply chains underscore once again the vulnerabilities and risks.

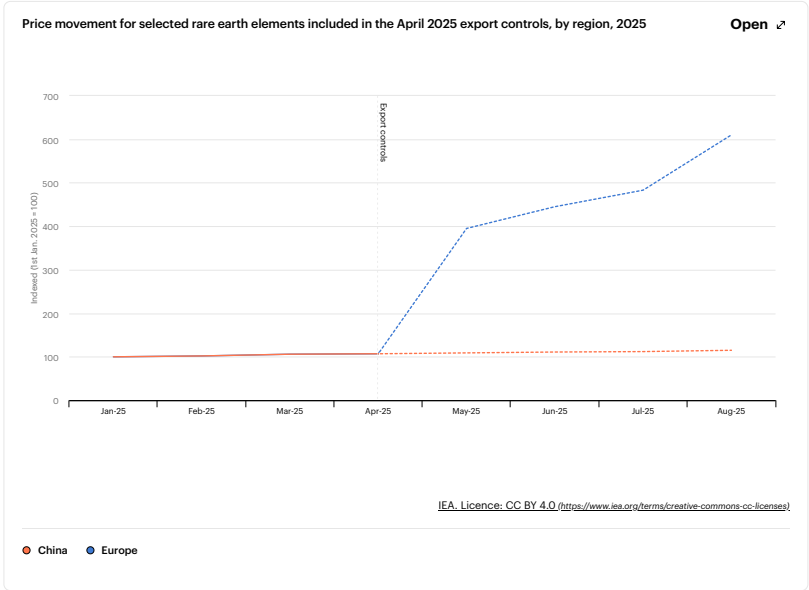
The rare earth supply chain is among the most highly concentrated across all stages of the value chain

The supply of rare earths remains among the least geographically diversified among all critical minerals. For rare earths used in magnets for various industries – notably neodymium, praseodymium, dysprosium and terbium – China accounted for around 60% of global mining output in 2024, followed by Myanmar, Australia and the United States. China's dominance is even greater in the separation and refining stages, representing about 91% of global production, with Malaysia a distant second.

Moreover, China has significantly strengthened its position in the manufacturing of rare earth-containing permanent magnets – magnets that retain their magnetic properties indefinitely without the need for external power. Two decades ago, China accounted for around 50% of the production of sintered permanent magnets commonly used in cars, wind turbines, industrial motors, data centres and defence systems. This share has risen significantly to 94% today, making China the world's single largest supplier of the component critical to the manufacturing of the most powerful motors that are used for many cutting-edge applications. Such high market concentration leaves global supply chains in strategic sectors – such as energy, automotive, defence and AI data centres – vulnerable to potential disruptions.



A notable development came on 4 April 2025 when the Chinese government introduced export controls on seven heavy rare earth elements, as well as all related compounds, metals and magnets. As export volumes fell sharply in April and May, many carmakers in the United States, Europe, and elsewhere struggled to obtain permanent magnets, with some forced to cut utilisation rates or even temporarily shut down factories. Even after trade volumes recovered, rare earth prices in importing countries remained elevated – with European prices reaching up to six times those in China – hurting the cost competitiveness of rare earth-based products manufactured outside China.



The new rare earth export controls pose major risks for a range of strategic sectors such as energy, defence and semiconductors

On 9 October 2025, the Ministry of Commerce of China announced further export controls on rare earth elements and related products, equipment and technologies. The new controls require foreign companies to obtain a license from China to export “parts, components and assemblies” containing Chinese-sourced rare earth materials or produced using Chinese rare earth technologies. The rule was applied with immediate effect to products made in China. However, from 1 December 2025, the controls will be escalated to include “internationally made” products containing Chinese-sourced materials ¹ or manufactured using Chinese technologies, even if they are traded domestically.

The inclusion of “parts, components and assemblies”, beyond the previous isolated controls on select rare earth magnets and materials, could have a dramatic impact on global supply chains, as many strategic sectors rely on products and components containing the controlled Chinese rare earth elements. These sectors include energy, automotive, defence, semiconductors, aerospace, industrial motors and AI data centres.

Moreover, the list of rare earth elements subject to controls has been expanded to include five additional elements – holmium, erbium, thulium, europium and ytterbium – on top of the seven elements initially restricted in April, with the new measures taking effect from 8 November. The inclusion of holmium is particularly significant, as many permanent magnet makers have been revising their approach to replace the previously restricted rare earths with holmium since April 2025. New controls were also announced on a wide range of equipment for processing rare earths, including for milling, separation, and refining – also effective from 8 November.

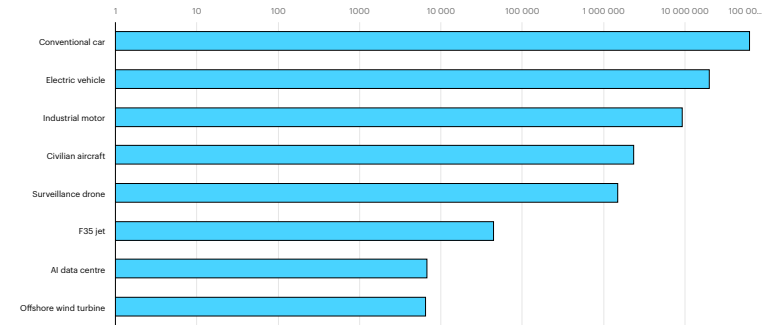
These new export controls are a marked escalation of the restrictions on rare earths. In addition to energy technologies, defence and semiconductor supply chains could be particularly affected if export licences for components containing rare earth elements are delayed or denied.

In 2024, China exported 58 000 tonnes of rare earth magnets – enough to manufacture components to make millions of cars, industrial motors or aircraft – or to build thousands of strategic military systems, data centres or wind turbines. Prolonged delays or denials in licensing could threaten revenues, competitiveness and employment for global industrial value chains.

The export controls could also significantly undermine international efforts to diversify rare earth supply chains and scale up strategic manufacturing. The new restrictions on equipment for processing rare earths risk constraining the ability of emerging projects to refine raw materials and produce permanent magnets. This could introduce major operational hurdles for nascent industrial ecosystems, resulting in slower development and increased vulnerability to supply shocks.

Number of items containing rare earth oxides equivalent to China's rare earth magnet export volumes, 2024

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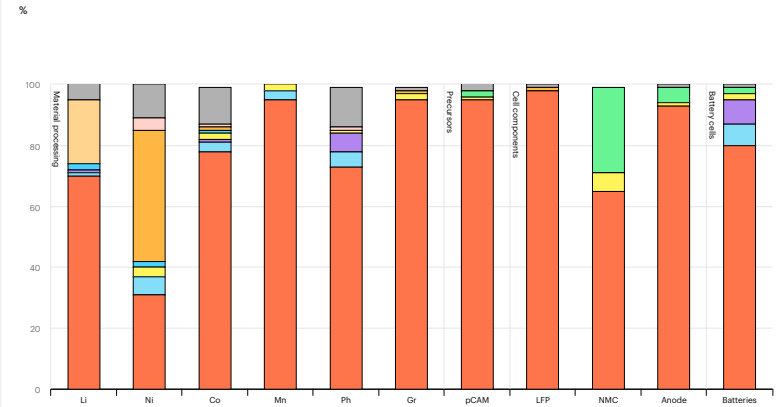
It's not only rare earths: New export controls also strain global battery supply chains

It is not only rare earth elements that are impacted. On 9 October 2025, China also announced major export controls on lithium-ion battery supply chains, effective from 8 November. The new controls expand on previous measures and cover a much broader range of battery materials, technologies and equipment across multiple stages of the supply chain. They now include battery cells and packs for high-performance applications, cathode precursors, an expanded scope of anode materials, a broader coverage of lithium iron phosphate (LFP) cathode materials, and battery and material production equipment and technologies.

China currently dominates the midstream and downstream supply chains for batteries globally, with shares of 80% or more in many key areas. In some segments such as precursor cathode materials and LFP cathode materials, China maintains a near monopoly, with shares of 95% or above. This exceptional concentration creates multiple points of vulnerability across the supply chain. ²

The global midstream and downstream battery supply chain, 2024

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In the short term, if export approvals for companies are delayed, the international market may face tight supplies of battery materials. This could lead to increased costs for batteries, with potential knock-on effects on the affordability of EVs and storage. The new restrictions also create risks for strategic sectors which depend on lithium-ion batteries, such as defence, aerospace, AI data centres, and even medical applications.

Looking further ahead, the new controls target some critical chokepoints in global battery supply chains, notably graphite anode material and cathode material precursors for which supply options outside China are extremely limited. If these supplies are disrupted, this could severely restrict the ability of the rest of the world to produce batteries, with potentially significant strategic and economic consequences.

LFP batteries are a case in point, with markets expanding rapidly (<https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase>). They represent half of the global electric car battery market and the majority of the energy storage market. While China currently dominates this segment, efforts are underway to develop LFP battery production outside China. However, new restrictions on LFP cathode materials could impede these initiatives, reinforcing China's dominance in this technology, with major implications for energy storage deployment.

The simultaneous restrictions on battery equipment and technologies could also lead to even greater market concentration in China, as they could significantly hinder countries' efforts to develop diversified battery supply chains. If restrictions are sustained, this could lead to major revenue and job losses for producers of battery materials around the world.

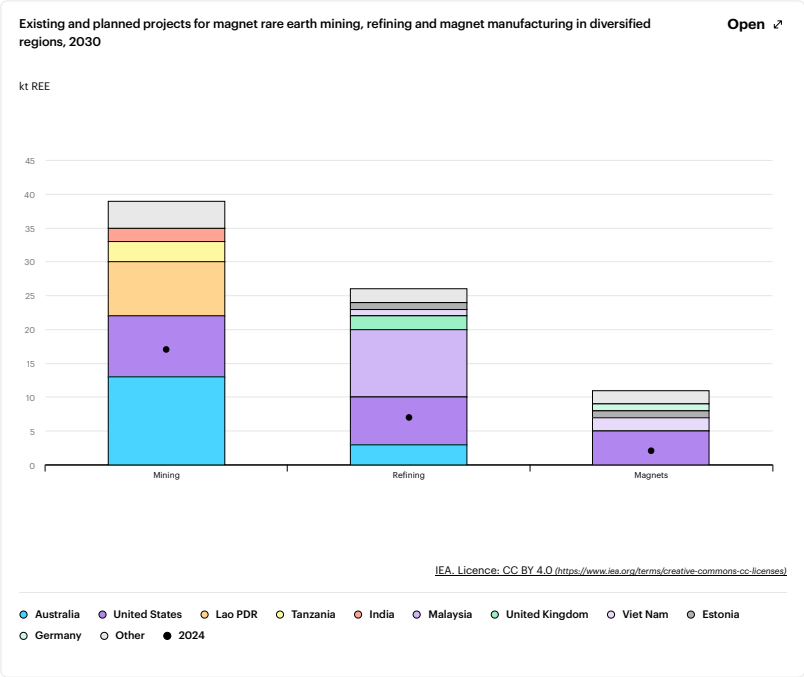
Efforts must now be sharply focused on accelerating strategic projects for diversification

There remains some uncertainty over enforcement of the latest export controls. As the geopolitical context continues to evolve, trade negotiations could alter the scope or stringency of the restrictions. Nevertheless, the latest developments underline the crucial importance of advancing diversification to ensure the long-term resilience of global supply chains.

Diversification in the rare earths market has been limited by several factors. In the upstream segment, only a handful of mines outside China and Myanmar are operating at scale, and newly announced projects typically have long lead times, averaging around eight years. Refining development is even more nascent, with only a few industrial-scale facilities operating outside China today – in Malaysia, the United States and Estonia. Furthermore, separation and refining processes are technically complex, and many rare earth ores for magnets contain radioactive elements such as uranium and thorium, with few countries having the infrastructure to manage these by-products safely.

A number of projects are currently under development across various regions. Mining projects are being developed in the United States, Australia, Brazil, Tanzania and India. Several separation and refining plants are also expanding or gearing up for operations, in the United States, Australia and Malaysia.

However, planned capacity for permanent magnet manufacturing outside China is notably lower than for mining and refining, posing a key source of concern. Several new plants began operations in 2025, notably in the United States (MP Materials) and Estonia (Neo Performance Materials), while other projects are accelerating in the United States, Korea, Viet Nam and Germany. Continued efforts through targeted policy support and strategic partnerships will nonetheless be essential to bring more projects online. The cooperation between France and Japan on a project (<https://www.carester.fr/caremag-lancement/>) to produce rare earth oxides in Lacq, France, illustrates how cross-country cooperation can link different parts of the supply chain.



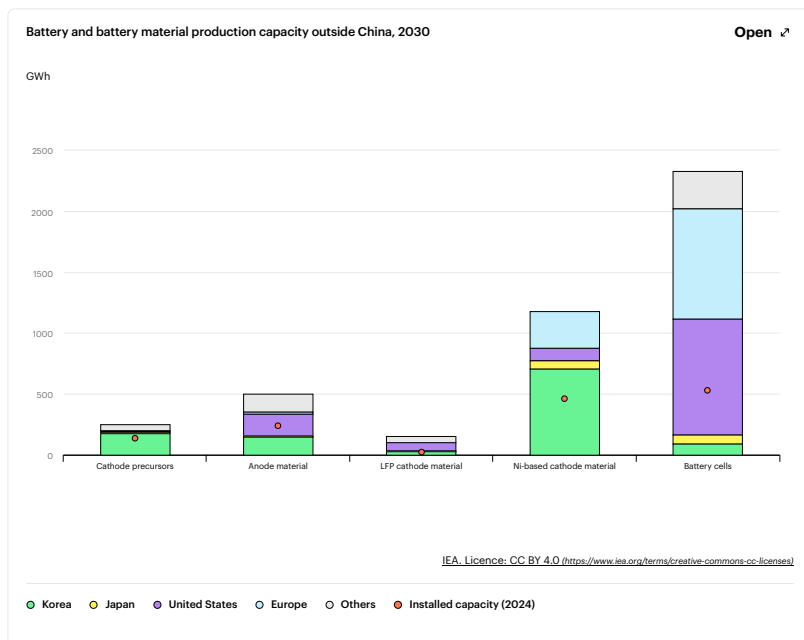
Diversification efforts for battery supply chains need to look beyond cells

As with rare earths, there are growing opportunities for diversification emerging across battery supply chains. However, in contrast to rare earths, while substantial capacity expansions are underway in downstream battery cell production, the pipeline for midstream battery material production – such as precursor cathode materials, anode materials, and cathode materials – is considerably more limited.

Korea is currently the leading source of diversified battery material production outside China – and the project pipeline indicates that it is set to remain the largest midstream diversification hub by 2030. However, the country continues to rely on imports of precursor cathode materials and other upstream inputs from China. Moreover, cathode material production in Korea is predominantly focused on nickel-based material, offering little opportunity of diversifying the LFP supply chain.

The United States and Europe are also set to play growing roles in battery supply chain diversification. Based on the pipeline, they are set to lead the expansion of battery production capacity, each accounting for around 40% of capacity outside China by 2030. The United States has several midstream projects under development, notably in LFP cathode and anode materials, which could help mitigate two of the major vulnerabilities in the supply chain, though these remain insufficient to offset reliance on Chinese supplies.

Despite ongoing efforts in several regions, further action is essential to advance strategic projects targeting the most vulnerable segments in the global battery supply chain, including cathode precursors, anode materials, LFP cathode materials, refined battery metals, and production equipment.



¹ Those produced with more than 0.1% of select Chinese-sourced materials by value.

² The upcoming edition of the IEA's *Energy Technology Perspectives* will provide an in-depth assessment of the vulnerability of battery and other technology supply chains.

The IEA Critical Minerals Security Programme supports countries in addressing new challenges through cooperation and shared action

The urgency of today's challenges around critical mineral supply chains echoes a pivotal moment in the history of international collaboration in the energy field. In the early 1970s, when oil price shocks and fuel shortages strained many energy-importing countries, governments came together to create the IEA, building up emergency stocks to protect them from being held to ransom via oil supplies in the future. This landmark cooperation has helped limit the severe economic impacts of oil supply disruptions for decades.

Now, critical minerals have become key components of strategic industries and economic growth. This is why the IEA has launched the Critical Minerals Security Programme – to help countries strengthen resilience against disruptions and promote supply diversification, just as they united in response to the oil crisis in 1974. The Programme builds on the Agency's long-standing experience in safeguarding energy security. As the IEA Executive Director mentioned in his recent opinion article (https://time.com/7315610/critical-mineral-energy-crisis-fatih-birol/?utm_content=buffer3bc04&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer), no country can tackle the challenges alone. However, with the collaborative spirit governments showed after the 1973 oil shock, countries can build more secure and resilient supply chains and reduce structural risks.

The IEA's Eric Buisson and Teo Lombardo contributed to this article.

References



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Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity

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ABSTRACT

Vehicle exhaust emissions have been decreasing due to stricter regulations and advancements in control strategies. However, non-exhaust emissions from brake and tire wear have not been extensively regulated in the past, and their relative contribution to particulate matter (PM) in urban areas is increasing. We examined the effect of a vehicle's mass and braking intensity on brake and tire particles based on on-road data collected from three different types of vehicles under real-world driving conditions. PM_{2.5} and PM₁₀ concentrations and particle size distributions were measured near the center and rear of the right front wheel, respectively. During the braking, the highest peaks in brake PM_{2.5} (520–4280 µg/m³) and PM₁₀ (950–8420 µg/m³) concentrations were observed from the heaviest vehicle, while the lowest peaks in brake PM_{2.5} (250–2440 µg/m³) and PM₁₀ (430–3890 µg/m³) concentrations were observed from the lightest vehicle. Similarly, the observed peaks in tire PM_{2.5} (340–4750 µg/m³) and PM₁₀ (810–8290 µg/m³) concentrations of the heaviest vehicle were shown to be the highest among the test vehicles, while the peaks in tire PM_{2.5} (220–2150 µg/m³) and PM₁₀ (370–3840 µg/m³) concentrations of the lightest vehicle were lower than other vehicles. A statistically significant difference in the peak values of PM_{2.5} and PM₁₀ concentrations was observed between the heaviest and lightest vehicles for both brake and tire particles. The braking deceleration rate was found to be an important factor in predicting the peaks in PM_{2.5} and PM₁₀ concentrations during major braking events for all three test vehicles. Brake particles showed a unimodal mass size distribution with a mode diameter of 3–4 µm, while tire particles showed a slightly larger mode diameter of 4–5 µm. The finding of this study provides insight into the effects of driving conditions and vehicle mass on brake and tire emissions.

1. Introduction

During the past decades, remarkable efforts have been made to reduce vehicle exhaust emissions, which are one of the major sources of particulate matter (PM) in urban environments. These efforts were based on a large body of research that has been focused on exhaust emissions such as particle size distribution, spatiotemporal distribution, and associated health effects (Beelen et al., 2008; Wang et al., 2016; Zhu et al., 2006). As a result, governments have gradually increased regulations to reduce exhaust emissions. In contrast, non-exhaust emission sources, including brake and tire wear, have not been investigated comprehensively, and therefore, have not been extensively regulated.

It has been shown that the contribution of the non-exhaust emission sources to PM₁₀ (PM with aerodynamic diameters less than or equal to 10 µm) is at a comparable level to the exhaust emissions (Bukowiecki et al., 2010). Moreover, the contribution of non-exhaust emission

sources to PM_{2.5} (PM with aerodynamic diameters less than or equal to 2.5 µm) has increased in recent years, while exhaust emissions have been continuously decreasing (Jeong et al., 2020). Given a predicted increase in the sales of electric and hybrid vehicles with low or zero exhaust emissions in the future (Axsen and Wolinetz, 2018), non-exhaust sources are likely to become more important worldwide (Rexeis and Hausberger, 2009).

The key contributors to non-exhaust PM are road dust and brake and tire wear, with minor contributions from the clutch and engine dust (Pant and Harrison, 2013). The contribution of brake wear particles to non-exhaust PM₁₀ varies depending on the sampling location and measurement method. Previous studies have shown that brake wear particles could contribute to 55 % of non-exhaust PM₁₀ in areas with high braking frequency (Harrison et al., 2012). It has been shown that the contribution of brake wear particles to PM_{2.5} at highways is approximately three times higher than the downtown sampling location

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(Jeong et al., 2019). In addition, the contribution of brake wear particles to $PM_{2.5}$ has been reported to increase during morning rush hours as a result of congested traffic condition. Brake wear particles have been found in ultrafine, fine, and coarse size ranges (Garg et al., 2000; Kwak et al., 2013; Sanders et al., 2003). More recently, brake wear particles have been reported in the nanometer size range (Farwick zum Hagen et al., 2019a; Liati et al., 2019; Puisney et al., 2018). A few factors, such as the driving style and braking intensity (Kwak et al., 2013), brake temperature (Gramstat et al., 2020; Kukutschová et al., 2011), and maintenance condition of the brakes (Grigoratos and Martini, 2015), have been reported to affect brake wear emissions.

On the other hand, fewer studies have focused on investigating tire wear emissions. Previous studies have shown that tire wear particles could contribute to 11% of total PM_{10} (Baensch-Baltruschat et al., 2020). While tire wear particles were mostly reported in the coarse size range (Gustafsson et al., 2008; Mathissen et al., 2011; Sommer et al., 2018), ultrafine particles have been observed in a few studies (Kim and Lee, 2018; Kumar et al., 2013), which are presumably generated during the evaporation and condensation processes of volatile tire compounds (Baensch-Baltruschat et al., 2020). The physical and chemical characteristics of the tire wear particles were shown to be a function of road features (Gustafsson et al., 2008), tire characteristics (Gustafsson and Eriksson, 2015), driving conditions and inertia load (Kim and Lee, 2018) based on different experimental setups.

A number of methods have been used for the measurement of brake and tire wear particles. Aside from the studies based on source apportionment, a large number of the previous studies on brake and tire wear emissions were performed in laboratory settings. Brake dynamometers were used for measuring brake wear particles where the brake pads were tested under different conditions inside a chamber without being attached

to any vehicle (Garg et al., 2000; Iijima et al., 2008; Kukutschová et al., 2011). Moreover, road simulator systems have been used for modeling the interaction between the road surface and tire, and studying tire wear particles under different road conditions (Gustafsson et al., 2008; Gustafsson and Eriksson, 2015). While laboratory measurements provide consistency across different tests, they cannot adequately represent real-world driving conditions. A few studies have been carried out on brake and tire wear emissions using on-road sampling (Farwick zum Hagen et al., 2019a; Kwak et al., 2013; Mathissen et al., 2011; Pirjola et al., 2010; Sanders et al., 2003). While these previous studies have discovered valuable information on the brake and tire wear particles, each study only focused on one vehicle, thus could not address the differences of brake and tire wear emissions across different vehicles.

In this study, we measured the brake and tire mass concentrations and size distributions from three test vehicles under real-world driving and braking conditions and investigated the effects of the vehicle mass and braking intensity on the brake and tire particles. To the best of our knowledge, this is the first study to investigate the effect of these factors on brake and tire particles using on-road measurements.

2. Methods

2.1. Experimental design

A schematic of the sampling system is provided in Fig. 1. The brake and tire particles were sampled from the right front wheel of the test vehicles. This is because during the braking event, the weight of the vehicle shifts forward; therefore, the front wheels experience more friction (Grigoratos and Martini, 2015). Three sampling inlets were installed near the brake and tire of the right front wheel as well as on the

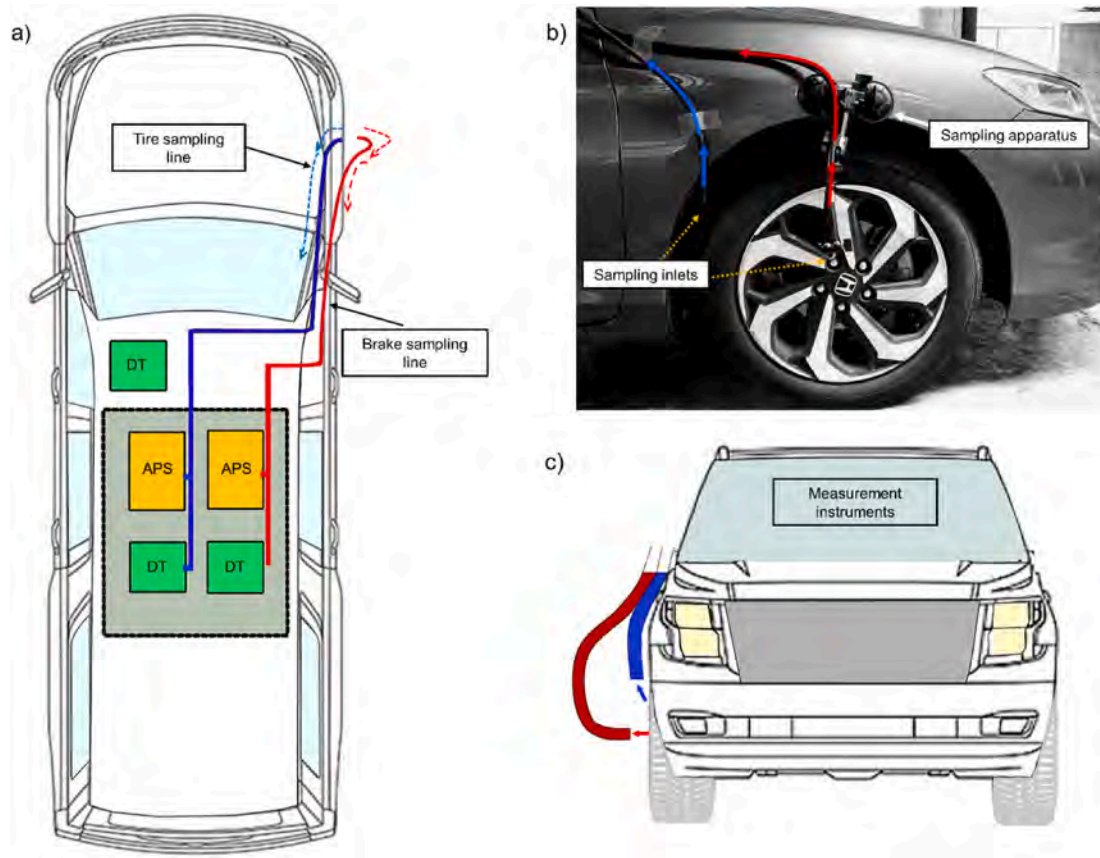


Fig. 1. Schematic diagrams for the test vehicle with the sampling configuration. (a) Top view. Illustration of the sampling instruments installed inside the vehicle, including APS (TSI APS 3321) and DT (TSI DustTrak 8532). (b) The test vehicle and sampling apparatus. Arrows show the direction of the sampling flow from the brake and tire. (c) Front view. The tire particles are measured from the rear side of the right front wheel. The brake particles are measured at the center of the right front wheel.

roof of the test vehicle for ambient PM measurements. A custom-made apparatus was used, which provided sufficient space between the sampling probe and the wheel under both straight and cornering driving conditions. The brake sampling probe was located 5 cm from the center of the wheel, while the tire sampling inlet was installed 2.5 cm from the top of the wheel. The brake and tire inlets were installed 30 cm apart from each other. Isokinetic sampling probes (8 mm ID) were used. Particle losses due to settling and curvature as well as aspiration efficiency were calculated based on classic aerosol theories (Hinds, 1999). The details of the isokinetic sampling design are discussed in Section A.1 of the supplemental information.

In this study, “brake particles” and “tire particles” refer to the particles collected from the brake and tire sampling inlets, respectively. While these particles were collected near the brake and tire, they could be mixed with other emission sources, whose relative contribution cannot be estimated without chemical speciation analysis and source apportionment. The mixing between the brake and tire particles at both inlets is also plausible. Therefore, the collected data should not be interpreted as solely constitute the brake and tire wear particles. Nevertheless, we do expect brake and tire wear emissions to have a great impact on the particles collected from their respective sampling inlets.

Since adding substantial and balanced loading to a vehicle without changing its center of gravity was not feasible, the on-road sampling was performed on three vehicles with different masses. A full-sized SUV (2016 Chevrolet Suburban), a mid-sized sedan (2016 Honda Accord), and a compact sedan (2017 Nissan Sentra) were tested on a pre-determined route. The details of the test vehicles are presented in Table 1. All of the test vehicles were equipped with all-season non-studded tires as well as ceramic disc brakes. Ceramic brakes can provide a stable thermal performance (Kumar and Kumaran, 2019; Sundarkrishnaa, 2015) and generate less PM compared to other types (Seo et al., 2021). While ceramic brake pads have been mostly popular in high-end vehicles due to their high cost (Li et al., 2020), they have become more widespread in recent years due to their durability and superior performance (Li et al., 2021).

The sampling route was a 5.5 km path in the Westwood neighborhood in Los Angeles. The sampling route included a mildly downhill terrain, with fairly straight residential streets, multiple stop signs, and low traffic. The instantaneous driving speed during the measurement did not exceed 75 km/h. On-road sampling took place between March and June 2019. Measurements generally took place between 7 p.m. and 11 p.m. when traffic was minimal. For each vehicle, brake temperature was measured before and after each round of sampling using a digital infrared thermometer (1052D, Etekcity Corp., Anaheim, CA). There was a minimum of 30 min resting period between two consecutive sampling sessions to ensure the brake temperature was less than 80 °C before each experiment. Section A.2 in the supplementary information summarizes the average brake temperatures before and after sampling sessions for each vehicle. The average ambient temperature and relative humidity during the sampling sessions were 21.2 °C and 73.7 %, respectively.

2.2. Instrument

Three DustTraks (8532, TSI Inc., Shoreview, MN) were used to concurrently measure PM_{2.5} and PM₁₀ concentrations from the brake and tire as well as in the ambient air. The brake and tire particle size distributions in the size range of 0.5–20 µm were determined by two Aerodynamic Particle Sizers (APS 3321, TSI Inc., Shoreview, MN) with a log

interval of 1 s, respectively. Velocity and GPS coordinates were logged using the GlobalSat data logger (DG-500, New Taipei City, Taiwan). The total sampling flow rate was 8 L per minute (LPM), which was provided by APS (5 LPM) and DustTrak (3 LPM). The electric power for running APS inside the vehicle was provided by a marine dual-purpose AGM Battery (AGM 105, West Marine, Watsonville, CA) and a power inverter (TruePower, 2000 PS, Promariner, Menomonee Falls, WI).

2.3. Quality assurance and quality control

Before the sampling began, the DustTrak monitors were zero-calibrated in the laboratory, and the GlobalSat data logger was synced to the global time. The DustTrak monitors were also collocated for 10-min before and after sampling on each vehicle. The resulting linear relationships were applied to adjust DustTrak data. Section A.3 of the supplemental information presents the collocation test results.

Previous studies have calibrated DustTrak data against gravimetric measurements for brake wear particles and reported an underestimation. A calibration factor of 5.7 ± 2.1 was reported during the measurement of PM_{2.5} from brake wear particles (Hagino et al., 2015). While a calibration factor for PM₁₀ was found to be 2.3 ± 0.2 during on-road brake wear sampling (Farwick zum Hagen et al., 2019a), laboratory measurements reported a calibration factor of 6.4 ± 0.7 for brake wear PM₁₀ (Farwick zum Hagen et al., 2019b). Based on these reported calibration factors in the literature, the average calibration factors of 5.7 and 4.4 were used for correcting brake and tire PM_{2.5} and PM₁₀ data from DustTrak in this study. PM_{2.5} and PM₁₀ DustTrak data collected at the roof of the vehicles were corrected with previously reported ambient calibration factors of 0.52 and 0.33, respectively (Chung et al., 2001; Rivas et al., 2017).

2.4. Data analysis

The correlation between the brake and tire PM concentrations and the average deceleration rates for all three vehicles was determined by linear regression analysis. Shapiro-Wilk and Kolmogorov-Smirnov tests were used to examine if the maximum brake and tire PM_{2.5} and PM₁₀ datasets at different braking intensity levels are normally distributed. Kruskal-Wallis ANOVA on ranks with a Bonferroni-Dunn post hoc was used to determine the significant differences in the brake and tire PM concentrations among different vehicles since some of the datasets did not pass the normality tests. R 3.4.0 and Microsoft Excel 2016 (Microsoft, Seattle, WA, USA) were used to summarize data and perform statistical analysis. All figures were generated with Sigmaplot 14.0 (Systat Software Inc., San Jose, CA).

3. Results and discussion

3.1. Determining major braking events

A decrease in the vehicle's velocity can occur with or without braking. Previous studies reported various ranges for the longitudinal deceleration rates during the braking events (Maurya and Bokare, 2012; Smith et al., 2003). It has been shown that only 5% of braking events occur under the deceleration rate of 0.5 m/s² and lower (Lee et al., 2007). In this study, deceleration events with (a) continuous deceleration for more than 3 s and (b) instantaneous deceleration rates of 0.5 m/s² or greater in magnitude were selected as major braking events. For each braking event, the arithmetic mean of the instantaneous

Table 1
Specifications of the test vehicles.

Make/Model	Year/Trim	Vehicle type	Mass (lbs)	Brake pad thickness (mm)	Tire make/model
Nissan Sentra	2017/S	Compact sedan	2857	6.2	Michelin Primacy MXV4
Honda Accord	2016/LX	Mid-size sedan	3543	8.8	Michelin Primacy MXV4
Chevrolet Suburban	2016/LS	Full-size SUV	5808	7.5	Michelin Defender LTX

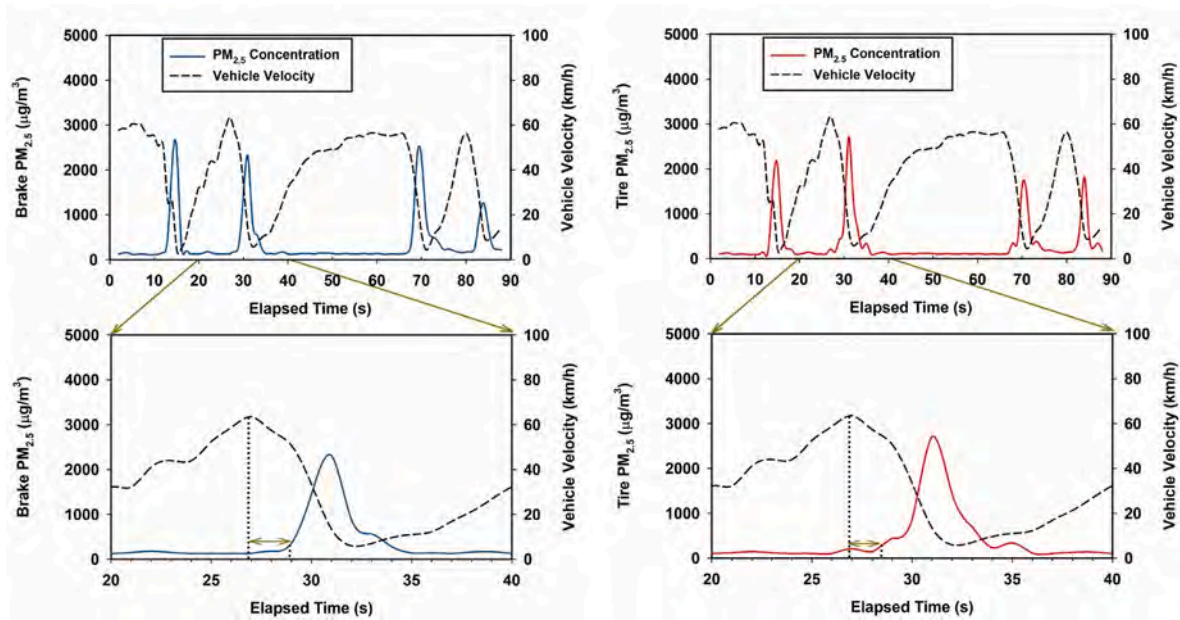


Fig. 2. A typical temporal profile of PM_{2.5} concentration and driving velocity of the Chevrolet Suburban (a) brake PM_{2.5}, (b) tire PM_{2.5}.

deceleration rates was calculated to represent the braking intensity.

Fig. 2 shows a representative time series of the PM_{2.5} concentration measured at the brake inlet of the Chevrolet Suburban and its instantaneous velocity. As shown in Fig. 2, braking leads to substantial increases in brake and tire PM concentrations and generates a peak in the PM concentration profile. Peak values in brake and tire PM_{2.5} and PM₁₀ concentrations during each braking event were identified and further used for analysis on the effect of braking intensity and mass. Fig. 2 also shows that there could be a delay between the onset of the braking and the observation of a peak in PM concentrations. This lag effect was taken

into consideration when identifying major braking events and their associated PM concentrations. A similar effect was reported in a recent study, presumably due to the particle residence time in the sampling line (Farwick zum Hagen et al., 2019a).

3.2. Effect of the braking intensity and vehicle mass on PM mass concentration

Fig. 3 shows that the deceleration rate was a statistically significant predictor of the brake and tire PM_{2.5} and PM₁₀ concentrations during

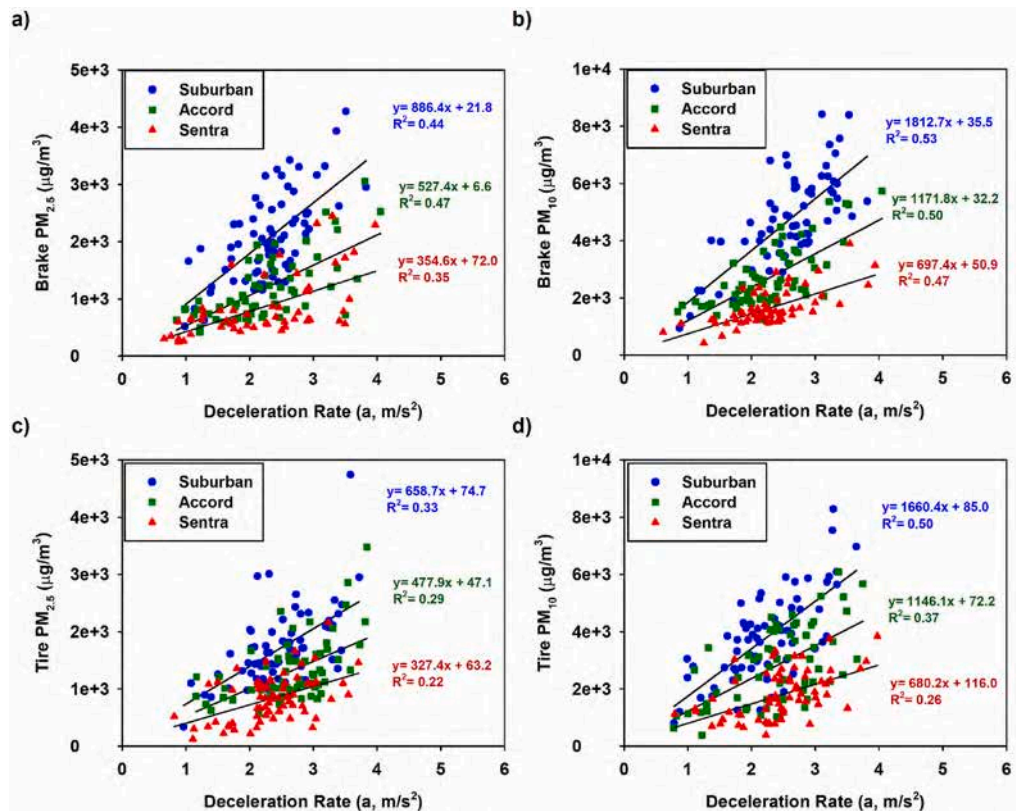


Fig. 3. Relationships between the peak values in PM concentrations and the average deceleration rate (p-value < 0.001) (a) brake PM_{2.5}, (b) brake PM₁₀, (c) tire PM_{2.5}, (d) tire PM₁₀.

major braking events. The strength of the linear regression (R^2) varies across the vehicles. In general, the correlation improves as the vehicle's mass increases, except for the Accord's brake $PM_{2.5}$, which shows a slightly stronger correlation compared to Chevrolet Suburban. For brake particles, PM_{10} shows a stronger positive correlation with the deceleration rate ($p < 0.001$, $R^2 = 0.47\text{--}0.53$) than $PM_{2.5}$ ($p < 0.001$, $R^2 = 0.35\text{--}0.47$). A similar trend was observed for tire particles, where a stronger linear relationship existed between the deceleration rate and PM_{10} ($p < 0.001$, $R^2 = 0.26\text{--}0.50$) than $PM_{2.5}$ ($p < 0.001$, $R^2 = 0.22\text{--}0.33$). In comparison, the deceleration rate was a stronger predictor for brake $PM_{2.5}$ ($p < 0.001$, $R^2 = 0.35\text{--}0.47$) than tire $PM_{2.5}$ ($p < 0.001$, $R^2 = 0.22\text{--}0.33$). For both $PM_{2.5}$ and PM_{10} concentrations, the slope of the regression for the brake PM concentrations was consistently greater than that for the tire. Section A.2 in the supplementary information summarizes the average ambient $PM_{2.5}$ and PM_{10} concentrations during the on-road sampling for each test vehicle.

The braking intensity was defined based on the arithmetic mean of the vehicle's instantaneous deceleration rate during each braking event. A braking deceleration of 0.2 g ($g = 9.81 \text{ m/s}^2$) has been used as the comfortable braking index level (Wu et al., 2009). Moreover, while 50% of the braking longitudinal deceleration rates were reported to be under 0.2 g, only 15% of the braking events were shown to have deceleration rates higher than 0.3 g (Lee et al., 2007). Therefore, braking events with an average deceleration rate of 0.3 g and higher were marked as heavy brakes ($a > 3.0 \text{ m/s}^2$); braking events with an average deceleration rate of 0.2 g and lower were marked as light brakes ($0.5 < a < 2.0 \text{ m/s}^2$); and those in between were categorized as moderate brakes.

As the braking becomes more intense, a more rapid decrease in the velocity of the vehicle and an elevated deceleration rate occurs. During heavy braking, as the vehicle's velocity decreases quickly, the kinetic energy of the vehicle is absorbed and further transformed into heat

through abrasion processes. The required friction force is mainly generated by the abrasion between the brake pad and the disc as well as the friction between the tire and the road pavement. The generated thermal energy affects the friction surfaces and eventually produces wear particles in various sizes. Since a stronger friction force is required for stopping heavier vehicles, a higher concentration of brake and tire particles would be expected. To verify this, the distribution of the brake and tire wear $PM_{2.5}$ and PM_{10} concentrations for three vehicles during the major braking events with respect to the braking intensity were compared.

Fig. 4 demonstrates the distribution of the brake and tire $PM_{2.5}$ and PM_{10} concentrations for three test vehicles with respect to the braking intensity. For both brake and tire particles, the differences in the median values of $PM_{2.5}$ and PM_{10} concentrations are statistically significant among the three vehicles regardless of the braking intensity level (Kruskal-Wallis $P < 0.05$), suggesting that there is a statistical difference between at least one pair of vehicles. A multiple comparison procedure (Dunn's Method) was then used to determine if the PM concentration distribution of a vehicle or vehicles was statistically different from the others. The $PM_{2.5}$ concentrations were significantly different between the Chevrolet Suburban and Nissan Sentra, regardless of the braking intensity level for both brake and tire particles (Dunn's Method, $p < 0.05$). Likewise, a significant difference was observed in the PM_{10} concentration between the Chevrolet Suburban and Nissan Sentra for both brake and tire particles regardless of the braking intensity level (Dunn's Method, $p < 0.05$). The differences in the $PM_{2.5}$ and PM_{10} concentrations between the Chevrolet Suburban and Honda Accord were always significant during heavy and moderate brakes for both brake and tire particles. However, for the light braking intensity, the difference between the Chevrolet Suburban and Honda Accord was not significant. A statistically significant difference was not observed between the Honda

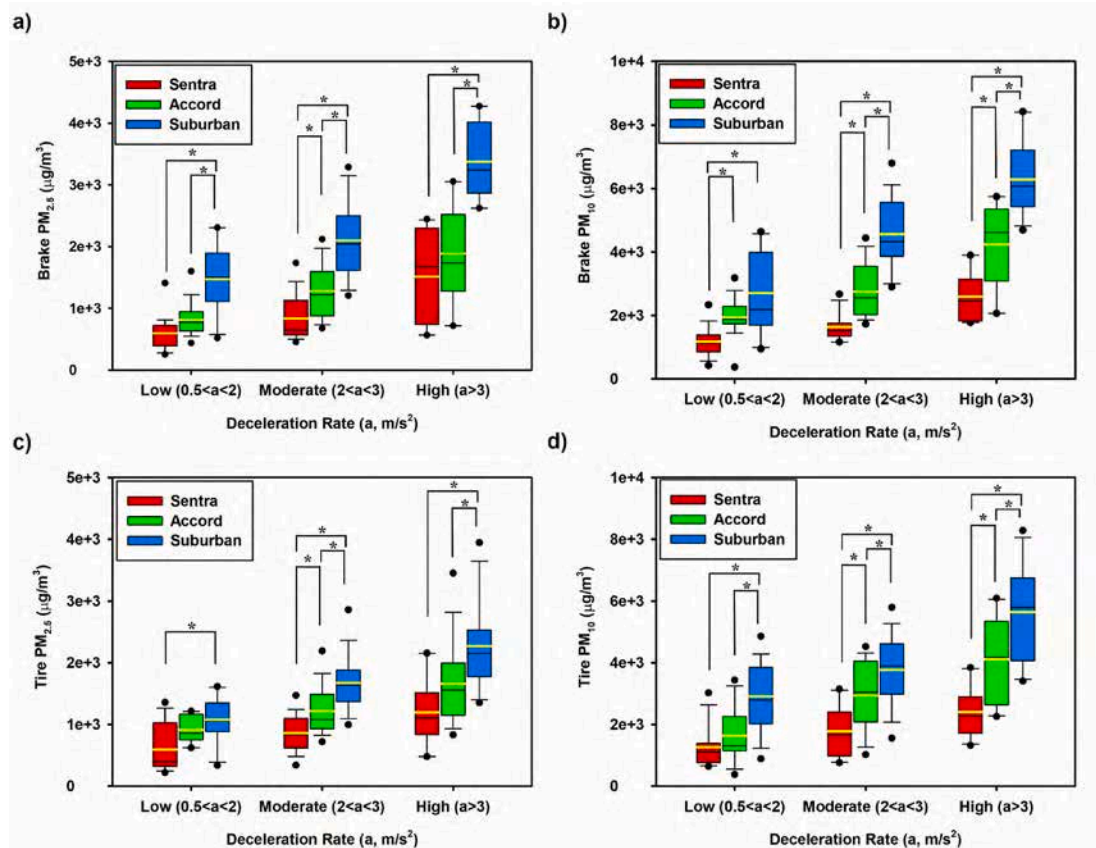


Fig. 4. Peak values in PM concentrations for the test vehicles at three deceleration rate (i.e., braking intensity) levels (a) brake $PM_{2.5}$, (b) brake PM_{10} , (c) tire $PM_{2.5}$, (d) tire PM_{10} .

Accord and Nissan Sentra, presumably due to a smaller difference in the masses of the two vehicles.

There are few studies that have discussed the effect of vehicle mass on non-exhaust PM emissions. Computer modeling of tire wear properties has previously suggested that vehicle inertia load can affect tire wear particle generation (Salminen, 2014). Moreover, studies on brake wear particles have discussed that inertia load is likely to affect brake wear particles (Garg et al., 2000). In addition, life cycle data have been used for estimating non-exhaust emissions based on the mass of the vehicles, expressing the significance of inertia load on non-exhaust PM generation (Simons, 2016). Overall, the results of this study confirm the findings in the previous works and indicate that vehicle mass can play a major role in predicting brake and tire PM concentrations during the braking.

3.3. Particle size distribution

Mass-based particle size distributions of the brake and tire particles are shown as contour plots in Fig. 5. To obtain mass-based size distributions, we assume particles are perfect spheres with a uniform density of 2.6 and 2.8 g/cm³ for brake and tire wear particles, respectively (Alemani et al., 2016; Hussein et al., 2008; Kwak et al., 2013). In Fig. 5,

the x and left y coordinates present the sampling elapsed time in seconds and the aerodynamic particle diameter in the logarithmic scale, respectively. The normalized mass concentration ($dM/d\log d_p$) for the particle diameters in the range of 0.5–20 μm at a given time is shown in different contour colors. The right y-axis shows the average deceleration rate during the braking events. As shown in Fig. 5, while not all braking events increase PM mass concentration, high PM concentrations were observed for most of them. Similar to Fig. 4, for both the brake and tire particles, higher PM concentrations are generated from the heavier vehicles during braking. This is more noticeable for the Chevrolet Suburban, presumably because its mass is approximately twice as heavy as that of the Nissan Sentra and approximately 60 % heavier than that of the Honda Accord. A substantial difference between the mass-based size distribution of the brake and tire particles was not observed.

Fig. 6 plots the average mass-based particle size distributions for the three test vehicles. Both brake and tire particles showed a unimodal mass size distribution with a mode diameter of 3–4 μm and 4–5 μm , respectively. The reported brake particle size distributions in the previous studies vary depending on the sampling setup and instrumentation. The brake particles have been reported in various size ranges, including ultrafine, fine, and coarse sizes (Farwick zum Hagen et al., 2019b; Kwak et al., 2013; Nosko and Olofsson, 2017). The results of this

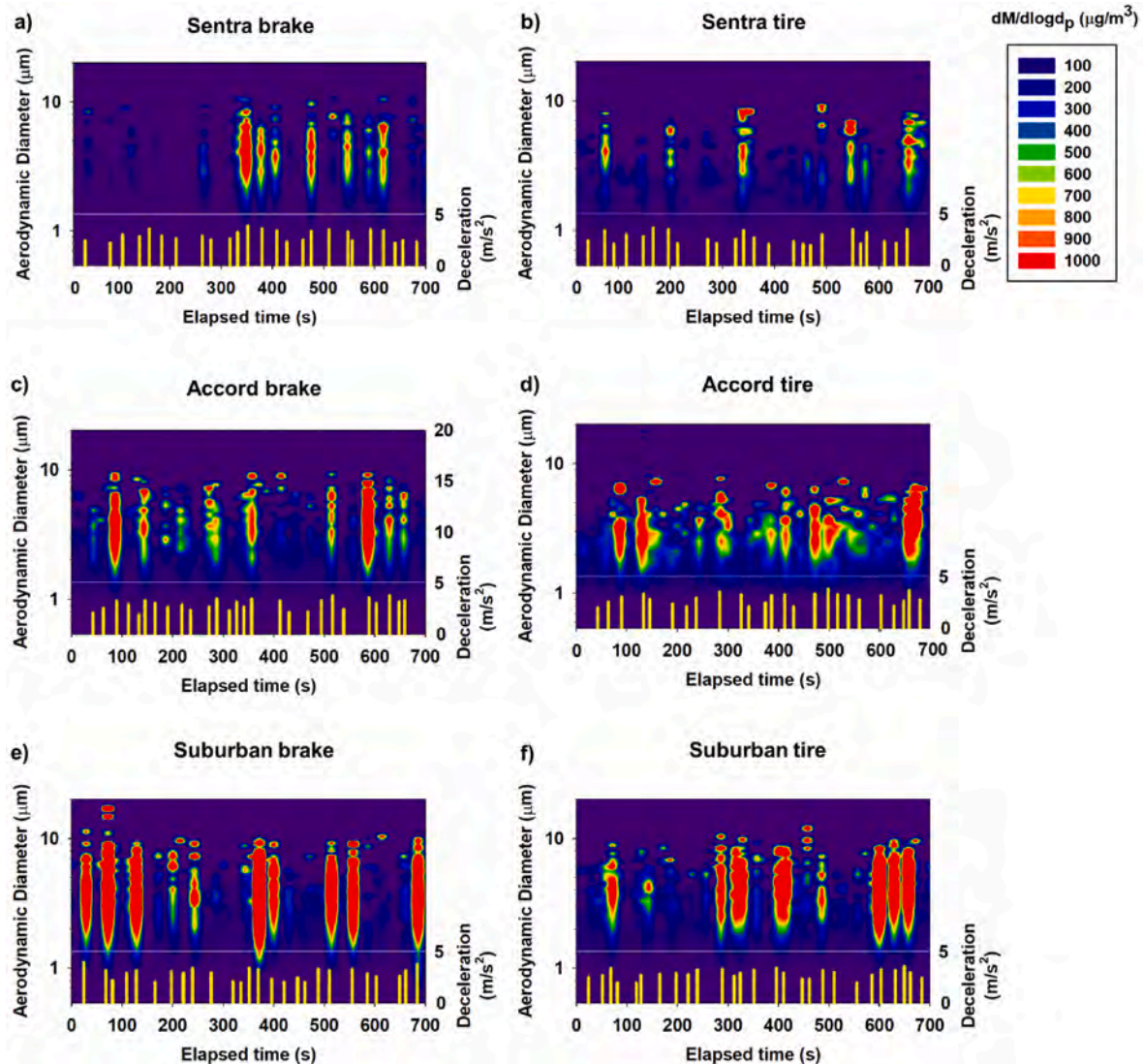


Fig. 5. Mass-based particle size distributions for brake and tire particles with regard to the braking deceleration rate during moderate and heavy braking events (a) Sentra brake, (b) Sentra tire, (c) Accord brake, (d) Accord tire, (e) Suburban brake, (f) Suburban tire.

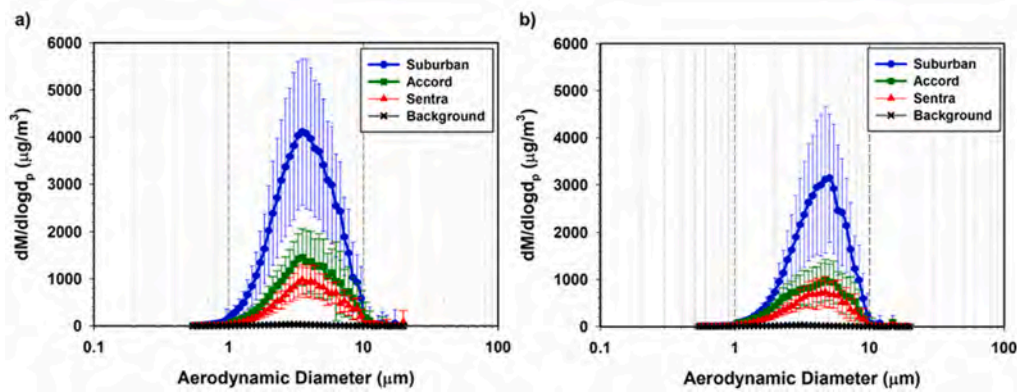


Fig. 6. Average mass-based particle size distribution during braking events for (a) brake particles and (b) tire particles (error bars: standard deviation).

study are in agreement with the findings of the previous study that reported a mass-based particle size distribution in the 1–10 μm size range (Kwak et al., 2013). Moreover, unimodal tire mass-based particle size distributions with mode diameters of 2–3 μm , 3–5 μm , and 3–4 μm have been reported (Hussein et al., 2008; Kim and Lee, 2018; Kwak et al., 2013). In general, our results on tire particle size distributions agree with the findings of these studies.

4. Discussion

One of the goals of this work was to study the effect of braking intensity on brake and tire particles. As shown in section 3.2, for each vehicle, higher brake and tire $\text{PM}_{2.5}$ and PM_{10} concentrations are observed during more intense braking events. However, it is important to note that at any given initial and final speed, the braking events with higher deceleration rates take less time, and therefore the particles are produced for a shorter period of time. Overall, the average durations of light ($0.5 < a < 2 \text{ m/s}^2$) vs. heavy ($a > 3 \text{ m/s}^2$) braking events for all test vehicles were $7.3 \pm 0.5 \text{ s}$ and $5.2 \pm 0.4 \text{ s}$, respectively, showing an approximately 40 % difference. This shorter braking time offsets the total amount of generated brake and tire particles during heavy braking events.

There are a few other factors that can affect the brake and tire particles. For instance, the aerodynamic drag may affect the vehicle braking intensity and concentrations of brake and tire particles. The aerodynamic drag has been reported to increase during windy conditions (Selvaraju and Parammasivam, 2019; Windsor, 2014) and affect the stopping distance and stopping time at higher driving speeds ($V > 100 \text{ km/h}$) (Haggag, 2016). However, in this study, the effect of aerodynamic drag on braking intensity was expected to be negligible due to low to medium driving speeds and low wind.

The brake temperature can also affect the brake wear particle size distribution. At a certain critical brake temperature (T_{crit}), particle number concentration has been shown to rapidly increase due to the generation of ultrafine particles (Alemani et al., 2018; Farwick zum Hagen et al., 2019a). While T_{crit} has been shown to be a function of brake lining material, most studies reported T_{crit} to be in the range of 140–190 $^{\circ}\text{C}$ (Alemani et al., 2018; Farwick zum Hagen et al., 2019a; 2019b; Nosko and Olofsson, 2017). A previous study using the Los Angeles City Traffic (LACT) cycle has shown that temperature transition occurs gradually (Farwick zum Hagen et al., 2019a). In fact, the brake temperature was reported to reach T_{crit} after 1 h of continuous driving (Farwick zum Hagen et al., 2019a). In this study, the brake temperature was below 80 $^{\circ}\text{C}$ at the beginning of each sampling session and reached up to 120 $^{\circ}\text{C}$ at the end of each 12-min session (Table A.2). Therefore, the range of brake temperature in this study was expected to be well below the T_{crit} (140–190 $^{\circ}\text{C}$) which is required for excessive ultrafine particle generation.

The goal of this work was to study the effect of vehicle mass on non-exhaust PM during different braking intensity levels. The effects of vehicle mass on non-exhaust PM emissions have received more attention in recent years with the global efforts for transportation electrification. Battery electric vehicles have shown to be heavier than vehicles with internal combustion engines due to the excessive battery weight (Timmers and Achten, 2018). While recent studies have shown the frequency of braking in the battery electric vehicles can be eight times lower due to the application of the regenerative braking system (Hall, 2017), more recent studies based on updated emission inventories have discussed that excessive weight of battery electric vehicles can minimize the positive effect of regenerative braking in reducing non-exhaust PM emissions (Beddows and Harrison, 2021). Therefore, future research is needed to better understand the overall impact of vehicle electrification on brake and tire wear emissions. The findings from the current study can provide insight into the effect of vehicle mass on brake and tire particles during various braking intensity levels and alleviate the gap of knowledge in this area.

5. Study limitations and future work

Chemical speciation has been shown to be useful in the identification of brake and tire wear particles (Lough et al., 2005). For instance, specific chemical elements have been used for tracing brake and tire wear particles (Wang et al., 2021). However, chemical speciation analysis would require collecting a large amount of PM samples during lengthy on-road sampling sessions, which was logistically prohibitive in the current study.

Accurate calibration factors for correcting PM concentrations measured by DustTrak is important. To the best of our knowledge, the DustTrak calibration factor for tire wear particles is not available in the literature. While DustTrak calibration factors for brake wear particles have been reported, they vary widely across different brake lining materials and sampling methods. Therefore, future studies are needed to provide more details about the DustTrak calibration factors of brake and tire wear particles.

Finally, the results of the current study showed that there could be a lag between the onset of the braking and observation of an increase in the concentration of the brake and tire particles. A similar observation has been reported previously during the on-road sampling of the brake wear particles (Farwick zum Hagen et al., 2019a). Since the instrument response time can vary, future research is needed to investigate the instrument response time during the real-time measurement of brake and tire wear particles.

6. Conclusion

In this study, three vehicles with different masses were tested to

investigate their effects on brake and tire particles under real-world driving conditions. On-road measurements were performed on three test vehicles with masses ranging from 2800 to 5800 lbs. A significant difference was observed in the brake and tire PM_{2.5} and PM₁₀ concentrations between the heaviest and lightest vehicles, indicating that there is a positive association between the vehicles' mass and the PM concentration at the brake and tire inlets. This study also demonstrated that the braking intensity is a strong predictor of the brake and tire PM_{2.5} and PM₁₀ concentrations. The brake and tire particles were measured in size range of 0.5–20 µm. Brake particles showed a unimodal mass size distribution with a mode diameter of 3–4 µm, while tire particles showed a slightly larger mode diameter of 4–5 µm. The findings of the current work provide novel information on the effect of vehicle and driving conditions on brake and tire particles.

CRedit authorship contribution statement

Farzan Oroumijeh: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Yifang Zhu:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aeaoa.2021.100121>.

References

- Aleman, M., Nosko, O., Metinoz, I., Olofsson, U., 2016. A study on emission of airborne wear particles from car brake friction pairs. *SAE Int. J. Mater. Manuf.* 9, 147–157. <https://doi.org/10.4271/2015-01-2665>.
- Aleman, M., Wahlström, J., Olofsson, U., 2018. On the influence of car brake system parameters on particulate matter emissions. *Wear* 396–397, 67–74. <https://doi.org/10.1016/j.wear.2017.11.011>.
- Axsen, J., Wolinetz, M., 2018. Reaching 30% plug-in vehicle sales by 2030: modeling incentive and sales mandate strategies in Canada. *Transport. Res. Transport Environ.* 65, 596–617. <https://doi.org/10.1016/j.trd.2018.09.012>.
- Baensch-Baltruschat, B., Kocher, B., Stock, F., Reifferscheid, G., 2020. Tyre and road wear particles (TRWP) - a review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. *Sci. Total Environ.* 733, 137823. <https://doi.org/10.1016/j.scitotenv.2020.137823>.
- Beddows, D.C.S., Harrison, R.M., 2021. PM₁₀ and PM_{2.5} emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles. *Atmos. Environ.* 244, 117886. <https://doi.org/10.1016/j.atmosenv.2020.117886>.
- Beelen, R., Hoek, G., van den Brandt, P.A., Goldbohm, R.A., Fischer, P., Schouten, L.J., Jerrett, M., Hughes, E., Armstrong, B., Brunekreef, B., 2008. Long-term effects of traffic-related air pollution on mortality in a Dutch cohort (NLCS-AIR study). *Environ. Health Perspect.* 116, 196–202. <https://doi.org/10.1289/ehp.10767>.
- Bukowiecki, N., Lienemann, P., Hill, M., Furger, M., Richard, A., Amato, F., Prévôt, A.S.H., Baltensperger, U., Buchmann, B., Gehrig, R., 2010. PM₁₀ emission factors for non-exhaust particles generated by road traffic in an urban street canyon and along a freeway in Switzerland. *Atmos. Environ.* 44, 2330–2340. <https://doi.org/10.1016/j.atmosenv.2010.03.039>.
- Chung, A., Chang, D.P.Y., Kleeman, M.J., Perry, K.D., Cahill, T.A., Dutcher, D., McDougall, E.M., Stroud, K., 2001. Comparison of real-time instruments used to monitor airborne particulate matter. *J. Air Waste Manag. Assoc.* 51, 109–120. <https://doi.org/10.1080/10473289.2001.10464254>.
- Farwick zum Hagen, F.H., Mathissen, M., Grabiec, T., Hennicke, T., Rettig, M., Grochowicz, J., Vogt, R., Benter, T., 2019a. On-road vehicle measurements of brake wear particle emissions. *Atmos. Environ.* 217, 116943. <https://doi.org/10.1016/j.atmosenv.2019.116943>.
- Farwick zum Hagen, F.H., Mathissen, M., Grabiec, T., Hennicke, T., Rettig, M., Grochowicz, J., Vogt, R., Benter, T., 2019b. Study of brake wear particle emissions: impact of braking and cruising conditions. *Environ. Sci. Technol.* 53, 5143–5150. <https://doi.org/10.1021/acs.est.8b07142>.
- Garg, B.D., Cadle, S.H., Mulawa, P.A., Groblicki, P.J., Laroo, C., Parr, G.A., 2000. Brake wear particulate matter emissions. *Environ. Sci. Technol.* 34, 4463–4469. <https://doi.org/10.1021/es001108h>.
- Gramstat, S., Mertens, T., Waninger, R., Lugovyy, D., 2020. Impacts on brake particle emission testing. *Atmosphere* 11. <https://doi.org/10.3390/atmos11101132>.
- Grigoratos, T., Martini, G., 2015. Brake wear particle emissions: a review. *Environ. Sci. Pollut. Res.* 22, 2491–2504. <https://doi.org/10.1007/s11356-014-3696-8>.
- Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Swietlicki, E., Bohgard, M., Lindbom, J., Ljungman, A., 2008. Properties and toxicological effects of particles from the interaction between tyres, road pavement and winter traction material. *Sci. Total Environ.* 393, 226–240. <https://doi.org/10.1016/J.SCITOTENV.2007.12.030>.
- Gustafsson, M., Eriksson, O., 2015. Emission of Inhalable Particles from Studded Tyre Wear of Road Pavements: a Comparative Study.
- Haggag, Salem A., 2016. Aerodynamic Forces Impact on Vehicle Braking Longitudinal Dynamics with a Sliding Mode Controller. *SAE Technical Papers*. <https://doi.org/10.4271/2016-01-0460>.
- Hagino, H., Oyama, M., Sasaki, S., 2015. Airborne brake wear particle emission due to braking and accelerating. *Wear* 334–335, 44–48. <https://doi.org/10.1016/j.wear.2015.04.012>.
- Hall, T.J., 2017. A comparison of braking behavior between an IC engine and pure electric vehicle in Los Angeles city driving conditions. *SAE Tech. Pap. Part F1301*. <https://doi.org/10.4271/2017-01-2518>.
- Harrison, R.M., Jones, A.M., Gietl, J., Yin, J., Green, D.C., 2012. Estimation of the contributions of brake dust, tire wear, and resuspension to nonexhaust traffic particles derived from atmospheric measurements. *Environ. Sci. Technol.* 46, 6523–6529. <https://doi.org/10.1021/es300894r>.
- Hinds, W.C., 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, second ed. Wiley, New York.
- Hussein, T., Johansson, C., Karlsson, H., Hansson, H.C., 2008. Factors affecting non-tailpipe aerosol particle emissions from paved roads: on-road measurements in Stockholm, Sweden. *Atmos. Environ. Times* 42, 688–702. <https://doi.org/10.1016/j.atmosenv.2007.09.064>.
- Iijima, A., Sato, K., Yano, K., Kato, M., Kozawa, K., Furuta, N., 2008. Emission factor for antimony in brake abrasion dusts as one of the major atmospheric antimony sources. *Environ. Sci. Technol.* 42, 2937–2942. <https://doi.org/10.1021/es702137g>.
- Jeong, C.-H., Traub, A., Huang, A., Hilker, N., Wang, J.M., Herod, D., Dabek-Zlotorzynska, E., Celio, V., Evans, G.J., 2020. Long-term analysis of PM_{2.5} from 2004 to 2017 in Toronto: composition, sources, and oxidative potential. *Environ. Pollut.* 263, 114652. <https://doi.org/10.1016/j.envpol.2020.114652>.
- Jeong, C.H., Wang, J.M., Hilker, N., Deboz, J., Sofowote, U., Su, Y., Noble, M., Healy, R. M., Munoz, T., Dabek-Zlotorzynska, E., Celio, V., White, L., Audette, C., Herod, D., Evans, G.J., 2019. Temporal and spatial variability of traffic-related PM_{2.5} sources: comparison of exhaust and non-exhaust emissions. *Atmos. Environ.* 198, 55–69. <https://doi.org/10.1016/j.atmosenv.2018.10.038>.
- Kim, G., Lee, S., 2018. Characteristics of tire wear particles generated by a tire simulator under various driving conditions. *Environ. Sci. Technol.* 52, 12153–12161. <https://doi.org/10.1021/acs.est.8b03459>.
- Kukutschová, J., Moravec, P., Tomášek, V., Matějka, V., Smolík, J., Schwarz, J., Seidlerová, J., Šafářová, K., Filip, P., 2011. On airborne nano/micro-sized wear particles released from low-metallic automotive brakes. *Environ. Pollut.* 159, 998–1006. <https://doi.org/10.1016/j.envpol.2010.11.036>.
- Kumar, P., Pirjola, L., Ketzler, M., Harrison, R.M., 2013. Nanoparticle emissions from 11 non-vehicle exhaust sources - a review. *Atmos. Environ.* <https://doi.org/10.1016/j.atmosenv.2012.11.011>.
- Kumar, V.V., Kumaran, S.S., 2019. Friction material composite: types of brake friction material formulations and effects of various ingredients on brake performance-a review. *Mater. Res. Express* 6. <https://doi.org/10.1088/2053-1591/ab2404>.
- Kwak, J.H., Kim, H., Lee, J., Lee, S., 2013. Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements. *Sci. Total Environ.* 458–460, 273–282. <https://doi.org/10.1016/j.scitotenv.2013.04.040>.
- Lee, S.E., Llaneras, E., Klauer, S.G., Sudweeks, J., 2007. *Analyses of Rear-End Crashes and Near-Crashes in the 100-Car Naturalistic Driving Study to Support Rear-Signaling Countermeasure Development*. U.S. Department of Transportation National Highway Traffic Safety Administration, Washington, D.C.
- Li, W., Yang, X., Wang, S., Xiao, J., Hou, Q., 2021. Research and prospect of ceramics for automotive disc-brakes. *Ceram. Int.* 47, 10442–10463. <https://doi.org/10.1016/j.ceramint.2020.12.206>.
- Li, W., Yang, X., Wang, S., Xiao, J., Hou, Q., 2020. Comprehensive analysis on the performance and material of automobile brake discs. *Metals* 10. <https://doi.org/10.3390/met10030377>.
- Liat, A., Schreiber, D., Lugovyy, D., Gramstat, S., Dimopoulos Eggenschwiler, P., 2019. Airborne particulate matter emissions from vehicle brakes in micro- and nano-scales: morphology and chemistry by electron microscopy. *Atmos. Environ.* 212, 281–289. <https://doi.org/10.1016/j.atmosenv.2019.05.037>.

- Lough, G.C., Schauer, J.J., Park, J.S., Shafer, M.M., Deminter, J.T., Weinstein, J.P., 2005. Emissions of metals associated with motor vehicle roadways. *Environ. Sci. Technol.* 39, 826–836. <https://doi.org/10.1021/es048715f>.
- Mathissen, M., Scheer, V., Vogt, R., Benter, T., 2011. Investigation on the potential generation of ultrafine particles from the tire-road interface. *Atmos. Environ.* 45, 6172–6179. <https://doi.org/10.1016/j.atmosenv.2011.08.032>.
- Maurya, A.K., Bokare, P.S., 2012. Study of deceleration behaviour of different vehicle types. *Int. J. Traffic Transport. Eng.* 2, 253–270. [https://doi.org/10.7708/ijtte.2012.2\(3\).07](https://doi.org/10.7708/ijtte.2012.2(3).07).
- Nosko, O., Olofsson, U., 2017. Quantification of ultrafine airborne particulate matter generated by the wear of car brake materials. *Wear* 374 (375), 92–96. <https://doi.org/10.1016/j.wear.2017.01.003>.
- Pant, P., Harrison, R.M., 2013. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. *Atmos. Environ.* 77, 78–97. <https://doi.org/10.1016/j.atmosenv.2013.04.028>.
- Pirjola, L., Johansson, C., Kupiainen, K., Stojiljkovic, A., Karlsson, H., Hussein, T., 2010. Road dust emissions from paved roads measured using different mobile systems. *J. Air Waste Manag. Assoc.* 60, 1422–1433. <https://doi.org/10.3155/1047-3289.60.12.1422>.
- Puisney, C., Oikonomou, E.K., Nowak, S., Chevillot, A., Casale, S., Baeza-Squiban, A., Berret, J.F., 2018. Brake wear (nano)particle characterization and toxicity on airway epithelial cells: in vitro. *Environ. Sci. Nano* 5, 1036–1044. <https://doi.org/10.1039/c7en00825b>.
- Rexeis, M., Hausberger, S., 2009. Trend of vehicle emission levels until 2020 - prognosis based on current vehicle measurements and future emission legislation. *Atmos. Environ.* 43, 4689–4698. <https://doi.org/10.1016/j.atmosenv.2008.09.034>.
- Rivas, I., Mazaheri, M., Viana, M., Moreno, T., Clifford, S., He, C., Bischof, O.F., Martins, V., Reche, C., Alastuey, A., Alvarez-Pedrerol, M., Sunyer, J., Morawska, L., Querol, X., 2017. Identification of technical problems affecting performance of DustTrak DRX aerosol monitors. *Sci. Total Environ.* 584 (585), 849–855. <https://doi.org/10.1016/j.scitotenv.2017.01.129>.
- Salminen, H., 2014. Parametrizing Tyre Wear Using a Brush Tyre Mode. Royal Institute of Technology, Stockholm.
- Sanders, P.G., Xu, N., Dalka, T.M., Maricq, M.M., 2003. Airborne brake wear debris: size distributions, composition, and a comparison of dynamometer and vehicle tests. *Environ. Sci. Technol.* 37, 4060–4069. <https://doi.org/10.1021/es034145s>.
- Selvaraju, P.N., Parammasivam, K.M., 2019. Empirical and numerical analysis of aerodynamic drag on a typical SUV car model at different locations of vortex generator. *J. Appl. Fluid Mech.* 12, 1487–1496. <https://doi.org/10.29252/JAFM.12.05.29674>.
- Seo, H., Joo, B., Park, J., Kim, Y.C., Lee, J.J., Jang, H., 2021. Effect of disc material on particulate matter emissions during high-temperature braking. *Tribol. Int.* 154, 106713. <https://doi.org/10.1016/j.triboint.2020.106713>.
- Simons, A., 2016. Road transport: new life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions inecoinvent v3. *Int. J. Life Cycle Assess.* 21, 1299–1313. <https://doi.org/10.1007/s11367-013-0642-9>.
- Smith, D.L., Najm, W.G., Lam, A.H., 2003. Analysis of braking and steering performance in car-following scenarios. *SAE Tech. Pap.* <https://doi.org/10.4271/2003-01-0283>.
- Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C., Gieré, R., 2018. Tire abrasion as a major source of microplastics in the environment. *Aerosol Air Qual. Res.* 18 <https://doi.org/10.4209/aaqr.2018.03.0099>, 2014–2028.
- Sundarkrishnaa, K., 2015. Friction Material Composites Copper-/Metal-free Material Design Perspective, second ed. Springer International Publishing.
- Timmers, V.R.J.H., Achten, P.A.J., 2018. Non-Exhaust PM Emissions from Battery Electric Vehicles, Non-exhaust Emissions. Elsevier Inc. <https://doi.org/10.1016/b978-0-12-811770-5.00012-1>.
- Wang, J.M., Jeong, C.H., Hilker, N., Healy, R.M., Sofowote, U., Deboz, J., Su, Y., Munoz, A., Evans, G.J., 2021. Quantifying metal emissions from vehicular traffic using real world emission factors. *Environ. Pollut.* 268, 115805. <https://doi.org/10.1016/j.envpol.2020.115805>.
- Wang, X., Grose, M.A., Caldow, R., Osmondson, B.L., Swanson, J.J., Chow, J.C., Watson, J.G., Kittelson, D.B., Li, Y., Xue, J., Jung, H., Hu, S., 2016. Improvement of Engine Exhaust Particle Sizer (EEPS) size distribution measurement - II. Engine exhaust particles. *J. Aerosol Sci.* 92, 83–94. <https://doi.org/10.1016/j.jaerosci.2015.11.003>.
- Windsor, S., 2014. Real world drag coefficient – is it wind averaged drag? The International Vehicle Aerodynamics Conference. Woodhead Publishing Limited. <https://doi.org/10.1533/9780081002452.1.3>.
- Wu, Z., Liu, Y., Pan, G., 2009. A smart car control model for brake comfort based on car following. *IEEE Trans. Intell. Transport. Syst.* 10, 42–46. <https://doi.org/10.1109/TITS.2008.2006777>.
- Zhu, Y., Kuhn, T., Mayo, P., Hinds, W.C., 2006. Comparison of daytime and nighttime concentration profiles and size distributions of ultrafine particles near a major highway. *Environ. Sci. Technol.* 40, 2531–2536. <https://doi.org/10.1021/es0516514>.



Contributions of non-tailpipe emissions to near-road PM_{2.5} and PM₁₀: A chemical mass balance study ☆

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Highlights

- Near-road PM₁₀ and PM_{2.5} samples were dominated by resuspended dust.
- Brake and tire wear contributed similarly to or more than tailpipe exhaust in PM_{2.5}
- Brake and tire wear contributions were 2–3 times the exhaust contributions in PM₁₀.
- Barium may serve as a unique marker for brake wear particles in Los Angeles.

Abstract

As the importance of non-tailpipe particles (NTP) over tailpipe emissions from urban traffic has been increasing, there is a need to evaluate NTP contributions to ambient particulate matter (PM) using representative source profiles. The Brake and Tire Wear Study conducted in Los Angeles, California in the winter of 2020 collected 64 PM_{2.5} and 64 PM₁₀ samples from 32 pairs of downwind-upwind measurements at two near-road locations (I-5 in Anaheim and I-710 in Long Beach). These samples were characterized for inorganic and organic markers and, along with locally-developed brake wear, tire wear, and road dust source profiles, subject to source apportionment using the effective-variance chemical mass balance (EV-CMB) model. Model results highlighted the dominance of resuspended dust in both PM_{2.5} (23–33%) and PM₁₀ (32–53%). Brake and tire wear contributed more to PM_{2.5} than tailpipe exhausts (diesel+gasoline) for I-5 (29–30% vs. 19–21%) while they were comparable for I-710 (15–17% vs. 15–19%). For PM₁₀, the brake and tire wear contributions were 2–3 times the exhaust contributions. Different fleet compositions on and near I-5 and I-710 appeared to influence the relative importance of NTP and exhaust sources. The downwind-upwind differences in source contributions were often insignificant, consistent with small and/or nearly equal impacts of adjacent highway traffic emissions on the downwind and upwind sites. The utility of sole markers, such as barium and zinc, to predict brake and tire wear abundances in ambient PM is evaluated.

Graphical abstract



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Introduction

Elevated pollutant concentrations in near-road environments have been a concern for health effects and disparity (Clark et al., 2017; Rowangould, 2013). Epidemiologic studies have linked vehicular emissions to health burdens, such as increased asthma attacks, cardiac and pulmonary diseases, impaired lung function, and low birth weights (Brandt et al., 2014; Brugge et al., 2007; Ghosh et al., 2016; HEI, 2022). Regulatory efforts by air quality agencies globally have resulted in decreasing tailpipe emissions over the years, but non-tailpipe emissions, such as brake and tire wear particles,

are not affected by these efforts (Harrison et al., 2021). Battery electric vehicles, which are gaining market penetration, achieve zero tailpipe emissions but potentially generate higher brake and tire wear emissions than conventional vehicles due to their heavier weights (Beddows and Harrison, 2021; Timmers and Achten, 2016). Thus, the importance of non-tailpipe particles (NTP) to ambient particulate matter (PM) increases (Amato et al., 2014; Denier van der Gon et al., 2013). The statewide California Air Resources Board's emission inventory (California Air Resources Board, 2021) estimates that brake and tire wear have exceeded tailpipe in $PM_{2.5}$ (particles with aerodynamic diameters $\leq 2.5\mu m$) emissions since 2020. This is of concern since brake and tire particles have higher metal contents, possibly resulting in higher toxicity and adverse health outcomes for traffic-impacted communities.

Brake wear resulting from abrasion of brake pads and rotors contains trace metals such as iron (Fe), manganese (Mn), copper (Cu), titanium (Ti), zinc (Zn), antimony (Sb), and barium (Ba) (Pant and Harrison, 2013). Rubber polymers, their derivatives, and carbon black dominate tire wear, while Zn and benzothiazoles are often used as tire wear markers (Klöckner et al., 2019; Pant and Harrison, 2013; Wik and Dave, 2009). Zinc oxide, organozinc compounds, and benzothiazoles are added to tire tread during the vulcanization process. Tire wear particles can contain polycyclic aromatic hydrocarbons (PAHs) and n-alkanes, likely created through volatilization during contact of the tire tread with road surfaces and subsequent condensation into the particle phase (Aatmeeyata and Sharma, 2010; Baensch-Baltruschat et al., 2020). NTP may also include resuspended road dust/wear which is rich in mineral elements such as silicon (Si), aluminum (Al), and calcium (Ca). Compared to tailpipe exhaust particles that are primarily submicron in size, NTP markers are found in both fine- and coarse-mode particles (Harrison et al., 2012; Lin et al., 2015; Lough et al., 2005).

Quantifying NTP contributions to fine- ($PM_{2.5}$) and coarse-mode (PM_{10} and $PM_{10-2.5}$: particles with aerodynamic diameters $\leq 10\mu m$ and between 2.5 and $10\mu m$, respectively) remains a challenge. Harrison et al. (2012) estimated brake wear, tire wear, and road dust contributions to size-segregated PM using Ba, Zn, and Si as markers and assuming brake-wear/Ba, tire-wear/Zn, and dust/Si mass ratios of 91, 50, and 3.6, respectively. This approach doesn't take into account that Zn can result from both brake and tire wear whereas there are possibly other sources of Ba, Zn, and/or Si in the study area. Factor analysis models such as principle component analysis (PCA) and positive matrix factorization (PMF) sought to discern NTP factor(s) in a multivariate dataset that contains major markers (Amato et al., 2011; Fabretti et al., 2009; Jalali Farahani et al., 2022; Lawrence et al., 2013). However, temporal correlations among NTP and tailpipe emissions often cause them to mix into single factor(s), thus biasing the source apportionment (Chen et al., 2010a). Despite of the uncertainty, NTP were found to rival exhaust particles in their abundances, particularly in urban PM_{10} and $PM_{10-2.5}$ (Harrison et al., 2021).

With a high population density and heavy traffic, elevated air pollution levels in the Los Angeles metropolitan region of southern California have been well documented. Hasheminassab et al., 2014a, Hasheminassab et al., 2014b attributed long-term $PM_{2.5}$ concentrations to vehicular

emissions, secondary nitrate, secondary sulfate, soil, aged sea salt, fresh sea salt, and biomass burning, with vehicular emissions accounting for ~20% of PM_{2.5} for the period of 2002–2013. NTP were not resolved in that study, though they were likely incorporated into vehicular emissions and/or soil factors. Habre et al. (2021) identified similar sources across Los Angeles in 2008–2009, but attributed 11% and 21% of PM_{2.5} to NTP (brake+tire) and exhaust particles, respectively, and 18% of PM_{10-2.5} to NTP (brake+tire). A more recent study (Jalali Farahani et al., 2022) near Los Angeles highways found similar contributions of NTP (brake+tire) and exhaust particles to PM₁₀, at 16% and 26%, respectively.

To further understand real-world non-tailpipe emissions and contributions to exposure, PM_{2.5} and PM₁₀ were sampled downwind and upwind of two major highways in Los Angeles during the winter of 2020 and subsequently analyzed for elemental and organic compositions (Lopez et al., 2023; Wang et al., 2023). These data were used in the effective variance-chemical mass balance (EV-CMB) model with explicit brake and tire wear source profiles to obtain source contribution estimates. The results add to literature and emission inventories that highlight the importance of NTP in urban air pollution while informing regulatory strategies needed to attain ambient air quality standards.

Section snippets

PM_{2.5} and PM₁₀ data

Time-integrated PM_{2.5} and PM₁₀ samples were collected near highway I-5 in Anaheim and near highway I-710 in Long Beach (Fig. 1) over a two-week period. I-5 and I-710 are paved with concrete and asphalt, respectively. On-site traffic counts during the tests indicated ~95% light-duty vehicles (LDV) and 5% heavy-duty vehicles (HDV) on I-5, representative of a typical southern California highway fleet, and ~90% LDV and 10% HDV on I-710, consistent with goods movement to and from the Ports of Long ...

Sensitivity tests

Sensitivity tests evaluate the performance of different source profile combinations in terms of r^2 , χ^2 , and %mass. To create a sample that is suitable for the sensitivity test, upwind concentrations at the I-5 site were subtracted from the corresponding downwind concentrations so that the differences could be fully attributed to traffic-related emissions including: 1) brake wear, 2) tire wear, 3) road dust, and 4) tailpipe exhausts. Since wind directions varied from time to time, here the ...

Conclusion

This paper documents EV-CMB-based source apportionment for PM_{2.5} and PM₁₀ samples collected at near-road sites downwind and upwind of I-5 and I-710 in Los Angeles. Dust, brake wear, and tire

wear source profiles were developed specifically for contemporary southern California. Sensitivity tests used the downwind-upwind differences in PM chemical composition caused by on-road traffic emissions. The optimal model revealed contributions of resuspended dust, brake wear, tire wear, and vehicle ...

Author contribution

L.-W. Antony Chen: Conceptualization; Methodology; Data curation; Formal analysis; Funding acquisition; Investigation; Writing - original draft. Xiaoliang Wang: Conceptualization; Data curation; Funding acquisition; Investigation; Writing - review & editing. Brenda Lopez: Data curation; Investigation; Writing - review & editing. Guoyuan Wu: Data curation; Investigation. Steven Sai Hang Ho: Data curation; Investigation. Judith C. Chow: Conceptualization; Resources; Writing - review & editing. ...

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lung-Wen Antony Chen reports financial support was provided by California Air Resources Board. Xiaoliang Wang reports financial support was provided by California Air Resources Board. Brenda Lopez reports financial support was provided by California Air Resources Board. Guoyuan Wu reports financial support was provided by California Air Resources Board. Heejung ...

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References (52)

F. Amato *et al.*

[Urban air quality: the challenge of traffic non-exhaust emissions](#)

J. Hazard Mater. (2014)

F. Amato *et al.*

Sources and variability of inhalable road dust particles in three European cities

Atmos. Environ. (2011)

B. Baensch-Baltruschat *et al.*

Tyre and road wear particles (TRWP)–A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment

Sci. Total Environ. (2020)

D.C.S. Beddows *et al.*

PM₁₀ and PM_{2.5} emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles

Atmos. Environ. (2021)

S. Brandt *et al.*

Cost of near-roadway and regional air pollution–attributable childhood asthma in Los Angeles County

J. Allergy Clin. Immunol. (2014)

J.C. Chow *et al.*

Similarities and differences in PM₁₀ chemical source profiles for geological dust from the San Joaquin Valley, California

Atmos. Environ. (2003)

J.F. Fabretti *et al.*

Elemental characterization and source identification of PM_{2.5} using Positive Matrix Factorization: the Malraux road tunnel, Nice, France

Atmos. Res. (2009)

M. Fadel *et al.*

PM_{2.5} characterization of primary and secondary organic aerosols in two urban-industrial areas in the East Mediterranean

J. Environ. Sci. (2021)

J.K. Gietl *et al.*

Identification of brake wear particles and derivation of a quantitative tracer for brake dust at a major road

Atmos. Environ. (2010)

R.M. Harrison *et al.*

Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: a review

Atmos. Environ. (2021)



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The chemical composition and sources of road dust, and of tire and road wear particles– A review

2024, Science of the Total Environment

Citation Excerpt :

...It is known that Zn and Cu provide limited selectivity because there are additional sources in traffic, and both may interact with each other as Zn is also a constituent of BW and Cu of TT. Therefore, several studies propose using multiple marker compounds or source profiles (Chen et al., 2023b). The share of pavement abrasion is derived from the remaining fraction $f(\text{pavement abrasion}) = 1 - f(\text{tire tread}) - f(\text{brake dust})$, because there is no marker element existing....

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Characterization and apportionment of carbonaceous aerosol emission factors from light-duty and heavy-duty vehicle fleets in Maharashtra, India

2024, Environmental Pollution

Citation Excerpt :

...On-road vehicular emissions in cities and large urban conglomerates are important source of carbonaceous aerosols (Brito et al., 2018). They result from fuel combustion, mechanical abrasion of tires, brakes, resuspension of road dust (De Miranda et al., 2018; Chen et al., 2023) and, secondary transformations (Gentner et al., 2017). Due to the diverse mix of vehicle types, ages, fuels, technologies and operating conditions, estimating the accurate real-world emissions becomes a challenge (Romero et al., 2020)....

Show abstract

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Citation Excerpt :

...Indoors, cooking, heating with solid fuels, smoking, and the use of aerosols and cleaning products can release particles (Kaplan, 2010). Traffic-related activities, like roadside dust and tire wear, add to outdoor PM levels, while indoor sources like candles and second-hand smoke contribute to indoor exposure (Chen et al., 2023). PM, especially the fine particulate matter known as PM_{2.5}, has been associated with a reduction in BMD and a connection to inflammation and osteoclast activity....

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2025, BMJ

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2024, Environmental Science and Technology



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June 12, 2023

Submitted electronically via email to: www.regulations.gov/docket/EERE-2021-VT-0033

U.S. Department of Energy
1904-AF47
1000 Independence Avenue, SW
Washington, DC 20585

Re: Petroleum-Equivalent Fuel Economy Calculation and Petition for Rulemaking (88 Fed. Reg. 21525 (April 11, 2023)).

To whom it may concern,

The American Fuel & Petrochemical Manufacturers (AFPM) appreciates the opportunity to comment on the U.S. Department of Energy's (DOE's or the Department's) proposal to revise its regulations regarding calculating a value for the petroleum-equivalent fuel (PEF) economy of electric vehicles (EVs) for use in determining compliance with the Corporate Average Fuel Economy (CAFE) program.¹ AFPM is a national trade association representing nearly all U.S. refining and petrochemical manufacturing capacity. AFPM members support more than three million quality jobs, contribute to our economic and national security, and enable the production of thousands of vital products used by families and businesses throughout the United States. AFPM members are also leaders in producing lower carbon fuels, such as renewable diesel and sustainable aviation fuel.

We support DOE's proposal to eliminate the fuel content factor of 0.15 because it is consistent with the plain language of the statute. However, DOE's proposal does not go far enough to ensure that the PEF for EVs facilitates accurate comparisons between EVs and internal combustion engine vehicles (ICEVs) under real-world driving conditions. In seeking to "update" PEF values in accordance with the four statutory factors contained in 49 U.S.C. §32904(a)(2)(B), DOE must consider the present energy efficiency of electric vehicles, the present national electrical generation and transmission efficiencies, broader energy conservation objectives and criteria, and current driving patterns of electric vehicles. These comments detail the substantial issues with DOE's analysis of these statutory factors.

AFPM requests the DOE to immediately eliminate the use of the fuel content factor, as proposed, and update the PEF using current, real-world data when applying the statutory factors set forth in 49 U.S.C. §32904(a)(2)(B). Given the extent of revisions to the PEF inputs to the

¹ 88 Fed. Reg. 21525, 21526 (April 11, 2023).

four statutory factors needed to finalize the PEF value for this year, AFPM also submits these comments as a petition for rulemaking for next year's update of inputs for the four statutory factors contained 49 U.S.C. §32904(a)(2)(B).

BACKGROUND

In 2000, DOE finalized a rule that utilized 49 U.S.C. §32905(a) and (c)² to calculate PEF for EVs even while DOE was *required* to use 49 U.S.C. §32904(a)(2)(B) to determine PEF for EVs, a fact the department acknowledged in during the rulemaking process.³ In using §32905 rather than §32904, DOE admitted that “[t]he true energy efficiency of both liquid and gaseous fueled alternative fuel vehicles is substantially overstated by the methods specified in 49 U.S.C. § 32905, since only 15 percent of their actual energy consumption is accounted for in determining their petroleum-equivalent fuel economy.”⁴ Yet, without congressional authorization, DOE still applied the “substantially overstated” 0.15 factor to EVs in “a manner similar to that prescribed for natural gas vehicles,”⁵ DOE took this action despite Congress explicitly limiting use of the 0.15 factor to “liquid alternative fuel[s] used to operate a dedicated automobile” thereby prohibiting its application to EVs.⁶

49 U.S.C. §32904(a)(2)(B) requires the DOE to review the PEF values “each year and determine and propose necessary revisions” based on four statutory factors contained in that provision. DOE has not done so for the past 20 years. It is long past due for the DOE to correct past mistakes regarding how the department calculates PEF. Going forward, DOE must annually assess inputs and propose necessary revisions, fully consistent with its statutory obligations.

I. DOE’s proposal to exclude the 0.15 fuel content factor from the PEF is required by the plain language of the statute.

In 1999, DOE proposed to calculate the PEF by examining *some* of the four statutory factors applicable to EVs contained in 49 U.S.C. §32904(a)(2)(B)⁷ and applying 49 U.S.C. §32905(a), which applied a fuel content factor of 0.15 for determining the petroleum equivalent fuel economy of *non-EV* alternative fuel vehicles.⁸ The application of the conversion factor in §32905(a) to EVs is directly contrary to the text of that section.

49 U.S.C. §32905(a) directs DOE to apply a fuel content factor of 0.15 to determine the petroleum equivalent fuel economy of *non-EV* alternative fuel vehicles.

² 65 Fed. Reg. 36985 (June 12, 2000).

³ Referencing the enactment of this provision as part of the Motor Vehicle Information and Cost Savings Act, DOE stated that 49 U.S.C. 32904(a)(2) “requires EPA to determine the petroleum-equivalent fuel economy values for electric vehicles taking into account [four statutory factors.]” 64 Fed. Reg. at 37906.

⁴ *Id.* at 37907.

⁵ *Id.*

⁶ 49 U.S.C. §32905(a).

⁷ For example, DOE examined the driving pattern of electric vehicles but proposed “for now” that this factor be assigned a value of 1.00. 64 Fed. Reg. at 37908. This meant that the PEF would not be adjusted on account of this known factor that inflates the PEF.

⁸ 64 Fed. Reg. 37905, 37907 (July 14, 1999).

Except as provided in subsection (c) of this section or **section 32904(a)(2)** of this title, for any model of dedicated automobile manufactured by a manufacturer after model year 1992, the fuel economy measured for that model shall be based on the fuel content of the alternative fuel used to operate the automobile. A gallon of a liquid alternative fuel used to operate a dedicated automobile is deemed to contain .15 gallon of fuel.⁹

The plain text of the .15 conversion factor specifically excepts vehicles subject to 32904(a)(2), which instructs DOE to calculate average fuel economy for EVs based on four statutory criteria:

If a manufacturer manufactures an electric vehicle, the Administrator shall include in the calculation of average fuel economy under paragraph (1) of this subsection equivalent petroleum based fuel economy values determined by the Secretary of Energy for various classes of electric vehicles. The Secretary shall review those values each year and determine and propose necessary revisions based on the following factors:

- (i) the approximate electrical energy efficiency of the vehicle, considering the kind of vehicle and the mission and weight of the vehicle.
- (ii) the national average electrical generation and transmission efficiencies.
- (iii) the need of the United States to conserve all forms of energy and the relative scarcity and value to the United States of all fuel used to generate electricity.
- (iv) the specific patterns of use of electric vehicles compared to petroleum-fueled vehicles.¹⁰

There is no statutory support for DOE to apply the fuel content conversion factor to EVs. DOE must change its approach to calculating PEF from that adopted in 2000 and include in the final rule a statement explaining that its new interpretation of the PEF calculation methodology is consistent with the plain language of the statute.

In the 2000 rule cited above, DOE articulated the “advantages” of using the non-EV criteria:

- “(i) It is consistent with existing regulatory and statutory procedures for other types of alternative fuel vehicles,
- (ii) It provides similar treatment to manufacturers of all types of alternative fuel vehicles, including electric vehicles,
- (iii) It is relatively simple and straightforward to apply, compared to other approaches considered.”¹¹

This rationale, however, does not square with the plain language of the law. Congress specially excluded EVs from the 0.15 conversion factor, instructing DOE to annually apply other factors to “various classes electric vehicles” in calculating their average fuel economy.¹²

⁹ 49 U.S.C. §32905(a) (emphasis added).

¹⁰ *Id.* at §32904(a)(2).

¹¹ *Id.*

¹² *Id.* at §32904(a)(2)(B).

A. DOE is correct to eliminate a fuel content factor that produces inaccurate estimates of EV efficiency.

In proposing to incorporate the 0.15 fuel content factor into the calculation of PEF for EVs in 1999, the DOE admitted that “[t]he true energy efficiency of both liquid and gaseous fueled alternative fuel vehicles is substantially overstated by the methods specified in 49 U.S.C. §32905, since only 15 percent of their actual energy consumption is accounted for in determining their petroleum-equivalent fuel economy.”¹³ DOE’s improper application of §32905 to EVs similarly overstates EVs’ fuel economy.

In response to comments on the 1999 proposed rule, the DOE stated that it “invested considerable time and effort in attempting to develop a method that could rigorously account for the advantages to the Nation offered by electric vehicles compared to conventional vehicles, [DOE] was unable to identify a method that was sufficiently objective, robust, and consistent with established policy direction.”¹⁴ DOE admitted it was giving “favorable treatment” to EVs due to the large credits that would be generated under the CAFE program and, without citation, claimed that “DOE believes that Congress intended the PEF to be an incentive for manufacturers to produce roadworthy electric vehicles that provide an alternative to conventional petroleum-powered vehicles.”¹⁵

Eliminating application of the fuel content factor will help to correct these past errors in misinterpreting the statute and deliberately overstating EV fuel economy by at least 667% (*i.e.*, 1 divided by 0.15).

II. The DOE must use current, representative data when annually revising the values based on the statutory factors in 49 U.S.C. §32904(a)(2)(B).

A. The plain language of the statute requires annual review of the PEF.

The statute requires DOE to review *each year* the petroleum-based fuel economy values for various classes of electric vehicles and to “determine and propose necessary revisions.”¹⁶ The first implication of this annual requirement is that the DOE must utilize current data. The DOE cannot, as it proposes, determine in 2023 that it will “keep the factor stable over the period of the standard setting years [2027-2031], unless there is a compelling reason to change the factor as a result of this review.”¹⁷ This reading runs counter to the statute’s annual review requirement. The DOE lacks any discretion to decide in 2023 that will it apply the same PEF through 2031. Moreover, DOE can cite no statutory support for the concept that there must be a “compelling” reason to change the PEF. The law mandates the DOE review those values every year and make necessary revisions based on the four statutory factors. Indeed, DOE must consider additional modifications to its proposed revisions, as discussed below.

¹³ 88 Fed. Reg. at 37907.

¹⁴ *Id.* at 36,989.

¹⁵ *Id.* at 36,990.

¹⁶ 49 U.S.C. §32904(a)(2)(B).

¹⁷ 88 Fed. Reg. at 21533.

B. The DOE improperly applied the four statutory factors.

The DOE's examination of the four statutory factors is cursory, impermissibly uses unrepresentative inputs, ignores broader realities affecting EVs, such as reduced electricity transmission efficiency, selectively assesses the need to conserve energy, and fails to update its assessment of EV utilization.

1. DOE's proposed PEF does not result in a "real world" assessment of fuel efficiency.

Despite the fact DOE last updated PEF more than twenty years ago, the DOE is *not* proposing to amend EV testing requirements. Specifically, the Department continues to rely on the Highway Fuel Economy Driving Cycle (HFEDS) and the Urban Dynamometer Driving Schedule (UDDS) for vehicle testing. DOE uses only these two testing cycles to measure the energy consumption of an EV and to translate this value in an equivalent measure based on gallons of gasoline to calculate "the resulting value in the PEF equation."¹⁸

HFEDS and UDDS are not representative of EV electrical energy efficiency during "typical use." HFEDS represents highway driving conditions characterized by constant speed operation of a vehicle, with limited representation of hills or acceleration/deceleration events. Vehicles evaluated under HFEDS reach a maximum speed of 58.9 miles per hour and slowly decelerate towards the end of the cycle. This cycle is unrepresentative of modern highway conditions and everyday operation of vehicles, including urban commuting.

As the Environmental Protection Agency (EPA) stated in 2006, "[w]hile the EPA fuel economy estimates [relying on testing only highway and city operation] have generally been a useful tool for comparing the relative fuel economy of different vehicles, they have been less useful for predicting the fuel economy that consumers can reasonably expect to achieve in the real world."¹⁹ EPA noted that the Highway Fuel Economy Test (HFET otherwise known as HFEDS) "was developed by EPA in 1974 and was designed to represent a mix of interstate highway and rural driving."²⁰ This test is also run "in mild climatic conditions (75° F) and [both the city and highway tests] have mild acceleration rates, and neither test is run with the use of fuel-consuming accessories, such as air-conditioning."²¹

In reflecting on its use of the original HFEDS tests to calculate vehicle fuel economy, the EPA also noted:

Since [the 1980s], there have been many changes affecting the way Americans drive—speed limits are higher, road congestion has increased, vehicle performance has increased, vehicle technologies have changed markedly, and more vehicles are equipped with energy-consuming accessories like air conditioning.²²

¹⁸ *Id.* at 21527.

¹⁹ *Id.* at 77873.

²⁰ *Id.* at 77874.

²¹ *Id.*

²² *Id.*

HFEDS's unchallenging operation of an EV results in unrealistically slower battery depletion, the method by which the EPA calculates EV fuel efficiency/GHG emissions. Notwithstanding these well-known developments, DOE has not examined any of these issues.

The UDDS cycle is more complex than HFEDS in that it simulates an urban route of 7.5 miles with a maximum speed of 56.7 mph. But this cycle lacks high speed operation, operation of the vehicle in varying climatic conditions or extended idling, all of which affect EV battery depletion. Like HFEDS, the UDDS is based on 1960s driving data.

DOE provides no technical support for its continued use of HFEDS and UDDS.²³ DOE says merely that it "*believes* the current methodology provides an accurate measure of the electrical energy efficiency of the relevant EV during typical use."²⁴ This belief is difficult to reconcile with the incorporation of changes in 2008 for calculating fuel economy for all vehicles, based on vehicle testing done at EPA's National Vehicle and Fuel Emissions Laboratory.²⁵ In 2008, EPA updated fuel economy ratings to incorporate faster speeds and acceleration, air conditioner use and colder temperatures. Yet DOE proposes, 15 years later to continue to rely on just two tests that do not incorporate these factors for EVs and knowingly overstate their fuel efficiency.²⁶

In the 20 years since DOE last updated its PEF calculation, additional data and information is available concerning how vehicles perform in the real world versus controlled laboratory testing. As the Fuel Economy Guide (a joint publication of DOE and EPA) notes there are numerous factors that can lower a vehicle's fuel economy, including:

- Aggressive driving (speed and hard acceleration and hard braking
- Excessive idling, accelerating, and braking in stop-and-go traffic
- Cold weather (warmed engines are more efficient). The impact is greater for short trips
- Driving with a heavy load or with the air conditioner running
- Improperly tuned engine or under-inflated tires
- Driving on mountainous or hilly terrain
- High-performance or snow tires
- Use of remote starters²⁷

DOE's refusal to adjust fuel economy ratings and other readily available information and its decision to "stick with" inaccurate testing protocols is on its face, arbitrary and capricious. A review of the docket for this rulemaking shows that DOE made no attempt, despite waiting more than two decades, to determine whether there are additional drive cycles or testing regimes that

²³ DOE is legally obligated under 49 U.S.C. §32904(c) to review and "propose necessary revisions" to PEF values.

²⁴ 88 Fed. Reg. at 21527 (emphasis added).

²⁵ See U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, <https://www.fueleconomy.gov/feg/ratings.shtml> (last visited June 9, 2023).

²⁶ DOE has not proposed any changes to 10 C.F.R. 474.3(a), which prescribes how PEF is calculated using HFEDS and UDDS. DOE proposes only that the value of the PEF under 10 C.F.R. 474.3(b) shall be 23,160 Watt-hours per gallon.

²⁷ Fuel Economy Guide Model Year 2023, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, U.S. Environmental Protection Agency, June 1, 2023.

are available now and are more representative of the energy consumption of an EV. DOE “entirely failed to consider an important aspect of the problem.”²⁸

As noted above, there are more representative, readily available tests. In 2006, EPA created and maintains today a 5-cycle formula to calculate the fuel economy of vehicles, adjusted with respect to the relative amount of city and highway driving and other vehicle operations. EPA’s duty cycles tests, the US06 cycle representing high-speed driving, the SC03 cycle which accounts for A/C operation and 95-degree heat conditions, and the cold Federal Test Procedure (run at 20 degrees) have been used by EPA for well over fifteen years to determine fuel economy and vehicle labeling.²⁹ And while these duty cycles are far from perfect, they are far more realistic of vehicle operation and consistent with the same fuel efficiency testing required for gasoline and diesel fueled vehicles.

The statute obliges the DOE to update its testing regime to apply, to the extent practicable, real world driving conditions. DOE ignores the myriad of electric power consuming features common on the majority of EVs sold in the U.S., including: heat pumps for heating the passenger cabin, heated seats and steering wheels, heated windshield wipers, heating (when idle) to maintain minimum acceptable battery temperatures, autopilot computing systems, infotainment/audio computing systems, and “sentry” camera systems energy efficiency should also reflect the fact that battery EVs are less efficient in cold weather and extremely hot weather.³⁰ Similarly, ignoring the effect of air-conditioning use on battery depletion in Southern and other States during the summer equally defies the reality of operating conditions faced by EVs.³¹ Finally, DOE should also consider EV weight, which makes EVs less efficient.³²

DOE neither acknowledges such factors, nor explains why the Department failed to review other credible vehicle testing methodologies, including international cycles such as the World Harmonized Light Vehicles Test Procedure (“WLTP”). Information regarding these testing cycles and expected benefits of moving towards additional on-road testing are readily available. But DOE appears not to even have looked at such alternatives before formulating the “belief” that existing HFEDS and UDDS are appropriate to measure electric vehicles for at least the next eight years. Nor has DOE examined more recent tests to evaluate electrified powertrains using

²⁸ *Motor Vehicle Manufacturers Association. v. State Farm Auto Mutual Insurance Co.*, 463 U.S. 29, 43 (1983).

²⁹ 71 Fed. Reg. 77872 (Dec. 27, 2006).

³⁰ AAA, *Electric Vehicle Range Testing*, AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe (February 2019), <https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf> (ambient temperature and related HVAC use can result in moderate to significant reduction in EV range); Di Wu et al., *Regional Heterogeneity in the Emissions Benefits of Electrified and Lightweight Light-Duty Vehicles*, Environ. Sci. Technol. 2019, 53, 18, 10560–10570 (July 23, 2019), <https://pubs.acs.org/doi/full/10.1021/acs.est.9b00648> (model-based and empirical data-driven studies agree that ambient temperature impacts EV efficiency).

³¹ AAA, *Electric Vehicle Range Testing*, AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe, *supra* (HVAC use can result in moderate to significant reduction in EV range); Maxwell B. Mortimer, *How Much Does Climate Control Affect EV Range?*, Car and Driver (Mar. 19, 2020), <https://www.caranddriver.com/news/a31739529/how-much-does-climate-control-affect-ev-range/> (Road test found reduced EV range when HVAC used).

³² Wu, *supra*. (In colder, rural areas, lightweight internal combustion engine vehicles can have lower greenhouse gas emissions on a lifecycle basis than EVs).

a methodology designed to make power ratings comparable to traditional ICEV power ratings.³³ DOE must update its analysis to establish a PEF that considers a “real world” assessment of EV fuel efficiency.

2. The statute explicitly requires annual revisions to the petroleum-based fuel economy values for various classes of electric vehicles.

The Secretary of DOE is required to establish a PEF “for various classes of electric vehicles” that reflects their actual energy efficiency.³⁴ DOE cannot, as it proposes, prescribe a single PEF for all EVs. First, it is widely apparent that the automobile and light duty vehicle (“LDV”) sector, which includes vehicles up to 10,000 pounds gross vehicle weight rating (“GVWR”),³⁵ is made up of distinct vehicle types used in diverse ways with varying energy efficiency. Delivery vans and small pickups used in commercial operations have different use patterns than individual vehicles used for commuting or larger vehicles used for hauling or towing equipment, other vehicles, or boats. For example, towing impacts EV efficiency.³⁶

Second, “electric vehicle” is not defined solely with respect to automobiles or LDVs. An “electric vehicle” is defined within §32904 with respect to whether the vehicle is “powered primarily by an electric motor drawing electrical current from a portable source.”³⁷ This is distinct from the definition of other vehicles (such as “passenger automobiles”) that are defined within 49 U.S.C. Chapter 329 and applicable to other sections of the chapter, including §32905.³⁸

Yet despite the wide sweep of the statutory requirement to calculate PEF, there is no apparent reference in the preamble or the docket for this rulemaking that the DOE gave any attention to the need to address “various classes” of EVs. Instead, The Department considered EVs of all different types, sizes and uses to be the same. Again, DOE ignores publicly available information that EVs have different GVWR, and are designed to capture certain market shares, and are increasingly tailored to different end uses.³⁹ DOE must establish PEFs to reflect the actual energy efficiency of various classes of EVs during real-world operation. For example, if EVs employ different battery chemistries, DOE must recognize some batteries are less energy dense, heavier, and/or less energy efficient. Certainly, vehicles with less efficient batteries and

³³ See, e.g., SAE J2908.

³⁴ 49 U.S.C. §32904(a)(2)(B).

³⁵ EPA utilizes 8,500 GVWR as the cut-off point for light duty vehicles, but 49 U.S.C. defines an “automobile” as including a 4-wheeled vehicle up to 10,000 lbs GVWR. 49 U.S.C. §32901(a)(3).

³⁶ Chris Perkins, *Why Electric Cars Aren't Yet Great for Towing*, Road & Track (Dec. 4, 2019), <https://www.roadandtrack.com/new-cars/car-technology/a30121167/electric-car-towing-range/> (a study found depleted EV range when a trailer is added to an EV).

³⁷ 9 U.S.C. §32904(a)(2)(A). In addition, §32904 requires the EPA Administrator to calculable average fuel economy for manufacturers subject to § 32902(b)-(d). This section requires separate fuel economy standards for passenger automobiles, non-passenger automobiles and work trucks and commercial medium- and heavy-duty on-highway vehicles. See 49 U.S.C. §32902(b)(1)(A)-(C).

³⁸ See, e.g., 49 U.S.C. §32901(a)(18).

³⁹ As the U.S. Department of Transportation has noted “[t]he EV market is evolving rapidly, with models available in a range of vehicle types, from compact cars and sedans to sport utility vehicles (SUVs) and pickup trucks.” See: U.S. Department of Transportation, Vehicle Types, <https://www.transportation.gov/rural/ev/toolkit/ev-basics/vehicle-types> (last visited June 9, 2023).

higher weights cannot be determined to have the same PEF as lighter EVs with more efficient batteries.

3. DOE must use current national average electrical generation and transmission efficiencies.

The statute directs DOE to utilize “national average electrical generation and transmission efficiencies” without reference to projecting what these averages will be in future years.⁴⁰ These national averages are to be calculated concurrently with the annual assessment of PEF values. Specifically, the Secretary of DOE is to review PEF values “each year and determine and propose necessary revisions . . . based on . . . the national average electrical generation and transmission efficiencies.”⁴¹ This statutory language provides explicit direction for the department *not* to engage in long-range planning or to use uncertain projections spanning 30 years, but to focus on “the most recent data.”⁴²

DOE, however, proposes to update electricity and generation inputs “to account for updated data and recent policy changes.”⁴³ To this end, DOE utilizes a weighted generation efficiency for the year 2029⁴⁴ and additionally references the potential impact of the Inflation Reduction Act (“IRA”) and the Infrastructure and Investment Jobs Act (“IIJA”) on electricity generation.⁴⁵ DOE does not explain how it is “accounting” for recent policy changes in the IRA and IIJA. DOE simply rejects the Annual Energy Outlook 2022 as not being “representative of more recent policy changes” without providing any quantification of how this projection is unrepresentative, this year, next year, or farther into the future.⁴⁶ Importantly, DOE does not calculate the PEF using known, actual, current power sector generation efficiency data, as required by statute.

DOE must also revise the generation efficiencies assumed for solar, wind, hydroelectric, and geothermal energy. DOE, without any explanation or reference, assumes the generation efficiency of these technologies is 100%.⁴⁷ There is simply no basis for DOE to assume every non-fossil or renewable fuel generator operates at 100 percent efficiency. Indeed, DOE’s own research on the topic states such an assumption is “not physically true.”⁴⁸ EIA calculates the efficiency of geothermal at 16 percent, conventional hydroelectric at 90 percent, solar photovoltaic at 12 percent, and wind at 26 percent. See EIA Table F1 below).⁴⁹ At minimum, DOE does not factor in any energy inputs needed in order to produce the mechanisms and equipment necessary to convert these sources of energy into electrical power.

⁴⁰ 49 U.S.C. §32904(a)(2)(B)(ii).

⁴¹ 49 U.S.C. §32904(a)(2)(B).

⁴² 88 Fed. Reg. at 21527.

⁴³ 88 Fed. Reg. at 21527.

⁴⁴ *Id.* at 21532.

⁴⁵ *Id.* at 21532.

⁴⁶ 88 Fed. Reg. at 21531.

⁴⁷ 88 Fed. Reg. at 21532.

⁴⁸ U.S. Department of Energy, “Accounting Methodology for Source Energy of Non-Combustible Renewable

Electricity Generation”, October 2016, <https://www.energy.gov/eere/analysis/articles/accounting-methodology-source-energy-non-combustible-renewable-electricity> (last accessed June 9, 2023)

⁴⁹ U.S. Energy Information Administration. Annual Energy Review 2011. Table F1. <https://www.eia.gov/totalenergy/data/annual/pdf/sec17.pdf> (last accessed June 9, 2023)

Table F1. Conversion Efficiencies of Noncombustible Renewable Energy Sources (Percent)	
Source	Notional Efficiency¹
Geothermal	16
Conventional Hydroelectric	90
Solar Photovoltaic	12
Solar Thermal Power	21
Wind	26

¹ Efficiencies may vary significantly for each technology based on site-specific technology and environmental factors. Factors shown represent engineering estimates for typical equipment under specific operational conditions.

Sources: **Geothermal:** Estimated by EIA on the basis of an informal survey of relevant plants. **Conventional Hydroelectric:** Based on published estimates for the efficiency of large-scale hydroelectric plants. See <http://www.usbr.gov/power/edu/pamphlet.pdf>. **Solar Photovoltaic:** Based on the average rated efficiency for a sample of commercially available modules. Rated efficiency is the conversion efficiency under standard test conditions, which represents a fixed, controlled operating point for the equipment; efficiency can vary with temperature and the strength of incident sunlight. Rated efficiencies are based on the direct current (DC) output of the module; since grid-tied applications require alternating current (AC) output, efficiencies are adjusted to account for a 20 percent reduction in output when converting from DC to AC. **Solar Thermal Power:** Estimated by dividing the rated maximum power available from the generator by the power available under standard solar conditions (1,000 W/m²) from the aperture area of solar collectors. **Wind:** Based on the average efficiency at rated wind speed for a sample of commercially available wind turbines. The rated wind speed is the minimum wind speed at which a turbine achieves its nameplate rated output under standard atmospheric conditions. Efficiency is calculated by dividing the nameplate rated power by the power available from the wind stream intercepted by the rotor disc at the rated wind speed.

Ignoring the EIA's 2022 Annual Energy Outlook report, DOE relied on the model "2021 Electrification 95 by 2050, Standard Scenario," from the National Renewable Energy Laboratory (NREL), which projects 95% renewable generation by 2050 and increasing electrification economy-wide.⁵⁰ The EIA, which provides DOE independent energy data, forecasts, and analyses, projects in its 2023 Annual Energy Outlook that by 2050 a sizable amount of U.S. electricity will still be generated from natural gas, while coal use will be significantly curtailed, albeit not eliminated.⁵¹ DOE's reliance on the NREL model's predictions far into the future is arbitrary and capricious.

In taking this approach, DOE both ignores the statutory requirement to address the PEF annually and fails to recognize that in 2022 60% of current electric generation is based on fossil-fuels and that generation efficiencies of non-fossil generation are well below 100 percent.⁵²

⁵⁰ *Id.* at 21531.

⁵¹ EIA, *Annual Energy Outlook AEO 2023* at 10, https://www.eia.gov/outlooks/aeo/pdf/AEO2023_Narrative.pdf. EIA's 2023 projections incorporate the IRA's policy changes.

⁵² EIA, *Frequently Asked Questions. What is U.S. electricity generation by source?*, <https://www.eia.gov/tools/faqs/faq.php?id=427&t=3#:~:text=In%202022%2C%20about%204%2C243%20billion,facilities%20in%20the%20United%20States.&text=About%2060%25%20of%20this%20electricity,%2C%20petroleum%2C%20and%20other%20gases> (last visited June 9, 2023).

EIA's Short-Term Energy Outlook currently projects that fossil fuels will be responsible for 57% of electricity generation in 2023 and 54% in 2024, when DOE may finalize this rule.⁵³

Moreover, DOE makes multiple assumptions regarding electrical generation using renewable energy sources and the transmission grid. First, DOE assumes the electrical grid is currently uniform, which it is not, and that it will uniformly expand across the nation. The North American Electric Reliability Corporation (NERC) prepared a 2022 Long-Term Reliability Assessment of the U.S. electrical grid and the six Regional Entities delivering power to the continental United States.⁵⁴ According to NERC's assessment, each Regional Entity has different electricity supply and demand, weather patterns, scheduled power plant outages, planned unit retirements, and other factors impacting the reliability of the electricity grid.⁵⁵ Moreover, the ability to permit grid infrastructure to expand the grid will vary by location.

While electricity supply improved in 2023 versus 2022, NERC noted that several operating regions are still at risk during periods of peak demand, including the Midcontinent ISO (which will face challenges in meeting above-normal peak demand), the SERC – Central area (where, compared to the summer of 2022, forecasted peak demand has risen by over 950 MW while growth in anticipated resources has remained flat) and the Southwest Power Pool (where reserve margins have fallen as a result of increasing peak demand and declining anticipated resources).⁵⁶

The Lawrence Berkley National Laboratory reports strong interest in clean energy. However, increasing delays in studying, building, and connecting new energy projects to the grid means that “much of this proposed capacity will not ultimately be built.”⁵⁷ The high-rate project withdrawal is reflected in the fact that only 21% of the projects (representing 14% of capacity) seeking connection from 2000 to 2017 were constructed as of the end of 2022.⁵⁸ Other challenges cited by the Berkeley National Lab that prevent timely operation of new renewable energy projects include increased interconnection wait times, reaching agreements with landowners and communities, power purchasers, supply chain constraints, and financing. DOE's evaluation should rely on the U.S. government's current assessment of renewable generation.

DOE also places an outsized reliance on generation of electricity from renewable sources to charge EVs.⁵⁹ The EIA reports renewable represented just 22% of electricity generation in 2022 and forecasts renewables will comprise 26% of electricity generation in 2024.⁶⁰ DOE also disregards the fact that the vast majority of EV charging occurs residentially during the overnight

⁵³ EIA, *Short-Term Energy Outlook* (June 2023), https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf. STEO data is accurate because the STEO is updated monthly. DOE can use updated information from implementation of the Inflation reduction Act when it annually updates the PEF.

⁵⁴ North American Electric Reliability Corporation, *2022 Long Term Reliability Assessment* (December 2022), https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf.

⁵⁵ *Id.* at 4.

⁵⁶ North American Electric Reliability Corporation, *2023 Summer Reliability Assessment* (May 2023), https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf.

⁵⁷ Berkeley Lab, *Electricity Markets and Policy: Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection*, <https://emp.lbl.gov/queues> (last visited June 9, 2023).

⁵⁸ *Id.*

⁵⁹ 88 Fed. Reg. 33240 (May 23, 2023).

⁶⁰ EIA, *Short-Term Energy Outlook*, *supra*.

hours, when solar electricity generation is not available, and wind remains intermittent.⁶¹ Indeed, real-world EV use data from California and other markets show that EV charging increases peak demand, straining the grid and requiring a larger amount of dispatchable fossil-fuel based generation.⁶²

DOE additionally fails to account for electricity (energy) lost during the EV charging process,⁶³ such as greater losses when charging batteries in a partial state of charge, losses across transformers⁶⁴ and significant charging losses that result from charging at less-than-ideal ambient temperatures.⁶⁵ DOE must also account for electricity (energy) lost when EVs are in park and idle mode but continue to use significant amounts of energy to operate on-board equipment, including cameras, sensors, and battery heating elements.⁶⁶

Rather than an unbiased assessment of “national average electrical generation and transmission efficiencies” by estimating generation mix in 2023 or 2024, DOE engages in speculation by using projections from 6 to 27 years in the future. The use of such an error-prone methodology stands in sharp contrast to the form in which it calculated PEF, *i.e.*, in values expressed down to a single watt-hour. In short, DOE must update its analysis for establishing PEFs for various EV classes to take into consideration the current national average electrical generation and transmission efficiencies.

4. DOE must consider all forms of energy conservation and relative scarcity and value.

Despite the requirement in 49 U.S.C. §32904(a)(2)(B)(iii) to consider the need to “conserve all forms of energy and the relative scarcity and value,”⁶⁷ DOE provides a cursory, outdated analysis, relying on assessments made more than twenty years ago. DOE proclaims that current and future sources of renewable electricity will be “in abundance” while the demand for fossil fuels “can change rapidly and be subject to market constraints.”⁶⁸

⁶¹ Shannon Osaka, *It's common to charge electric vehicles at night. That will be a problem*, Washington Post (Sep. 22, 2022), <https://www.washingtonpost.com/climate-environment/2022/09/22/its-common-charge-electric-vehicles-night-that-will-be-problem/>.

⁶² Siobhan Powell *et al.*, *Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption*, *Nature Energy* 7, 932–945 (2022), <https://doi.org/10.1038/s41560-022-01105-7> (home charging can strain the grid).

⁶³ John Voelker, *EVs Explained: Charging Losses*, Car and Driver (Apr. 10, 2021), <https://www.caranddriver.com/features/a36062942/evs-explained-charging-losses/> (Charging losses range from 12-15%).

⁶⁴ Elpiniki Apostolaki-Iosifidou, Paul Codani, & Willett Kempton, *Measurement of power loss during electric vehicle charging and discharging*, *Energy*, Volume 127, 2017, Issue C, 730-742, ISSN 0360-5442 (quantifies charging and discharging of transformers used to charge EVs).

⁶⁵ Yutaka Motoaki, Wenqi Yi, & Shawn Salisbury, *Empirical analysis of electric vehicle fast charging under cold temperatures*, *Energy Policy*, Volume 122, Nov. 2018, 162-168, ISSN 0301-4215, <https://doi.org/10.1016/j.enpol.2018.07.036> (charging deteriorates significantly in cold weather).

⁶⁶ Elpiniki Apostolaki-Iosifidou, *supra* (A power electronics unit that converts power from the AC line into DC battery voltage accounts for significant electricity losses).

⁶⁷ 88 Fed. Reg. at 21528.

⁶⁸ *Id.*

a. *DOE fails to explain its about-face regarding fossil fuel scarcity.*

DOE does not explain why it changed its assessment of the scarcity of fossil fuels. In its 2000 evaluation, DOE concluded scarcity “did not appear to be a concern and should not be a guiding factor in the PEF.”⁶⁹ In describing its analysis, DOE acknowledged it:

[P]erformed a careful and thorough analysis of the present and projected availability of energy resources. This analysis showed that fuels (raw resources) used to produce electricity are abundant, as are the raw resources to produce gasoline and diesel fuel (in fact, “proven reserves” of all of these energy resources tend to increase over time as new resources are discovered and better recovery techniques are developed). Since all these fuels are abundant, the concept of “relative scarcity” is difficult to quantify objectively, and in DOE’s judgment, should not be an appropriate guiding factor in the rulemaking at this time.⁷⁰

The DOE’s statement in 2000 appears largely to have been correct. During the past twenty years, the United States transformed from a net energy importer to a net energy exporter in 2019.⁷¹ Yet without further explanation, DOE now “preliminarily determined that there is a need to conserve finite energy resources, such as petroleum, given their limited nature and susceptibility to changing market constraints.”⁷² In contrast, DOE should, but does not, address the market constraints for foreign sources of critical minerals needed to produce EV batteries and copper for transmission wiring, as well as the scarcity of charging stations and electric generating units. Absent an explanation for a change in rationale, DOE’s determination is arbitrary and capricious.

b. *DOE fails to account for resource depletion associated with transitioning to renewable electricity.*

According to DOE, renewable energy for electric generation is not subject to “resource depletion.”⁷³ However, DOE does not account for the resources needed to manufacture, develop, and site renewable energy projects. Wind and sunshine, standing alone, do not produce electricity to charge EVs. Rather, the U.S. needs significant construction of renewable energy projects, transmission lines to connect renewable energy generation to distribution infrastructure and charging stations to support EV operation. The U.S. must upgrade or replace millions of transformers, conductors, panels, and substations. Wood Mackenzie concluded the U.S. needs to invest \$4.5 trillion to fully transition the U.S. power grid to renewables during the next 10-20 years, annual investments exceeding the U.S. defense budget.⁷⁴

It is true that the lifecycle GHG emissions associated with electric generation and storage from renewable energy sources are often much less than traditional electricity produced from coal

⁶⁹ 88 Fed. Reg. at 21527.

⁷⁰ 65 Fed. Reg. 36986, 36988 (June 12, 2020).

⁷¹ See EIA, U.S. energy facts explained, <https://www.eia.gov/energyexplained/us-energy-facts/imports-and-exports.php> (last visited June 9, 2023).

⁷² 88 Fed. Reg. at 21528.

⁷³ 88 Fed. Reg. at 21527.

⁷⁴ Dan Shreve and Wade Schauer, *Deep decarbonization requires deep pockets* (June 2019), <https://www.decarbonisation.think.woodmac.com/>.

and natural gas generators that do not employ carbon capture and sequestration technology. But there is considerable range in estimates of various power sources and renewable energy projects are not “emission free.”⁷⁵ Emissions from some forms of renewable electricity may even exceed that for natural gas generation.⁷⁶ EPA recently proposed that for coal-fired and natural gas-fired generation to continue to operate, a substantial proportion of the existing generation from these sources must either utilize carbon capture and sequestration or co-fire with low-GHG hydrogen within the time period that DOE is projecting that the proposed PEF will apply.⁷⁷ DOE took no steps in this proposed rule to account for this changing differential in relative GHG emissions among different forms of generation.

Upstream emissions occur with nearly all renewable energy projects – from mining minerals and metals for transmission lines, transformers, and turbines, to manufacturing and transporting all infrastructure equipment. But DOE ignores the challenge in securing critical materials, such as copper, needed to transmit power.⁷⁸ For example, the demand for copper needed to expand the electrical grid will rise by 53%, while copper supply will expand by only 16%.⁷⁹ Yet DOE does not account for *any* of these impacts or assess how these effects could impact the statutory need to conserve “all forms of energy.”

Disregarding this objective evidence, DOE continues to repeat an assessment it made 23 years ago, updated to reflect current non-statutory policy considerations, *i.e.*, that “current and future sources of electricity generation are and will be in relative abundance due to recent market and policy changes [citing the Inflation Reduction Act and the Infrastructure Investment and Jobs Act].”⁸⁰ But whether this alleged “abundance” of renewable electricity will be true in the future, it is not present in 2023, and DOE fails to recognize the very real barriers that exist for such future supply.

Despite DOE’s heavy reliance on the availability of renewable energy to calculate the PEF, there are multiple obstacles to growth for this generation resource. As noted in a recent policy analysis by the Massachusetts Institute of Technology:

Cost-effective renewable energy has largely been achieved, but there appear to be substantial barriers to building new renewable energy facilities. We identified 53 utility-scale wind, solar and geothermal energy projects that were delayed or blocked between 2008 and 2021 in 28 U.S. states. Using multi-level qualitative analysis, we have identified seven key sources of opposition.

⁷⁵ See National Renewable Energy Laboratory, *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*, www.nrel.gov/docs/fy21osti/80580.pdf.

⁷⁶ *Id.* Figure 2.

⁷⁷ See 88 Fed. Reg. 33240 (May 23, 2023). For example, EPA proposes that existing coal-fired generating units must either install carbon capture and sequestration (CCS) or co-fire with natural gas by 2030 or commit to shut down by 2032, 2035 or 2040. Under the proposed rule, existing large baseload combustion turbines (operating more than 50% of the time) that utilize natural gas will need to either install CCS and sequester 90% of CO₂ emissions by 2035 or start co-firing with low-GHG hydrogen by 2032.

⁷⁸ International Energy Agency, *The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions*, (Revised version, March 2022).

⁷⁹ James FERNYHOUGH, Copper Mine Flashes Warning of ‘Huge Crisis’ for World Supply, Bloomberg News, May 2, 2023.

⁸⁰ 88 Fed. Reg. at 21528.

Of the projects we studied, 34% faced significant delays and difficulties securing permits, 48% were cancelled permanently, and 26% resumed after being stopped for several months or years. Project delays and cancellations account for potential lost generation capacity of almost 4600 MW.⁸¹

Nothing in the current docket indicates that DOE has examined any of this readily available information.

c. DOE Fails to Account for Energy Used to Develop and Manufacture EVs and infrastructure.

DOE fails to consider the need to conserve all forms of energy associated with EV production and constructing the necessary EV charging infrastructure (e.g., metals, battery storage, concrete, and other energy-intensive endeavors). Thus, the proposed rule presents an artificially narrow analysis of the relative supply of various sources of energy within the United States and does not consider any real-world constraints on electricity and other energy resources devoted to EVs, even those that are apparent now and will still exist within MY 2027. DOE must evaluate the full range of the nation's need to conserve energy. This demands that DOE fully evaluate the lifecycle energy demand/conservation associated with the production of EV batteries (mining metals), the minerals and concrete needed to build more electricity generation, transmission, and storage, and charging infrastructure.

DOE's failure to consider the need to conserve all these forms of energy is not just contrary to the plain language of the statute but also contrary to prior interpretations of the statute. For example, in discussing the application of Title III of the Energy Policy and Conservation Act to EVs, the Department of Transportation indicated that "energy conservation rather than just petroleum conservation is the intent of Congress [as reflected in the purposes of the Energy Policy and Conservation Act] . . . In stating the purposes relating to conservation, particularly regarding automobiles, this section speaks of energy conservation, not just the conservation of petroleum."⁸²

In contrast to this statutory focus, DOE's analysis of the need to conserve energy and the relative scarcity and value of fuels focuses almost entirely on the EV market. Specifically, as part of the required analysis, DOE examined: (a) current EV technology and market penetration; (b) effects of PEF on the production of "inefficient ICE vehicles" and (c) a rejection of the legal theory behind the calculation of PEF in 2020. But DOE cannot crosswalk these considerations back to the statute which requires that revisions to PEF be based on "[t]he need of the United States to conserve *all forms of energy* . . ."⁸³ Instead, DOE must conduct a comprehensive and thoughtful analysis of the lifecycle energy use of EVs versus ICE vehicles.

AFPM requests the DOE use current, and not projected, data to update the PEF to reflect the requirement to conserve all forms of energy and relative scarcity and value. Given that annual

⁸¹ Lawrence Susskind *et al.*, *Sources of opposition to renewable energy projects in the United States*, Energy Policy, Volume 165 (June 2022).

⁸² Advisability of Regulating Electric Vehicles for Energy Conservation, A Report to the Congress from the Secretary of Transportation, August 1976 at 5-6.

⁸³ 49 U.S.C. §32904(a)(2)(B).

revisions are required by statute, there is no plausible reason to base the PEF on long term predictions rather than current data.

5. The DOE is legally obligated to revise the PEF according to current patterns of EV use.

DOE is required to base any PEF revisions on “the specific patterns of use of electric vehicles.”⁸⁴ In the proposed rule, however, DOE retained a driving pattern factor of 1.0 simply because it “believes” that current EVs are “equivalently capable vehicles” and likely to be used in a similar manner to gasoline-powered or hybrid vehicles. This conclusion is inapposite to publicly available data showing significant differences between EVs and ICEVs.

DOE provides no support for this sweeping conclusion, nor is there any evidence that DOE considered available information on EV driving patterns, EV ownership, and range issues for EV vehicles. The proposed rule’s evaluation of this statutory factor consists of a mere two paragraphs of text. This text, in turn, cites only a “Fact Sheet” regarding a White House announcement and discusses a “neighborhood” vehicle and indicates that such a vehicle “might merit application of the driving factor.”⁸⁵ This is not even close to the level of analysis required to counter the known differences between EVs and ICEVs that make certain vehicles in appropriate for certain driving applications. DOE has no basis to conclude technologies are perfect substitutes.

It is abundantly clear that DOE failed to provide sufficient information to support its conclusion that the use of EVs and ICEVs is equivalent. DOE provides no supporting information for this conclusion and cannot “shift the burden” to commenters simply by requesting comments on “whether to keep the driving pattern factor at a value of 1.00.”⁸⁶ The duty imposed by 49 U.S.C. §32904 is explicit, [t]he Secretary *shall review* [PEF values] . . . based on [four enumerated statutory factors].⁸⁷ This requires an affirmative assessment and a determination made by DOE.

Available information indicates that the utilization of ICEVs and EVs is decidedly different:

- EVs have less range, both technically and practically. As noted by JD Power, “the majority of EVs provide between 200 and 300 miles of range on a full charge.”⁸⁸ This same article, however, also noted that EVs with less than 200-mile ranges (such as the 2022 Nissan Leaf at 149 miles or the 2022 Mazda MX-30 at 100 miles) are “either affordable or focused on performance.”⁸⁹
- With respect to longer range vehicles, claimed vehicle ranges of up to 516 miles are available, but this range comes at considerable cost. The number 1 range-rated vehicle by Car and Driver, the 2023 Lucid Air, carries a base price of \$113,650. And while three out of the ten top-rated EVs by Car and Driver were more “reasonably priced” from

⁸⁴ 49 U.S.C. §32904(a)(2)(iv).

⁸⁵ 88 Fed. Reg. 21530, n. 40.

⁸⁶ 88 Fed. Reg. at 21530.

⁸⁷ 49 U.S.C. 32904(a)(2)(B) (emphasis added).

⁸⁸ See Sebastian Blanco, *List of EVs Sorted by Range* (Sept. 1, 2022), www.jdpower.com/cars/shopping-guides/list-of-evs-sorted-by-range.

⁸⁹ *Id.*

\$44,630 to \$56,630, all other models within the top 10 cost anywhere from \$74,800 to \$110,295.⁹⁰

- Aside from cost impacting the practical availability of vehicles to the average consumer, other studies have shown that the average electric car is driven 9,059 miles per year, compared with 12,758 miles for gas-powered vehicles and that there is a strong relationship between an EV's range and driving behavior.⁹¹
- Increasing only EV range is not the answer to increasing EV use. Consumers pay an additional \$10,000 to yield an additional 26.5 miles of range. To deliver the 440 miles of range currently provided by ICEVs, EVs would need to add an additional 161 miles. Assuming no other changes in used EV pricing, a 3-year-old EV would need to cost, on average, *an additional \$60,000*.⁹²
- Inaccurate EPA range estimates for electric cars increases range anxiety.⁹³ Consequently, EVs are more likely to be commuter/errand cars, while consumers use ICEVs for longer trips and towing.⁹⁴
- EVs have less range, and sometimes significantly less range, in cold and hot temperatures. Recent reports note ambient temperature and HVAC use can result in significant reductions of EV driving range and equivalent fuel economy.⁹⁵
- Consumers have strong preferences for ICEVs. An AP-NORC poll found only 19% of Americans are "very likely or extremely likely" to go electric.⁹⁶ Gallup similarly poured water on the enthusiasm claim, suggesting Americans are "slow to adopt electric vehicles."⁹⁷ More troubling for EV backers: Even if this push was possible, the U.S. Energy Information Administration (EIA) forecasted just 9% of U.S. vehicles would be

⁹⁰ See Nicholas Wallace, Austin Irwin, & Nick Kurczewski, *Longest Range Electric Cars for 2023, Ranked* (Mar. 23, 2023), <https://www.caranddriver.com/features/g32634624/ev-longest-driving-range/>.

⁹¹ iSeeCars, *The Most and Least Driven Electric Cars* (May 22, 2023), <https://www.iseecars.com/most-driven-evs-study>.

⁸⁵ *Id.*

⁹³ Sean Tucker, *Those EPA range estimates for electric cars may be unreliable*, Kelley Blue Book, MarketWatch (May 1, 2023).

⁹⁴ Sasha Lekach & Alex Kwanten, *EV Survey Shows Range Anxiety High While Charging Costs Remain Low*, Forbes (June 28, 2022); Chris Perkins, *supra* (depleted EV range when towing suggests ICE more likely to be used for this purpose); iSeeCars, *supra* (On average, EVs are driven, 059 miles a year, compared to 12,758 miles for gas-powered vehicles).

⁹⁵ AAA, *Electric Vehicle Range Testing*, AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe, *supra*. Wu, *supra* and Roland Dauphin *et al.*, *Evaluation of plug-in hybrid vehicles in real-world conditions by simulation*, Transportation Research Part D: Transport and Environment, Volume 119 (June 2023), <https://www.sciencedirect.com/science/article/pii/S1361920923001189>; K.C. Colwell, *Tested: How Cold Weather Affects EV Range*, Car and Driver (May 25, 2018), <https://www.caranddriver.com/features/a20915996/tested-how-cold-weather-affects-ev-range-feature/> (*Fuel economy drops by 19 percent in 36-degree weather versus 56-degree weather*).

⁹⁶ Energy Policy Institute at the University of Chicago, *Climate Attitudes, Findings from a 2023 Survey of Adults Age 18 and Older*, <https://apnorc.org/wp-content/uploads/2023/04/EPIC-factsheets.pdf>.

⁹⁷ Megan Brennan, *Most Americans Are Not Completely Sold on Electric Vehicles*, Gallup (April 12, 2023), <https://news.gallup.com/poll/474095/americans-not-completely-sold-electric-vehicles.aspx>.

electric by 2050.”⁹⁸ In fact, 18% of California EV owners discontinue EV use when they subsequently purchase an ICEV.⁹⁹

AFPM therefore disagrees with the DOE’s conclusions regarding the statutory factor contained in §32904(a)(2)(B)(iv) and requests the DOE update the PEF to reflect “specific patterns of use of electric vehicles compared to petroleum-fueled vehicles.”

III. DOE Has Not Complied with Regulatory Review Requirements.

Given possible wide-ranging impacts of the proposed rule, it is not evident how DOE has complied with Executive Orders 12866 and 13563 concerning a reasoned determination of costs and benefits, to tailor regulations to impose the least burden on society, to select approaches that maximize net benefits or to identify available alternatives. Nothing in the proposed rule or docket speaks to such an analysis.

IV. Conclusion

Presuming that it is possible for DOE to stay within the constraints of providing adequate notice and the opportunity for comment, DOE must make major alterations to its proposed recalculation of PEF prior to finalization. At minimum, DOE must:

- Omit the use of the fuel content factor.
- Use real-world driving cycles to measure EV efficiency.
- Evaluate all “classes” of EVs, including heavier EVs
- Use current, not projected, energy mix and electricity and transmission and distribution efficiencies and energy losses.
- Correct the efficiency factors utilized in the calculation of PEF values to accurately assess efficiencies related to solar, wind, hydroelectric and geothermal power.
- Consider all forms of energy conservation, relative scarcity, and value, including the life cycle energy requirements to produce adequate electricity, charging infrastructure, and EVs.
- Account for the different use patterns of EVs.

Consistent with its statutory obligation, DOE should remove the 0.15 fuel content conversion factor for MY2024 (and beyond) and incorporate the comments above when proposing necessary revisions” based on four statutory factors contained in that provision for 49 USC §32904(a)(2)(B). If DOE cannot revise all inputs to the four statutory factors to reflect current, real-world data, then DOE should consider these comments and supporting documentation as a petition for rulemaking for next year’s PEF update.

⁹⁸ Annual Energy Outlook 2022 (March 3, 2022). Retrieved from <https://www.eia.gov/outlooks/aeo/narrative/consumption/sub-topic-01.php> .
https://www.realclearenergy.org/articles/2023/05/03/new_epa_rule_shows_joe_bidens_ev_push_is_just_a_pipe_dream_897320.html.

⁹⁹ Scott Hardman & Gil Tal, *Understanding discontinuance among California’s electric vehicle owners*, Nature Energy 6, 538–545 (Apr. 26, 2021), <https://www.nature.com/articles/s41560-021-00814-9> (10% of California EV owners discontinue subsequent EV purchases).

* * * * *

AFPM appreciates this opportunity to submit comments on this proposed rule. If you have questions or need more information, please do not hesitate to contact me at lbellas@afpm.org or (301) 775-9969 (mobile).

Sincerely,

Leslie Bellas

Leslie Bellas
Vice President
Regulatory Affairs
American Fuel & Petrochemical Manufacturers

Kugler v. Yocum

[L. A. No. 29549. In Bank. Oct. 1, 1968.]

CAROL J. KUGLER et al., Plaintiffs and Respondents, v. NORMA YOCUM et al.,
Defendants and Appellants.

COUNSEL

Don D. Bercu, City Attorney, for Defendants and Appellants.

Weinstein, Shelley & Proctor, Weinstein & Shelley and Robert C. Proctor, Jr., for Plaintiffs
and Respondents.

Charles P. Scully as Amicus Curiae on behalf of Plaintiffs and Respondents.

OPINION

TOBRINER, J.

We hold here that an ordinance which decrees that the salaries of certain city employees shall be no less than the average of those of an adjoining city and those of an adjoining county does not unlawfully delegate legislative power because the power to legislate has been expressed and exerted in the enactment of the policy of such parity; future adjustment in salaries pursuant to that formula is no more than the automatic execution of that policy; that process is protected from any abusive or arbitrary consequences by its own inherent safeguards.

Plaintiffs, residents of the City of Alhambra, bring mandate to compel defendants, as members of the city council of that city, either to adopt a proposed initiative ordinance or to call a special citywide election to vote upon it. Although plaintiffs had obtained the

required number of signatures to secure the election, the city council refused to hold it; the council likewise rejected the proposed ordinance.

The proposed ordinance reads, in relevant part, as follows: "Except as otherwise provided for herein the monthly salaries of the members of the Fire Department in each classification shall not be less than an amount computed as follows: Beginning January 1, 1965, and the first day of each succeeding year thereafter, the City Manager of the City of Alhambra shall determine the then existing monthly salaries of each classification of like or comparable grades or ranks of the Fire Departments of the City of Los Angeles and the County of Los Angeles. The average of the salaries for the comparable grades or ranks of the members of the Fire Departments of the City of Los Angeles and the County of Los Angeles shall be the minimum salaries payable by the City of Alhambra to the members of its Fire Department of the same or comparable **[69 Cal. 2d 374]** grades or ranks." Thus the proposed ordinance provides that in setting the salaries of the firemen, the council could not fix them at an amount less than the average of the salaries received by the firemen of the City of Los Angeles and the salaries received by the firemen of the County of Los Angeles.

After the council's refusal to submit the ordinance to the electorate plaintiffs brought this action in the Superior Court of Los Angeles County to compel defendants to do so. That court found that plaintiffs had followed the proper procedure, fn. 1 that the proposed ordinance was a proper subject for the exercise of the initiative power of the Alhambra electors, and that, if enacted, the ordinance would not improperly delegate the council's legislative power. Accordingly, the court issued a peremptory writ of mandate compelling the defendants to call a special election for consideration of the ordinance. Defendants have appealed from this judgment.

[1] The trial court correctly concluded that the subject matter of the proposed ordinance, that is the salaries of city firemen, falls within the electorate's initiative power. The city charter provides that the "Council ... shall have the power to ... establish ... the amount of [the fire division's] ... salaries" (§ 81) and that the "electors ... shall have the right to ... adopt ... any ordinance which the council might enact" (§ 176). Since in dealing with wage rates, the city council acts in its "legislative" rather than its "administrative" capacity (Spencer v. City of Alhambra (1941) 44 Cal. App. 2d 75, 77 [111 P.2d 910]; Collins v. City & County of San Francisco (1952) 112 Cal. App. 2d 719, 730 [247 P.2d 362]; City & County of San Francisco v. Boyd (1943) 22 Cal. 2d 685 [140 P.2d 666]), wage rates are a proper subject for adoption as an ordinance by a city council and, accordingly, pursuant to section 176, for enactment by an initiative. **[69 Cal. 2d 375]**

[2] [See fn. 2] Defendant's main contention rests upon the proposition that the enactment of the ordinance by either the council or the electorate would constitute an unlawful delegation of legislative power. fn. 2 They point out that no representative of Alhambra can either predict or control the exact wage rates that will be established in the City or the County of Los Angeles. Accordingly, they argue, the proposed ordinance, in fixing the Los Angeles rates as the minimum for Alhambra firemen's salaries, would unlawfully delegate legislative power to those parties who establish salaries for Los Angeles firemen.

[3a] At the outset, we note that the doctrine prohibiting delegation of legislative power, although much criticized as applied (see, e.g., Witkin, Summary of Cal. Law (7th ed. 1960) p. 1834; 1 Davis, Administrative Law Treatise (1958) § 2.01), is well established in California. "The power ... to change a law of the state is necessarily legislative in character, and is vested exclusively in the legislature and cannot be delegated by it" (Dougherty v. Austin (1892) 94 Cal. 601, 606-607 [28 P. 834, 29 P. 1092, 16 L.R.A. 161]; see also People v. Johnson (1892) 95 Cal. 471, 475 [31 P. 611]; People v. Wheeler (1902) 136 Cal. 652, 655 [69 P. 435]; Coulter v. Pool (1921) 187 Cal. 181, 190 [201 P. 120]; Duskin v. State Board of Dry Cleaners (1962) 58 Cal. 2d 155, 161-162 [23 Cal. Rptr. 404, 373 P.2d 468].) Moreover, the same doctrine precludes delegation of the legislative powers of a city (City of Redwood City v. Moore (1965) 231 Cal. App. 2d 563, 576 [42 Cal. Rptr. 72], and cases cited therein; see generally 2 McQuillin, The Law of Municipal Corporations (3d ed. 1966) § 10.39, p. 843, and cases cited at fn. 63).

Several equally well established principles, however, serve to limit the scope of the doctrine proscribing delegations of legislative power. For example, legislative power may properly **[69 Cal. 2d 376]** be delegated if channeled by a sufficient standard. "It is well settled that the legislature may commit to an administrative officer the power to determine whether the facts of a particular case bring it within a rule or standard previously established by the legislature" (Dominguez Land Corp. v. Daugherty (1925) 196 Cal. 468, 484 [238 P. 703]; see also State Board of Dry Cleaners v. Thrift-D-Lux Cleaners, Inc. (1953) 40 Cal. 2d 436, 448 [254 P.2d 29]; Case Note (1959) 6 U.C.L.A.L.Rev. 312 and cases cited therein.)

A related doctrine holds: "The essentials of the legislative function are the determination and formulation of the legislative policy. Generally speaking, attainment of the ends, including how and by what means they are to be achieved, may constitutionally be left in the hands of others. The Legislature may, after declaring a policy and fixing a primary standard, confer upon executive or administrative officers the 'power to fill up the details' by prescribing administrative rules and regulations to promote the purposes of the legislation and to carry it into effect" (First Industrial Loan Co. v. Daugherty (1945) 26

Cal. 2d 545, 549 [159 P.2d 921].) Similarly, the cases establish that "[w]hile the legislative body cannot delegate its power to make a law, it can make a law to delegate a power to determine some fact or state of things upon which the law makes or intends to make its own action depend." (Wheeler v. Gregg (1949) 90 Cal. App. 2d 348, 363 [203 P.2d 37].)

We have said that the purpose of the doctrine that legislative power cannot be delegated is to assure that "truly fundamental issues [will] be resolved by the Legislature" and that a "grant of authority [is] ... accompanied by safeguards adequate to prevent its abuse." (Wilke & Holzheiser, Inc. v. Department of Alcoholic Beverage Control (1966) 65 Cal. 2d 349, 369 [55 Cal. Rptr. 23, 420 P.2d 735]; see also Jaffe, An Essay on Delegation of Legislative Power (1947) 47 Colum.L.Rev. 359, 561; 1 Davis, Administrative Law Treatise, supra, § 2.15; Gaylord v. City of Pasadena (1917) 175 Cal. 433, 437 [166 P. 348]; Warren v. Marion County (1960) 222 Ore. 307, 313-315 [353 P.2d 257]; Lien v. City of Ketchikan (Alaska 1963) 383 P.2d 721, 723-724; Group Health Ins. v. Howell (1963) 40 N.J. 436, 445, 447 [193 A.2d 103]; Heath v. Mayor & City Council of Baltimore (1946) 187 Md. 296, 303 [49 A.2d 799] (dictum).) [4a] This doctrine rests upon the premise that the legislative body must itself effectively resolve the truly fundamental issues. It cannot escape responsibility by explicitly delegating that function to others or by failing to **[69 Cal. 2d 377]** establish an effective mechanism to assure the proper implementation of its policy decisions.

[5a] In the instant case, the adoption of the proposed ordinance, either through promulgation by the Alhambra City Council or by initiative, will constitute the legislative body's resolution of the "fundamental issue." Once the legislative body has determined the issue of policy, i.e., that the Alhambra wages for firemen should be on a parity with Los Angeles, that body has resolved the "fundamental issue"; the subsequent filling in of the facts in application and execution of the policy does not constitute legislative delegation. Thus the decision on the legislative policy has not been delegated; the implementation of the policy by reference to Los Angeles salaries is not the delegation of it.

Whatever the motivation for the legislative policy, Alhambra will have rendered and pronounced it. The policy may be based upon the recognition that Alhambra could not recruit firemen at lesser rates than those paid in the adjoining County and City of Los Angeles. The policy may rest upon the fact that Los Angeles possesses a superior ability to canvass comparable wages for firemen and perform the research necessary to reach a fair salary decision. In any event, Alhambra will have reached the fundamental decision: the policy of parity with Los Angeles.

Alhambra's formula for salary adjustments based upon the Los Angeles rates does not differ from other formulae, recognized as lawful, that tie adjustments in compensation for

employees into future events which do not lie within the power or control of the legislative body. The elemental illustration of such a formula is that which relates a wage adjustment to future dates or time periods for periodic adjustments. Moreover, adjustment may be linked to the cost of living, to average earnings or prevailing wages of a comparable occupation, to prevailing wages or average earnings generally, or to any number of such desiderata. The fact that the formula operates upon eventualities which may lie outside the control of the legislative body and within the control of other persons does not convert the legislative action into an unlawful delegation. fn. 3

In upholding the prevailing wage statutes this court has recognized that a statute, which set minimum wages for contractors **[69 Cal. 2d 378]** performing public work as those "prevailing" in the locality, did not "delegate" legislative power. In *Metropolitan Water Dist. v. Whitsett* (1932) 215 Cal. 400 [10 P.2d 751], this court rejected a variety of attacks on the statutory provision fn. 4 that "Not less than the general prevailing rate of per diem wages for work of a similar character in the locality in which the work is performed ... shall be paid all laborers, workmen and mechanics employed by or on behalf of the state of California." (P. 404.) petitioner contended "(1) that said act is void for uncertainty ... and (3) that the act makes an invalid delegation of legislative power." (P. 406.) The court points out that "The petitioner concedes that the object to be accomplished may be directed by the legislature to be carried into effect by subordinate officers and bodies having better opportunities for accomplishing the object, or doing the thing understandingly, and that the legislature may delegate the power to determine some fact or state of things upon which the law makes, or intends to make, its own action depend" (P. 418.) Holding that the statute has not "delegated to the board power to make law" (p. 419), the court stated: "Unless the power thus granted to fix the salary or wages of its own employees is an unlawful delegation of power to the board, and we do not intimate that it is, or that it would be conceded by the petitioner to be unlawful, the power granted by the statute under attack to fix a minimum wage for the employees of contractors with the district would not be an unlawful delegation." (P. 419.)

Although the prevailing wage statute, like the questioned ordinance, entails the alleged dual dangers which defendants contemplate here: that the legislative body will neither know in advance nor control the level of the "general prevailing rate of per diem wages," this court did not strike down the statute on that ground but sustained it. The *Whitsett* decision **[69 Cal. 2d 379]** has an even deeper significance in the present matter because in substance it applies to the kind of enactment we ponder here. The instant ordinance in essence adopts the "prevailing" rate for firemen in the larger locality which Alhambra adjoins. Although such a rate is fixed by a governmental rather than a private agency, that

factor is an inevitable one, since firemen are employed by public and not private entities, and it surely cannot serve to render one enactment an unlawful delegation of legislative power and the other not. Hence Whitsett, in substance, disposes of the present issue. fn. 5

Decisions in other states likewise sustain the power of the legislative body to base compensation for the involved employees upon comparable prevailing wages. In *Baughn v. Gorrell & Riley* (1949) 311 Ky. 537 [224 S.W.2d 436], for example, a statute requiring the board of education to ascertain the prevailing rates of wages and pay not less than this rate on public works projects was attacked as an unlawful delegation of legislative power to those who, cumulatively, "set" the prevailing rate. In rejecting this contention, the court said: "In the eyes of the Legislature, wages paid under agreements between labor organizations and employers constitute a fair criteria [sic] of reasonable compensation for different types of work. It will be noted these wages are agreed upon as the result of bargaining between labor on one side and the employer on the other ... [T]he competitive market will tend to establish a fair wage." (311 Ky. at p. 541.) The court concluded that "the Legislature has not delegated the exercise of its legislative function to private persons or interests." (311 Ky. at p. 542.) fn. 6

[4b] Nor does the fact that a third party, whether private or governmental, performs some role in the application and **[69 Cal. 2d 380]** implementation of an established legislative scheme render the legislation invalid as an unlawful delegation. Thus, in *Brock v. Superior Court* (1937) 9 Cal. 2d 291, [71 P.2d 209, 114 A.L.R. 127], a statute precluding the California Director of Agriculture from entering into a marketing agreement without the assent of a percentage of persons engaged in the industry was attacked as an unlawful delegation to those private persons. In rejecting this contention, this court said: "a statute is not invalid merely because it provides for consent of interested persons to the contemplated regulation." (9 Cal.2d at p. 299.) fn. 7

Furthermore, we find here, as we said in *Wilke & Holzheiser, [69 Cal. 2d 381] Inc. v. Department of Alcoholic Beverage Control*, supra, 65 Cal. 2d 349, 369, that the "grant of authority [is] ... accompanied by safeguards adequate to prevent its abuse." [6] As Professor Davis has stated, "The need is usually not for standards but for safeguards. ... [T]he most perceptive courts are motivated much more by the degree of protection against arbitrariness than by the doctrine about standards" (1 Davis, *Administrative Law Treatise*, supra, § 2.15.) The requirement for "standards" is but one method for the effective implementation of the legislative policy decision; the requirement possesses no sacrosanct quality in itself so long as its purpose may otherwise be assured.

The Oregon case of *Warren v. Marion County*, supra, 222 Ore. 307, illustrates the point that safeguards inherent in a statute which protect against its arbitrary exploitation obviate the need for standards. fn. 8 In that case, the following ordinance was attacked as an invalid delegation of legislative power because it failed to provide sufficient standards: "ORS 215.108 Building code ordinance. (1) The governing body of a county may adopt ordinances establishing building codes for the county, or any portion thereof, in conformity with the standards set forth in ORS 215.104. ... (2) Any governing body of a county which adopts ordinances establishing building codes shall by ordinance provide procedures for appeals from decisions made under the authority of the ordinances establishing building codes." In rejecting this challenge, the Oregon Supreme Court stated: "It is now apparent that the requirement of expressed standards has, in most instances, been little more than a judicial fetish for legislative language, the recitation of which provides no additional safeguards to persons affected by the exercise of the delegated authority. ... [T]he important consideration is not whether the statute **[69 Cal. 2d 382]** delegating the power expresses standards, but whether the procedure established for the exercise of the power furnishes adequate safeguards to those who are affected by the administrative action." (222 Ore. at p. 314.) The court concluded: "We believe that the appeals procedure required by ORS 215.108(2) provided a sufficient safeguard to persons wishing to contest administrative action in the enforcement of the code." (P. 315.)

[5b] The proposed Alhambra ordinance contains built-in and automatic protections that serve as safeguards against exploitive consequences from the operation of the proposed ordinance. Los Angeles is no more anxious to pay its firemen exorbitant compensation than is Alhambra. Los Angeles as an employer will be motivated to avoid the incurrence of an excessive wage scale; the interplay of competitive economic forces and bargaining power will tend to settle the wages at a realistic level. As we noted in an analogous area involving the establishment of prices: "the Legislature could reasonably assume that competition ... coupled with ... bargaining power ... would provide a safeguard against excessive prices. In all probability, that safeguard is at least as effective as any which the Legislature could be expected to provide by promulgating explicit standards" (*Wilke & Holzheiser, Inc. v. Department of Alcoholic Beverage Control*, supra, 65 Cal. 2d 349, 367-368.)

The criteria set up by the proposed enactment reasonably relate to the fulfillment of the legislative purposes. If an external private or governmental body will be involved in the application of the legislative scheme, it must be an agency that the Legislature can expect will reasonably perform its function. If, for instance, the statute provides that salaries are to be adjusted to future changes in the cost of living, the legislation must designate a body, such as the United States Department of Labor, which may be expected to reasonably

perform the function of ascertaining the cost of living. Such a qualification to the operation of the statute parallels that placed upon the ministerial officer who is designated to formulate the rules or regulations under a statute which expresses the legislative policy in the matter. Thus the officer cannot promulgate a rule or regulation "which cannot be said to be reasonably necessary or appropriate to subserving or promoting the interests and purposes of the statute." (*First Industrial Loan Co. v. Daugherty*, *supra*, 26 Cal. 2d 545, 550.)

Applying these criteria to the instant situation, we conclude **[69 Cal. 2d 383]** that the City of Alhambra could properly expect that the appropriate bodies of the City of Los Angeles and the County of Los Angeles would reasonably discharge their obligations. Once Alhambra establishes the policy of parity between the Alhambra and the Los Angeles wages, the fact that the Los Angeles governing bodies participate in setting Los Angeles salaries does not defeat the Alhambra legislation since Alhambra could expect that the authorities would reasonably investigate, negotiate, and finally determine such salaries. Thus the designated method appropriately attains the purposes of the ordinance.

Indeed, the method comports with the practical necessities of city governments. As an effort both to achieve fair wage rates and to compete effectively for competent employees, many city governments have based employee wages to some degree on rates paid in surrounding communities. (For discussion of similar provisions in other cities, see, e.g., *San Bernardino Fire & Police Protective League v. City of San Bernardino*, *supra*, 199 Cal. App. 2d 401; *Walker v. County of Los Angeles*, *supra*, 55 Cal. 2d 626; *Parker v. Bowron* (1953) 40 Cal. 2d 344 [254 P.2d 6]; *Adams v. Wolff*, *supra*, 84 Cal. App. 2d 435; see, for instance, *Culver City Ordinance No. 193 1/2*.) Reliance on rates in other communities, moreover, obviates any need for the expense, perhaps oppressive in smaller communities, of surveys or other expert assistance in determining appropriate wage scales.

In sum, the ordinance in question, if enacted, would not unlawfully delegate legislative power. As long ago as 1917 this court recognized that legislative bodies have neither the resources nor the expertise to deal adequately with every minor question potentially within their jurisdiction. "Even a casual observer of governmental growth and development must have observed the ever-increasing multiplicity and complexity of administrative affairs -- national, state, and municipal--and even the occasional reader of the law must have perceived that from necessity, if for no better grounded reason, it has become increasingly imperative that many quasi-legislative and quasi-judicial functions, which in smaller communities and under more primitive conditions were performed directly by the legislative or judicial branches of the government, are intrusted to departments, boards,

commissions, and agents. No sound objection can longer be successfully advanced to this growing method of transacting public business. These things must be done in this way or they cannot be done **[69 Cal. 2d 384]** at all" (Gaylord v. City of Pasadena, supra, 175 Cal. 433, 436.)

The complexity of government in the span of a half century since that analysis has illustrated its verity. Doctrinaire legal concepts should not be invoked to impede the reasonable exercise of legislative power properly designed to frustrate abuse. [3b] Only in the event of a total abdication of that power, through failure either to render basic policy decisions or to assure that they are implemented as made, will this court intrude on legislative enactment because it is an "unlawful delegation," and then only to preserve the representative character of the process of reaching legislative decision.

The judgment of the trial court granting a peremptory writ of mandate is affirmed.

Traynor, C. J., Peters, J., Mosk, J., and Sullivan, J., concurred.

BURKE, J.

I dissent. If by charter amendment the people of Alhambra undertook to establish a minimum wage for members of the Fire Department of the City of Alhambra by reference to an average (to be computed periodically) of the wages generally prevailing for work of a similar character in, for example, all of the cities in the same county (County of Los Angeles) or all of the cities and unincorporated areas within a more limited geographical area, or even of a substantial number of such communities of comparable size and with similar fire problems, then I could agree that under the prevailing wage cases there would be no question of unlawful delegation of legislative authority. As an amendment to the organic law of the city this would be a lawful limitation upon the exercise of the legislative power of the local legislative body and also upon the initiative power of the city's electorate. But this is not what is attempted here. The city charter sets forth how the legislative power of the city is to be exercised and places equal power to legislate in the council and the electorate; what one may do so may the other. But here, one, the electorate by initiative ordinance, seeks to limit the future exercise of power by the other and this violates fundamental concepts of municipal law. Such a limitation upon future actions by the council or, if attempted by the council, upon future actions by the electorate, is void and could only be effected by an amendment of the city's organic law--the city charter. The latter may be amended only in the manner prescribed in the Constitution. **[69 Cal. 2d 385]**

Furthermore, when an ordinance selects from the community only two public agencies and specifies that the average wage paid by those two agencies from year to year shall be the minimum wage to be paid to Alhambra firemen, there has plainly been an invalid delegation to the legislative bodies of those agencies of the authority vested by Alhambra's Charter in the Alhambra City Council to "establish" the salaries of the Alhambra Fire Department. That such a delegation of legislative power and responsibility is illegal was the holding of the court in *Mitchell v. Walker*, 140 Cal. App. 2d 239 [295 P.2d 90], in which case this court denied a hearing. The majority opinion erroneously, I submit, disapproves the Walker decision (fn. 6, ante, pp. 379-380).

The ordinance under consideration here would strip from Alhambra's City Council its discretion to determine one end of the wage scale (the minimum), and delegate that discretion to the governing bodies of two outside public agencies which are entirely without responsibility to the City of Alhambra, its employees, voters, or taxpayers. This seems to me to offend democratic principles in addition to the basic requirements of the city's charter. The record affords no basis whatever for the assumption indulged in by the majority that the average wage paid by the two handpicked agencies represents the prevailing wage in the general area. Obviously, the size of a city, the types of structures (residential, industrial, multi-dwellings), the heights of its buildings, the classes of fire equipment, living conditions, etc., vary to a great degree within a geographical area the size of Los Angeles County and wages may vary to a considerable degree depending upon local conditions. Furthermore, the tax resources which a small city, such as Alhambra (population 64,500), has with which to cope with such problems may be substantially different from those of Los Angeles (population 2,743,500). Under our system of government such inquiries and policy determinations are for the duly elected and responsible officials of the particular city involved and not for this court.

In my view, the Alhambra City Council itself could not validly delegate its authority and responsibilities in the manner here attempted by the proposed ordinance. Since under section 176 of the Alhambra City Charter the electorate purports to exercise directly by means of the initiative only such legislative action as the council itself could lawfully enact, the ordinance in question was properly refused submission to the voters. No one suggests that the initiative may be used to **[69 Cal. 2d 386]** enact legislation which the council itself could not enact. It follows that the judgment granting the writ should be reversed.

McComb, J., concurred.

FN 1. The portions of the charter relevant to the procedure provide as follows: Section 81: "The council, subject to the provisions of this Charter, shall have power to organize the fire

division and ... establish the number of its members and the amount of their salaries" Section 176: "The electors of the city shall have the right to propose, by petition, and to adopt at the polls, any ordinance which the council might enact." Section 179: "Upon presentation to the council of such petition, ... it must either adopt and enact such measure without alteration, or submit the same to the electorate at the next city election occurring subsequent to sixty days after the filing of said petition. But if said petition requests the calling of a special election and is signed and verified as herein provided and by electors in number equal to twenty-five per cent of said vote, then such ordinance, if not so adopted and enacted by the council, must be submitted to the electorate at a special election to be called within sixty days from the presentation of such petition."

FN 2. Defendants urge a somewhat indirect argument against the validity of the proposed ordinance based upon an attempted distinction between the powers of the city council and those of the electorate. They assert that if the voters approved the ordinance, the city council, under the Alhambra Charter, would never be able to repeal it; only the electorate can repeal an ordinance enacted by initiative. The unavailability of a specific method of repeal of an ordinance, however, does not affect the type or scope of an ordinance that the electorate in the first instance can enact. Section 176 of the city charter governs the latter question. If the policy underlying the rule that the city council cannot undo what the electorate has voted to do by initiative is deemed unwise, the remedy lies in either a frontal attack on that rule or a formal amendment of section 176 to narrow the electorate's initiative power. Accordingly, we reject defendants' indirect attempt to subvert section 176.

FN 3. The proposed Alhambra ordinance provides merely for a finding of the average Los Angeles earnings before the Alhambra council fixes the salaries. The Alhambra council thereafter decides what the salaries will be; it determines whether higher rates will be paid in any or all of the classifications. The Alhambra city manager reports to the council his findings upon the average Los Angeles rates; these serve only as a basement for the council's action; the council itself sets the salaries; the council exercises, and does not delegate, legislative power.

FN 4. The current counterpart of the statute involved in *Whitsett* is Labor Code section 1773. Although this court has not directly confronted an attack on the validity of section 1773, we have implicitly sustained it. (*Franklin v. City of Riverside* (1962) 58 Cal. 2d 114 [23 Cal. Rptr. 401, 373 P.2d 465]; contra, *Parrack v. City of Phoenix* (1959) 86 Ariz. 88 [340 P.2d 997]; *Adams v. City of Albuquerque* (1957) 62 N.M. 208 [307 P.2d 792].) Moreover, the federal Walsh-Healey Act (41 U.S.C. § 35(b)) contains the same prevailing wage

provision for contracts with the federal government; its validity has been upheld. (*Perkins v. Lukens Steel Co.* (1940) 310 U.S. 113 [84 L. Ed. 1108, 60 S. Ct. 869].)

FN 5. *Walker v. County of Los Angeles* (1961) 55 Cal. 2d 626 [12 Cal. Rptr. 671, 361 P.2d 247], which involved a county requirement that employees receive a salary at least equal to that paid to comparable persons in private employment, makes the same point. We characterized the county board of supervisors' duty as a "fact-finding function ... in finally fixing the rate of compensation at or above the minimum coincident with the prevailing wage found" and stated that this fact-finding function "precede[s] ... the legislative act." (55 Cal.2d at p. 635; see also *San Bernardino Fire & Police Protective League v. City of San Bernardino* (1962) 199 Cal. App. 2d 401, 416 [18 Cal. Rptr. 757].) That which "precedes legislative action" cannot literally constitute a delegation of the power to legislate.

FN 6. The California cases of *In re Burke* (1923) 190 Cal. 326 [212 P. 193], and *Adams v. Wolff* (1948) 84 Cal. App. 2d 435 [190 P.2d 665], cited by defendants, do not pass upon the present issue. *Burke* involves an attempted adoption of a future statute of another state; the court specifically reserves the point here at issue, as does *Wolff*. The cited case of *Mitchell v. Walker* (1956) 140 Cal. App. 2d 239 [295 P.2d 90], does conflict with part of our ruling in the instant case, and to that extent it is disapproved.

In upholding the definition of prohibited drugs by future decision of a recognized private pharmaceutical institution, the Supreme Court of Wisconsin, in *State v. Wakeen* (1953) 263 Wis. 401, 411 [57 N.W.2d 364], held: "This is not a case of the delegation of legislative powers. The publications referred to in the statute are not published in response to any delegation of power, legislative or otherwise, by the statute. The compendia are published independently of the statute and not in response to it." (*Italics added.*) Similarly, in our case an independent, authoritative source determines the comparable Los Angeles rates, and such decision is made "independently of the statute and not in response to it." For other out-of-state cases, see *Crowley v. Thornbrough* (1956) 226 Ark. 768, and cases cited at page 774 [294 S.W.2d 62], and *State ex rel. Kirschner v. Urquhart* (1957) 50 Wn.2d 131 [310 P.2d 261]. See generally 1 Davis, *Administrative Law Treatise*, *supra*, § 2.14; Note (1934) 34 Colum.L.Rev. 1077, 1084-1086.

FN 7. In *Currin v. Wallace* (1939) 306 U.S. 1 [83 L. Ed. 441, 59 S. Ct. 379], a similar challenge was levelled against the Tobacco Inspection Act of 1935, a statute authorizing the federal Secretary of Agriculture to designate markets to be regulated only if two-thirds of the growers affected favored such a designation. The Supreme Court upheld the act, noting that "[t]his is not a case where Congress has attempted to abdicate, or to transfer to others, the essential legislative functions with which it is vested by the Constitution. ... So far as

growers of tobacco are concerned, the required referendum does not involve any delegation of legislative authority. Congress has merely placed a restriction upon its own regulation by withholding its operation as to a given market 'unless two-thirds of the growers voting favor it.' ... Here it is Congress that exercises its legislative authority in making the regulation and in prescribing the conditions of its application. The required favorable vote upon the referendum is one of these conditions." (306 U.S. at pp. 15-16 [83 L.Ed. at pp. 451-452]; see also *Parker v. Brown* (1943) 317 U.S. 341, 352 [87 L. Ed. 315, 326, 62 S. Ct. 307]; *Floresta, Inc. v. City Council* (1961) 190 Cal. App. 2d 599, 610 fn. 4 [12 Cal. Rptr. 182] and cases cited therein.)

The private act of the producer in entering into a contract setting a price for the resale of his own brand is neither the performance of a legislative function nor the exercise of an unlawfully delegated power. (*Scoville Mfg. Co. v. Skaggs etc. Drug Stores* (1955) 45 Cal. 2d 881 [291 P.2d 936]; see *Wilke & Holzheiser, Inc. v. Department of Alcoholic Beverage Control*, *supra*, 65 Cal. 2d 349, 369.)

FN 8. Other cases have also recognized that "standards" constitute merely one method, albeit the most common one, of assuring that the legislative body does not unlawfully delegate its power. The New Jersey Supreme Court, in striking down a delegation to The Medical Society of New Jersey, stated: "We think such a power ... may not validly be delegated by the Legislature to a private body ... at least where the exercise of such power is not accompanied by adequate legislative standards or safeguards whereby an applicant may be protected against arbitrary or self-motivated action" (*Group Health Ins. v. Howell*, *supra*, 40 N.J. 436, 445.) (Italics added.) The Supreme Court of Maryland has asserted: "[A]n ordinance which delegates a part of the police power to a zoning board may be valid, even though it confers upon the board a certain discretion in the exercise of that power, provided that its discretion is sufficiently limited by rules and standards to protect the people against any arbitrary or unreasonable exercise of power." (*Heath v. Mayor & City Council of Baltimore*, *supra*, 187 Md. 296, 303 (dictum).)

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42 USC 7543: State standards

Text contains those laws in effect on November 18, 2025

From Title 42-THE PUBLIC HEALTH AND WELFARE

CHAPTER 85-AIR POLLUTION PREVENTION AND CONTROL

SUBCHAPTER II-EMISSION STANDARDS FOR MOVING SOURCES

Part A-Motor Vehicle Emission and Fuel Standards

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§7543. State standards

(a) Prohibition

No State or any political subdivision thereof shall adopt or attempt to enforce any standard relating to the control of emissions from new motor vehicles or new motor vehicle engines subject to this part. No State shall require certification, inspection, or any other approval relating to the control of emissions from any new motor vehicle or new motor vehicle engine as condition precedent to the initial retail sale, titling (if any), or registration of such motor vehicle, motor vehicle engine, or equipment.

(b) Waiver

(1) The Administrator shall, after notice and opportunity for public hearing, waive application of this section to any State which has adopted standards (other than crankcase emission standards) for the control of emissions from new motor vehicles or new motor vehicle engines prior to March 30, 1966, if the State determines that the State standards will be, in the aggregate, at least as protective of public health and welfare as applicable Federal standards. No such waiver shall be granted if the Administrator finds that-

(A) the determination of the State is arbitrary and capricious,

(B) such State does not need such State standards to meet compelling and extraordinary conditions, or

(C) such State standards and accompanying enforcement procedures are not consistent with section 7521(a) of this title.

(2) If each State standard is at least as stringent as the comparable applicable Federal standard, such State standard shall be deemed to be at least as protective of health and welfare as such Federal standards for purposes of paragraph (1).

(3) In the case of any new motor vehicle or new motor vehicle engine to which State standards apply pursuant to a waiver granted under paragraph (1), compliance with such State standards shall be treated as compliance with applicable Federal standards for purposes of this subchapter.

(c) Certification of vehicle parts or engine parts

Whenever a regulation with respect to any motor vehicle part or motor vehicle engine part is in effect under section 7541(a)(2) of this title, no State or political subdivision thereof shall adopt or attempt to enforce any standard or any requirement of certification, inspection, or approval which relates to motor vehicle emissions and is applicable to the same aspect of such part. The preceding sentence shall not apply in the case of a State with respect to which a waiver is in effect under subsection (b).

(d) Control, regulation, or restrictions on registered or licensed motor vehicles

Nothing in this part shall preclude or deny to any State or political subdivision thereof the right otherwise to control, regulate, or restrict the use, operation, or movement of registered or licensed motor vehicles.

(e) Nonroad engines or vehicles

(1) Prohibition on certain State standards

No State or any political subdivision thereof shall adopt or attempt to enforce any standard or other requirement relating to the control of emissions from either of the following new nonroad engines or nonroad vehicles subject to regulation under this chapter-

(A) New engines which are used in construction equipment or vehicles or used in farm equipment or vehicles and which are smaller than 175 horsepower.

(B) New locomotives or new engines used in locomotives.

Subsection (b) shall not apply for purposes of this paragraph.

(2) Other nonroad engines or vehicles

(A) In the case of any nonroad vehicles or engines other than those referred to in subparagraph (A) or (B) of paragraph (1), the Administrator shall, after notice and opportunity for public hearing, authorize California to adopt and enforce standards and other requirements relating to the control of emissions from such vehicles or engines if California determines that California standards will be, in the aggregate, at least as protective of public health and welfare as applicable Federal standards. No such authorization shall be granted if the Administrator finds that-

- (i) the determination of California is arbitrary and capricious,
- (ii) California does not need such California standards to meet compelling and extraordinary conditions, or
- (iii) California standards and accompanying enforcement procedures are not consistent with this section.

(B) Any State other than California which has plan provisions approved under part D of subchapter I may adopt and enforce, after notice to the Administrator, for any period, standards relating to control of emissions from nonroad vehicles or engines (other than those referred to in subparagraph (A) or (B) of paragraph (1)) and take such other actions as are referred to in subparagraph (A) of this paragraph respecting such vehicles or engines if-

- (i) such standards and implementation and enforcement are identical, for the period concerned, to the California standards authorized by the Administrator under subparagraph (A), and
- (ii) California and such State adopt such standards at least 2 years before commencement of the period for which the standards take effect.

The Administrator shall issue regulations to implement this subsection.

(July 14, 1955, ch. 360, title II, §209, formerly §208, as added Pub. L. 90-148, §2, Nov. 21, 1967, 81 Stat. 501 ; renumbered and amended Pub. L. 91-604, §§8(a), 11(a)(2)(A), 15(c)(2), Dec. 31, 1970, 84 Stat. 1694 , 1705, 1713; Pub. L. 95-95, title II, §§207, 221, Aug. 7, 1977, 91 Stat. 755 , 762; Pub. L. 101-549, title II, §222(b), Nov. 15, 1990, 104 Stat. 2502 .)

EDITORIAL NOTES

CODIFICATION

Section was formerly classified to section 1857f-6a of this title.

PRIOR PROVISIONS

A prior section 209 of act July 14, 1955, as added Nov. 21, 1967, Pub. L. 90-148, §2, 81 Stat. 502 , was renumbered section 210 by Pub. L. 91-604 and is classified to section 7544 of this title.

Another prior section 209 of act July 14, 1955, ch. 360, title II, as added Oct. 20, 1965, Pub. L. 89-272, title I, §101(8), 79 Stat. 995 , related to appropriations for the fiscal years ending June 30, 1966, 1967, 1968, and 1969, and was classified to section 1857f-8 of this title, prior to repeal by Pub. L. 89-675, §2(b), Oct. 15, 1966, 80 Stat. 954 .

AMENDMENTS

1990-Subsec. (e). Pub. L. 101-549 added subsec. (e).

1977-Subsec. (b). Pub. L. 95-95, §207, designated existing provisions as par. (1), substituted "March 30, 1966, if the State determines that the State standards will be, in the aggregate, at least as protective of public health and welfare as applicable Federal standards" for "March 30, 1966, unless he finds that such State does not require standards more stringent than applicable Federal standards to meet compelling the extraordinary conditions or that such State standards and accompanying enforcement procedures are not consistent with section 7521(a) of this title", added subpars. (A), (B), and (C), and added pars. (2) and (3).

Subsecs. (c), (d). Pub. L. 95-95, §221, added subsec. (c) and redesignated former subsec. (c) as (d).

1970-Subsec. (a). Pub. L. 91-604, §11(a)(2)(A), substituted "part" for "subchapter".

Subsec. (b). Pub. L. 91-604, §15(c)(2), substituted "Administrator" for "Secretary".

Subsec. (c). Pub. L. 91-604, §11(a)(2)(A), substituted "part" for "subchapter".

STATUTORY NOTES AND RELATED SUBSIDIARIES

EFFECTIVE DATE OF 1977 AMENDMENT

Amendment by Pub. L. 95-95 effective Aug. 7, 1977, except as otherwise expressly provided, see section 406(d) of Pub. L. 95-95, set out as a note under section 7401 of this title.

MODIFICATION OR RESCISSION OF RULES, REGULATIONS, ORDERS, DETERMINATIONS, CONTRACTS, CERTIFICATIONS, AUTHORIZATIONS, DELEGATIONS, AND OTHER ACTIONS

All rules, regulations, orders, determinations, contracts, certifications, authorizations, delegations, or other actions duly issued, made, or taken by or pursuant to act July 14, 1955, the Clean Air Act, as in effect immediately prior to the date of enactment of Pub. L. 95–95 [Aug. 7, 1977] to continue in full force and effect until modified or rescinded in accordance with act July 14, 1955, as amended by Pub. L. 95–95 [this chapter], see section 406(b) of Pub. L. 95–95, set out as an Effective Date of 1977 Amendment note under section 7401 of this title.

**IN THE UNITED STATES DISTRICT COURT FOR THE
EASTERN DISTRICT OF CALIFORNIA**

**CENTRAL VALLEY CHRYSLER-
JEEP, et al.,**

Plaintiffs,

v.

**CATHERINE E. WITHERSPOON, in
her official capacity as Executive
Director of the California Air Resources
Board, et al.,**

Defendants.

**CV F 04-6663 AWI LJO
(NEW DJ)**

**MEMORANDUM OPINION AND
ORDER (1) GRANTING IN
PART AND DENYING IN PART
DEFENDANT AND
DEFENDANT-INTERVENORS'
MOTION FOR JUDGMENT ON
THE PLEADINGS AND
(2) LIMITING DISCOVERY OF
GLOBAL WARMING SCIENCE
DOCUMENTS**

(Document #226)

This case concerns the legality of environmental regulations imposed by a state administrative agency. Plaintiffs seek declaratory and injunctive relief on the basis that the regulations violate and are preempted by federal law. This court has federal question jurisdiction pursuant to 28 U.S.C. § 1331.

BACKGROUND

A. California Health and Safety Code § 43018.5

In 2002, the California Legislature enacted Assembly Bill Number 1493, codified at California Health and Safety Code § 43018.5. Section 43018.5(a) required the California Air Resources Board ("CARB") to "develop and adopt regulations that achieve the maximum feasible and cost-effective reduction of greenhouse gas emissions from motor vehicles." Section

1 43018.5 only authorizes regulations that apply to vehicles manufactured in the 2009 model year
2 or after. Cal. Health & Safety Code § 43018.5(b)(1). “Maximum feasible and cost-effective
3 reduction of greenhouse gas emissions” refers to reductions that are “[c]apable of being
4 successfully accomplished within the time provided by this section, taking into account
5 environmental, economic, social, and technological factors” and are “[e]conomical to an owner
6 or operator of a vehicle, taking into account the full life-cycle costs of a vehicle.” Cal. Health &
7 Safety Code § 43018.5(i)(2).

8 At a public hearing in September 2004, CARB approved regulatory amendments
9 (“California regulations” or “regulations”) adding greenhouse gas emission standards to
10 California’s existing motor vehicle standards. See FAC Ex. A. CARB, through its normal
11 process, ultimately adopted the regulatory language in its Resolution 04-28. Id.

12 CARB made factual findings to support its adoption of the regulations. CARB found that
13 “[o]ver the past century the temperatures in the northern hemisphere have changed at a rate faster
14 than at any other time over the last millennium, and that change is because human activities are
15 altering the chemical composition of the atmosphere through the buildup of greenhouse gases
16 and other pollutants.” FAC Ex. A at 9. CARB further noted that “the global climate is changing
17 at a rate unmatched in the past one thousand years” and climate change is affecting California.
18 Id. CARB found that the proposed standards would significantly reduce greenhouse gas
19 emissions. FAC Ex. A at 14.

20 The regulations addressed four greenhouse gases: carbon dioxide, methane, nitrous
21 oxide, and hydrofluorocarbons. Cal. Code Regs. tit. 13, § 1961.1(e)(4). The regulations weight
22 the emission of each gas based on its “global warming potential.” Cal. Code Regs. tit. 13,
23 § 1961.1(e)(6). Compliance with the regulations is based on “fleet average” greenhouse gas
24 emissions. Cal. Code Regs. tit. 13, § 1961.1(a)(1)(A). The average is defined separately for two
25 categories of vehicles: (1) passenger cars and light duty trucks under 3,750 pounds, and (2) light
26 duty trucks over 3,750 pounds and medium duty passenger vehicles. Id. The standards set
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28

emissions limits beginning in model year 2009 that become more stringent each year through 2016. Id. Manufacturers who fail to comply face civil penalties. See Cal. Health & Safety Code § 43211.

Manufacturers that meet the standards for model year 2009 or surpass the standards in any later year will accrue credits. Cal. Code Regs. tit. 13, § 1961.1(b)(1). These credits may be used to offset that manufacturer's emissions in a later year, may be transferred between vehicle categories, or may be sold to another manufacturer. Id. A manufacturer who does not meet the standards may avoid the civil penalty for noncompliance by offsetting their failures within a five-year period. Cal. Code Regs. tit. 13, § 1961.1(b)(3). Manufacturers can also comply by earning credits for using alternative fuels that produce lower greenhouse gas emissions. Cal. Code Regs. tit. 13, § 1961.1(a)(1)(B).

B. The Clean Air Act

In 1963, Congress expanded its role in addressing air pollution by enacting the Clean Air Act. Pub. L. No. 88-206, 77 Stat. 392 (1963). Section 209(a) of the Clean Air Act, codified at 42 U.S.C. § 7543(a),¹ generally preempts state regulation of motor vehicle emissions. Section 209(b) provides an exemption to 209(a) for rules adopted by the State of California that receive a waiver from the Environmental Protection Agency ("EPA"). 42 U.S.C. § 7543(b)(1);² see

¹ In relevant part, 42 U.S.C. § 7543(a) provides as follows: "No State or any political subdivision thereof shall adopt or attempt to enforce any standard relating to the control of emissions from new motor vehicles or new motor vehicle engines subject to this part."

² In full, 42 U.S.C. § 7543(b)(1) provides as follows:

The Administrator shall, after notice and opportunity for public hearing, waive application of this section to any State which has adopted standards (other than crankcase emission standards) for the control of emissions from new motor vehicles or new motor vehicle engines prior to March 30, 1966, if the State determines that the State standards will be, in the aggregate, at least as protective of public health and welfare as applicable Federal standards. No such waiver shall be granted if the Administrator finds that—

(A) the determination of the State is arbitrary and capricious,
(B) such State does not need such State standards to meet

1 Engine Mfrs. Ass'n v. EPA, 88 F.3d 1075, 1080 (D.C. Cir. 1996) (noting that, under the terms of
 2 section 209(b), "California is the only state that qualifies for the waiver, because it was the only
 3 state that had adopted emissions control standards prior to March 30, 1966"). In order to receive
 4 such a waiver, the state standards must be, "in the aggregate," at least as protective as federal
 5 standards. 42 U.S.C. § 7543(b)(1). The EPA may deny a waiver if it finds that the state's
 6 determination is "arbitrary and capricious," that the state standards are not needed to meet
 7 "compelling and extraordinary conditions," or that the state standards are not consistent with 42
 8 U.S.C. § 7521(a). Id. Though only California's regulations may receive a waiver, other states
 9 may elect to adopt such California standards under Clean Air Act section 177, rather than being
 10 governed by the federal scheme. 42 U.S.C. § 7507.

11 On September 8, 2003, the EPA concluded that "in light of the language, history,
 12 structure and context of the [Clean Air Act] and Congress'[s] decision to give DOT authority to
 13 regulate fuel economy under EPCA, it is clear that EPA does not have authority to regulate motor
 14 vehicle emissions of CO₂ and other [greenhouse gases] under the [Clean Air Act]." Control of
 15 Emissions from New Highway Vehicles and Engines, 68 Fed. Reg. 52,922, 52,929 (September 8,
 16 2003). The District of Columbia Circuit upheld the EPA's decision, and the case is currently
 17 before the Supreme Court. See Massachusetts v. EPA, 415 F.3d 50 (D.C. Cir. 2005), *cert.*
 18 *granted*, 126 S. Ct. 2960 (2006).

19 On December 21, 2005, CARB requested that the EPA grant the California regulations a
 20 section 209(b) waiver, which the EPA has yet to provide. Defs.' RJN Ex. C.

21 **C. The Energy Policy and Conservation Act**

22 Enacted in 1975, the Energy Policy and Conservation Act ("EPCA") established federal
 23 fuel economy standards for new vehicles. Pub. L. No. 94-163, 89 Stat. 871 (1975). The EPCA

24
 25
 26 compelling and extraordinary conditions, or
 27 (C) such State standards and accompanying enforcement
 28 procedures are not consistent with section 7521(a) of this title.

1 authorizes the National Highway Traffic Safety Administration³ (“NHTSA”) to set a minimum
 2 corporate average fuel economy (“CAFE”) for a manufacturer’s fleet of new vehicles. 49 U.S.C.
 3 §§ 32902(a), 32902(c).

4 The EPCA provides that the CAFE standards must be set at the “maximum feasible
 5 average fuel economy level.” 49 U.S.C. §§ 32902(a), 32902(c). In setting the maximum feasible
 6 level, NHTSA “shall consider technological feasibility, economic practicability, the effect of
 7 other motor vehicle standards of the Government on fuel economy, and the need of the United
 8 States to conserve energy.” 49 U.S.C. § 32902(f). This requires NHTSA to consider the effect
 9 on fuel economy of state regulations that receive an EPA waiver under Clean Air Act section
 10 209. EPCA § 301, 89 Stat. at 905; see Light Truck Average Fuel Economy Standard, Model
 11 Year 2004, 67 Fed. Reg. 16,052, 16,057 (April 4, 2002) (to be codified at 49 C.F.R. pt. 533)
 12 (considering the effect of California’s low emission vehicle regulations in setting CAFE
 13 standard). The EPCA contains an express preemption provision:

14 When an average fuel economy standard prescribed under this
 15 chapter is in effect, a State or a political subdivision of a State may
 16 not adopt or enforce a law or regulation related to fuel economy
 standards or average fuel economy standards for automobiles
 covered by an average fuel economy standard under this chapter.

17 42 U.S.C. § 32919.

18 **D. This Lawsuit**

19 On December 7, 2004, Plaintiffs⁴ filed suit against Catherine E. Witherspoon, CARB’s
 20

21 ³ The EPCA expressly provided that the Secretary of Transportation would
 22 administer the program. See, e.g., 49 U.S.C. § 32902(a). The Secretary delegated these
 responsibilities to the National Highway Traffic Safety Administration. 49 C.F.R. § 1.50(f).

23 ⁴ Plaintiffs in the FAC include the following automobile dealerships located in
 24 Modesto, Turlock, Merced, Madera, Lemoore, Tulare, and Porterville: Central Valley Chrysler-
 25 Jeep, Inc.; Kitahara Pontiac GMC Buick, Inc.; Madera Ford Mercury, Inc.; Madera Chevrolet;
 26 Frontier Dodge, Inc.; Tom Fields Motors, Inc.; Pistoressi Chrysler Dodge Jeep; Bob Williams
 27 Chevrolet; Courtesy Oldsmobile Cadillac, Inc.; Merle Stone Chevrolet, Inc.; Merle Stone
 Porterville, Inc.; Sturgeon and Beck Incorporated; and Swanson Fahrney Ford, Inc. General
 Motors Corporation, DaimlerChrysler Corporation, the Tulare County Farm Bureau, and the
 Alliance of Automobile Manufacturers are also plaintiffs. The Association of International
 Automobile Manufacturers (“AIAM” or “Plaintiff-Intervenor”) has intervened as a plaintiff.

1 executive director, to prevent enforcement of the California regulations.⁵ In their first amended
2 complaint (“FAC”), filed February 16, 2005, Plaintiffs seek declaratory and injunctive relief on
3 the following claims:

4 1. Count I – Preemption under the Energy Policy and Conservation Act of 1975
5 (“EPCA”), 49 U.S.C. §§ 32902-32919.

6 2. Count II – Preemption under § 209(a) of the Federal Clean Air Act, 42 U.S.C.
7 § 7543(a).

8 3. Count III – Preemption under the foreign policy of the United States and the foreign
9 affairs powers of the Federal Government.

10 4. Count IV – Violation of the Dormant Commerce Clause of the United States
11 Constitution.

12 5. Count V – Violation of the Sherman Act, 15 U.S.C. § 1.

13 On June 1, 2006, Defendant and Defendant-Intervenors jointly filed a motion for
14 judgment on the pleadings contending that each of Plaintiffs’ and Plaintiff-Intervenor’s causes of
15 action had failed to state a claim upon which relief can be granted.⁶ On July 24, 2006, Plaintiffs
16 filed a memorandum in opposition to the motion. On the same day, Plaintiff-Intervenor filed a
17 separate memorandum, also opposing the motion. On August 17, 2006, Defendant and
18 Defendant-Intervenors filed a reply to the opposition. On September 7, 2006, Plaintiffs filed an
19 ex parte motion for leave to file a surreply brief, to which Defendants objected. On September
20 11, 2006, the court granted Plaintiffs’ ex parte motion. On September 15, 2006, the court heard
21 the motion for judgment on the pleadings.
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24 ⁵ Sierra Club, Bluewater Network, Global Exchange, Rainforest Action Network,
and Natural Resources Defense Council have intervened as defendants.

25 ⁶ States that have adopted California’s emission standards, along with the City of
26 New York, have collectively filed briefs as amici arguing in favor of judgment on the pleadings.
27 The amici are the States of New York, Connecticut, Maine, New Jersey, Oregon, Rhode Island,
Vermont, Washington, the Commonwealth of Massachusetts, and the City of New York.

LEGAL STANDARD

Where Rule 12(c) is used to raise the defense of failure to state a claim, “the motion for judgment on the pleadings faces the same test as a motion under Rule 12(b) (6).” McGlinchy v. Shell Chemical Co., 845 F.2d 802, 810 (9th Cir. 1988). Dismissal of a complaint is proper if “it appears beyond doubt that the plaintiff can prove no set of facts in support of his claim which would entitle him to relief.” Conley v. Gibson, 355 U.S. 41, 45-46 (1957). When determining a motion for judgment on the pleadings, the court should assume the allegations in the complaint to be true and construe them in the light most favorable to the plaintiff. McGlinchey, 845 F.2d at 810. However, “conclusory allegations without more are insufficient to defeat a motion [for judgment on the pleadings].” Id. A complaint may be dismissed as a matter of law if there is a lack of a cognizable legal theory or if there are insufficient facts alleged under a cognizable legal theory. Balistreri v. Pacifica Police Dep’t, 901 F.2d 696, 699 (9th Cir. 1990). The court must determine whether or not it appears to a certainty under existing law that no relief can be granted under any set of facts that might be proved in support of a plaintiff’s claims. De La Crux v. Tormey, 582 F.2d 45, 48 (9th Cir. 1978), *cert. denied*, 441 U.S. 965 (1979).

DISCUSSION

A. EPCA Preemption

Plaintiffs and Plaintiff-Intervenor⁷ (collectively “Plaintiffs”) allege that the EPCA preempts the California regulations. They contend that the California regulations are expressly preempted because they are “related to fuel economy standards” under 42 U.S.C. § 32919(a). Plaintiffs also urge the court to find that the EPCA preempts the entire field of fuel economy regulations and that the California regulations are invalid because they fall within that field.

⁷ AIAM’s Complaint in Intervention alleges that the California regulations are preempted under both the EPCA and the Clean Air Act. Defendants do not provide any basis to grant judgment on the pleadings with respect to AIAM’s claims distinct from its arguments for dismissal of Counts I and II of the FAC. Accordingly, the court’s analysis of EPCA and Clean Air Act preemption applies to both Plaintiffs’ FAC and Plaintiff-Intervenor’s Complaint in Intervention.

1 Because Plaintiffs have stated a claim for preemption of the regulations based on their actual
2 conflict with the EPCA, the court declines to decide at this stage whether the other theories of
3 preemption have merit.

4 The Supremacy Clause, U.S. Const., art. VI, cl. 2, “invalidates state laws that ‘interfere
5 with, or are contrary to,’ federal law.” Hillsborough County v. Automated Med. Labs., Inc., 471
6 U.S. 707, 712-13 (1985) (quoting Gibbons v. Ogden, 9 Wheat. 1, 211 (1824) (Marshall, C. J.)).
7 Congress, when acting within its constitutional limits, may preempt state law by expressly stating
8 its intent to do so. Id. at 713 (citing Jones v. Rath Packing Co., 430 U.S. 519, 525 (1977)). In
9 the absence of such express language, a court can infer Congress’s intent to preempt all state law
10 in a particular area “where the scheme of federal regulation is sufficiently comprehensive to
11 make reasonable the inference that Congress ‘left no room’ for supplementary state regulation.”
12 Id. (quoting Rice v. Santa Fe Elevator Corp., 331 U.S. 218, 230 (1947)). “In addition to express
13 or implied pre-emption, a state law also is invalid to the extent that it ‘actually conflicts with a
14 . . . federal statute.’” Int’l Paper Co. v. Ouellette, 479 U.S. 481, 491-92 (1987). Such a conflict
15 can result in preemption where it is impossible for a private party to comply with both the state
16 and federal requirements. English v. Gen. Elec. Co., 496 U.S. 72, 79 (1990). Conflict
17 preemption can also be found where “the state law ‘stands as an obstacle to the accomplishment
18 and execution of the full purposes and objectives of Congress.’” Int’l Paper, 479 U.S. at 491-92
19 (quoting Hines v. Davidowitz, 312 U.S. 52, 67 (1941)).

20 In Geier v. American Honda Motor Co., 529 U.S. 861, 874-86 (2000), the Supreme Court
21 discussed the circumstances in which a more-restrictive state law “actually conflicts” with a
22 federal regulatory scheme. That case concerned whether a state tort law attaching liability for an
23 automobile manufacturer’s failure to install an airbag conflicted with the regulatory scheme
24 administered by the Department of Transportation (“DOT”). Id. at 874. Based on its authority
25 under the National Traffic and Motor Vehicle Safety Act of 1966, the DOT had issued a safety
26 standard that did not require airbags in every vehicle, but instead mandated a mix of several
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1 different passive restraint systems, including airbags. Id. at 878. The Court considered the
2 DOT's reasons for imposing a variety of restraints, rather than requiring all vehicles to use
3 airbags. Id. at 875. DOT had considered, among other things, the potential safety risks of
4 employing airbags, their high cost, and public reluctance to use them. Id. at 877-78. DOT had
5 concluded that an "all-airbag" standard would threaten a consumer backlash over perceived or
6 real safety risks. Id. at 879. On the other hand "a mix of devices would help develop data on
7 comparative effectiveness, would allow the industry time to overcome the safety problems and
8 the high production costs associated with airbags, and would facilitate the development of
9 alternative, cheaper, and safer passive restraint systems" while avoiding the backlash. Id. The
10 safety standard also provided for the gradual phase-in of passive restraints to allow the
11 manufacturers more time to develop airbags and other devices and to develop information about
12 the effectiveness of various systems. Id. The Court held that the state law, though it shared some
13 of the federal standard's goals, nevertheless presented an obstacle to the accomplishment the
14 federal objectives and was preempted. Id. at 885; see also Gade v. Nat'l Solid Wastes Mgmt.
15 Ass'n, 505 U.S. 88, 107 (1992) (holding that, regardless of the state statute's purposes, it is
16 preempted if it "sufficiently interferes with federal regulation").

17 Plaintiffs contend that the California regulations stand as an obstacle to the
18 accomplishment of the objectives of the EPCA. Under the EPCA, NHTSA sets CAFE standards
19 at the "maximum feasible level" after considering various statutory factors. 49 U.S.C.
20 §§ 32902(a), 32902(c); see 49 U.S.C. § 32902(f). The factors Congress requires NHTSA to
21 consider provide insight into the objectives of the CAFE program. NHTSA must consider
22 "technological feasibility, economic practicability, the effect of other motor vehicle standards of
23 the Government on fuel economy, and the need of the United States to conserve energy." 49
24 U.S.C. § 32902(f). In setting its maximum feasible level, NHTSA must also consider the effect
25 of fuel economy requirements on safety. Competitive Enter. Inst. v. NHTSA, 956 F.2d 321, 327
26 (D.C. Cir. 1992).

1 The court finds that it is also appropriate to “place some weight” upon NHTSA’s
 2 interpretation of the EPCA’s objectives. See Geier, 529 U.S. at 883. This is because NHTSA “is
 3 likely to have a thorough understanding of its own regulation and its objectives and is ‘uniquely
 4 qualified’ to comprehend the likely impact of state requirements.”⁸ Id. According to NHTSA,
 5 one of the goals of the CAFE program is “improving motor vehicle fuel economy.” Average
 6 Fuel Economy Standards for Light Trucks Model Years 2008-2011, 71 Fed. Reg. 17,566, 17,667
 7 (April 6, 2006) (to be codified at 49 C.F.R. pts. 523-33, 537). To do so, NHTSA must set fuel
 8 economy at the “maximum feasible level” while “avoiding serious adverse economic effects on
 9 manufacturers and maintaining a reasonable amount of consumer choice among a broad variety
 10 of vehicles.” Id. Accordingly, Congress “carefully drafted” the CAFE program to require fuel
 11 economy restrictions “that do not have the effect of either ‘imposing impossible burdens or
 12 unduly limiting consumer choice as to capacity and performance of motor vehicles.’” Id.
 13 (quoting H. Rep. No. 94-340, at 87 (1975).)

14 Based on the language of the EPCA and NHTSA’s statements, the court finds that among
 15 the objectives of the CAFE program are maximizing fuel economy, avoiding economic harm to
 16 the automobile industry, maintaining consumer choice, and ensuring vehicle safety. Plaintiffs’
 17 FAC alleges that the enforcement of the California regulations will have a damaging impact on
 18 the objectives of CAFE. The FAC alleges that some manufacturers will need to improve the
 19 average fuel economy level for some of their passenger automobiles to 44 miles per gallon,
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21 ⁸ At oral argument, Defendants pointed out that the Supreme Court in Geier
 22 acknowledged that it would have reached the same result “even without giving DOT’s own view
 23 special weight,” making the language endorsing consideration of the agency’s view of its goals
 24 dicta. 529 U.S. at 886. The Ninth Circuit has nevertheless cited Geier for the proposition that
 25 preemption can turn on an agency’s opinion. See Oxygenated Fuels Ass’n v. Davis, 331 F.3d
 26 665, 672 (9th Cir. 2003) (holding that Geier was distinguishable and preemption was
 27 inappropriate because, among other reasons, EPA had not interpreted its governing statute to
 preempt the state regulation). In any event, the Supreme Court’s rationale for considering the
 agency’s view of its goals and the effect of a state statute is convincing. The court therefore gives
 weight to these opinions of NHTSA without ceding its duty to decide the issue of preemption de
 novo. See Smiley v. Citibank (S.D.), N.A., 517 U.S. 735, 744 (1996); Ass’n of Civilian
Technicians v. Fed. Labor Relations Auth., 200 F.3d 590, 592 (9th Cir. 2000).

1 whereas the current federal standard requires an average of only 27.5 miles per gallon. FAC
2 ¶ 78. The California regulations require a fuel economy standard “approaching” 27 miles per
3 gallon for certain vehicles that must only meet the “light duty truck” standard of 22.2 miles per
4 gallon under the federal scheme. FAC ¶ 79. Plaintiffs allege in the FAC that the regulations, by
5 requiring motor vehicles to attain substantially higher fuel economy, will result in higher retail
6 prices to the consumer and higher costs and burdens on the industry. FAC ¶ 77. As a result, the
7 regulations allegedly “will have an acute, clear, direct and substantial impact [on] the
8 performance, price, and availability of vehicles that will be sold in California” and “on some
9 manufacturers’ activities to comply with the national fuel economy standards as efficiently and
10 safely as possible, and in a manner that maximizes consumer choices and minimizes adverse
11 effects on employment.” Id.

12 The FAC alleges that vehicle manufacturers are currently designing their vehicles for
13 model year 2009. FAC ¶ 81. According to the FAC, the technologies and vehicle changes the
14 automobile industry is currently developing cannot fully comply with the California regulations.
15 FAC ¶ 86. The FAC alleges that enforcement of the California regulations will force them to (1)
16 face sanctions for noncompliance in model year 2009, (2) incur increased cost by redesigning
17 vehicles already slated for production in model year 2009, making the sale of vehicles
18 unprofitable in many instances, or (3) restrict the sale of the vehicles that threaten compliance,
19 foregoing the opportunity to recover investment and production costs and profits they anticipated
20 for those vehicles. FAC ¶ 81. Plaintiffs allege that, if a manufacturer chooses to redirect its
21 engineers and developers to redesign vehicles for California, it will sacrifice its efforts to
22 introduce new products in markets other than California, resulting in lost sales for manufacturers
23 and lost goodwill and profits for dealers. FAC ¶ 82. The FAC also alleges that some
24 manufacturers will have to spend hundreds of millions of dollars to develop model year 2009
25 vehicles that comply. FAC ¶ 101(c). These expenditures will allegedly result in price increases
26 with the effect of reducing sales and goodwill for the manufacturers and the dealers. Id. The
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1 FAC alleges that the California regulations will also cause manufacturers to restrict or eliminate
2 the sale of some types of vehicles in California. FAC ¶ 84. As a result, Plaintiffs contend,
3 consumers will turn to the used-vehicle market or will select vehicles less suited to their needs or
4 business demands. Id.

5 The FAC also alleges that enforcement of the California regulations will result in less
6 safe automobiles and increased vehicle-related fatalities. FAC ¶¶ 87-92. According to the FAC,
7 the regulations, once fully implemented, will “likely require the industry to produce a fleet of
8 smaller, lighter-weight vehicles for California.” FAC ¶ 90. The FAC cites a report to Congress
9 concluding that a decrease in vehicle size, “without a concurrent upgrading of their occupant
10 protection capability, would likely lead to an increase in the rate of highway deaths and serious
11 injuries.” FAC ¶ 88. Plaintiffs allege that, according to an analysis using NHTSA’s predictive
12 model, the California regulation will result in an increase of 258 fatalities in California in 2020,
13 and an increase of 530 fatalities in 2030. FAC ¶ 91.

14 Along with NHTSA’s evaluation of CAFE’s objectives, the court also considers its
15 opinion that the California regulations would disrupt the achievement of those objectives. See
16 Geier, 529 U.S. at 883. NHTSA concludes that a state carbon dioxide emission standard
17 requiring better fuel economy than the CAFE level “would upset the efforts of NHTSA to
18 balance and achieve Congress’s competing goals.” Standards for Light Trucks, 71 Fed. Reg. at
19 17,667. A state standard set above that determined by NHTSA under the statutory guidelines
20 “would negate the agency’s analysis and decisionmaking” that it arrives at “only after
21 considering extensive technical information such as detailed product information submitted by
22 the vehicle manufacturers and NAS’ report on the future of the CAFE program and conducting
23 analyses of potential impacts on employment and safety.” Id. at 17,667-68. Accordingly,

24 NHTSA concludes that it is disruptive to the orderly
25 implementation of the CAFE program, and to NHTSA’s
26 reasonable balancing of competing concerns, to have two different
27 governmental entities assessing the need to conserve energy,
28 technological feasibility, economic practicability, employment,
vehicle safety and other concerns, and making inconsistent

1 judgments made [sic] about how quickly and how much of that
 2 single pool of technology could and should be required to be
 installed consistent with those concerns.

3 Id. at 17,668. Thus, NHTSA has decided, echoing Plaintiffs' factual allegations, that such
 4 conflicting standards risk "serious adverse economic consequences for motor vehicle
 5 manufacturers and unduly limited choices for consumers." Id.

6 On a motion for judgement on the pleadings, the court accepts as true Plaintiffs' factual
 7 allegations about the effects of the California regulations. McGlinchey, 845 F.2d at 810.
 8 Defendants do not contend that Plaintiffs have failed to adequately allege facts supporting their
 9 claims that California regulations will risk higher prices, decreased choices and safety for the
 10 consumer, and decreased profitability and lost goodwill for manufacturers and dealers.⁹
 11 Defendants instead contend that Congress intended to permit the California regulations
 12 regardless of such impacts.

13 Defendants argue that California's regulations are permissible because the EPCA requires
 14 NHTSA to take such regulations into account in setting the CAFE level. The EPCA provides
 15 that NHTSA, "[w]hen deciding maximum feasible average fuel economy . . . shall consider . . .
 16 the effect of other motor vehicle standards of the Government on fuel economy" 49 U.S.C.
 17 § 32902(f). Defendants point out that the phrase "other motor vehicle standards" encompasses
 18 "California standards approved by EPA under section 209(b)." Reply 9:18-19; see EPCA § 301,
 19 89 Stat. at 905. Defendants clarify the proposition, stating that the "NHTSA is not required to
 20 consider California's standards unless EPA, another federal agency, has approved them." Reply
 21 14:27-28. Defendants further allege that the Clean Air Act requires the EPA, when deciding
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25 ⁹ In their reply brief, Defendants contend that the California regulations are
 26 consistent with the EPCA's "primary purpose": improving fuel economy. Defs.' Reply 17 n.3.
 27 They do not dispute, however, that maximizing safety, consumer choice, and the economic well-
 being of the automobile industry are also among the EPCA's goals.

whether to grant a waiver, to make determinations similar to those on which CAFE is based.¹⁰ Plaintiffs do not dispute that, under section 32902(f), NHTSA must consider regulations that receive a waiver under 209(b).

Defendants argue that when Congress adopted the EPCA in 1975, it knew that motor vehicle emission standards affect fuel economy. See H.R. Rep. No. 94-340, at 86-87, 90-91 (1975), *reprinted in* 1975 U.S.C.C.A.N. 1762, 1848-49, 1852-53. Certain California emission standards then in place decreased average fuel economy. Id. at 87. The EPCA permitted manufacturers to apply for a relaxation of the average fuel economy standard if the federal standards, including those California standards granted a waiver under section 209(b), resulted in lower fuel economy. EPCA § 301, 89 Stat. at 904-05; H.R. Rep. No. 94-340, at 90-91; see Center for Auto Safety v. NHTSA, 793 F.2d 1322, 1325 & n.12 (D.C. Cir. 1986). Defendants contend that Congress integrated section 209 standards into the EPCA by requiring NHTSA to account for “other motor vehicle standards of the Government on fuel economy” 49 U.S.C. § 32902(f).

Defendants argue that state law does not stand as an obstacle to a federal statute when the federal government “contemplates coexistence between” the two regulatory schemes, citing Skysign International v. City & County of Honolulu, 276 F.3d 1109, 1117 (9th Cir. 2002). In Skysign, the Ninth Circuit considered whether a municipal ordinance barring aerial advertising was preempted by the FAA regulatory scheme. Id. at 1113. After deciding that FAA regulation did not preempt the field of aerial advertising, the court addressed whether conflict preemption barred the ordinance. Id. at 1117. At the outset, the court noted that, in a conflict preemption

¹⁰ Plaintiffs construed this line of argument as a contention that the EPA would only grant a waiver if it decided that the EPCA did not preempt the regulations and filed a surreply brief refuting that argument. See Pls.’ Ex Parte Mot. for Leave to File Surreply 1:7-12. Defendants disclaim making any contention that the EPA would consider whether the EPCA preempted the California regulations or consider whether the regulations affect the “goals and purposes” of the EPCA. Defs.’ Objection to Pls.’ Surreply Brief 3:12-18. Defendants concede that the EPA’s review of the regulations is limited by the criteria in section 209(b). Id. at 3:18-20.

1 analysis, “state law cannot *by its mere existence* stand as such an obstacle when the federal
2 government contemplates coexistence between federal and local regulatory schemes.” Id.
3 (emphasis added). The court was careful to qualify that the federal government, by merely
4 authorizing the states to act, did not immunize state regulations from conflict preemption
5 scrutiny: “Of course, even when the federal government has evinced its intent to leave the states
6 and localities some room in which to regulate, some local regulation may transgress those
7 boundaries by interfering with the underlying federal purposes.” Id. at 1118 n.5. The court noted
8 that the FAA had granted permission for the aerial advertisement with the explicit instruction that
9 the advertiser abide by local laws and ordinances related to aerial signs. Id. at 1117-18. The
10 FAA had also made explicit statements in public documents that its grant of permission did not
11 supercede any “local, state, or city ordinance(s) prohibiting aerial advertising.” Id. at 1118.
12 Given the FAA’s explicit deference to local ordinances prohibiting aerial advertising, the court
13 concluded that the ordinance at issue did not “impede the federal policy or purpose” of the FAA
14 permission scheme. Id.

15 Defendants’ reliance on Skysign is misplaced. It does not stand for the proposition that
16 state law does not stand as an obstacle whenever the federal government contemplates the
17 coexistence between federal and state regulatory schemes. See id. at 1117-18 & n.5. The
18 holding is much more circumscribed, requiring courts to look beyond the mere fact that federal
19 and state regulations coexist and to analyze the extent the state law “interfer[es] with the
20 underlying federal purposes.” Id. at 1118 n.5. Here, unlike in Skysign, NHTSA has not
21 expressly or impliedly claimed that the California regulations are permissible or can be
22 harmonized with the EPCA scheme. Instead NHTSA has explicitly found that the challenged
23 regulations would disrupt the CAFE program. See Standards for Light Trucks, 71 Fed. Reg. at
24 17,668.

25 Defendants also cite in support Merrill Lynch, Pierce, Fenner & Smith, Inc. v. Ware, 414
26 U.S. 117, 126 (1973). The Court in that case emphasized the value of protecting “the sensitive
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interrelationship” between federal and state regulation of securities. Id. at 126-27. Nevertheless, the Court held that conflicting state law was preempted “to the extent necessary to protect the achievement of the aims” of the federal regulatory scheme.¹¹ Id. at 127.

Neither Skysign or Merrill Lynch stands for the proposition that congressional authorization of a state regulation immunizes it from a conflict preemption challenge. Rather, each requires an analysis of whether the state regulation, even if authorized, is an obstacle to the objectives of the federal scheme. Skysign, 276 F.3d at 1118 n.5; Merrill Lynch, 414 U.S. at 127.

Defendants contend that the EPCA and regulations that receive an EPA waiver under section 209(b) comprise “an overlapping federal scheme.” Defs.’ Reply 14:27-15:3. They point out that the EPA under the Clean Air Act, like NHTSA pursuant to the EPCA, considers the technological feasibility and economic practicability of emission standards. Defendants note that the EPA, when scheduling implementation of regulations that have received a waiver, allows such a regulation to take effect only “after such period as the Administrator finds necessary to permit the development and application of the requisite technology, giving appropriate consideration to the cost of compliance within such period.” 42 U.S.C. § 7521(a)(2).

Nothing in the statutory language or the legislative history of the Clean Air Act, the EPCA, or any other statute before the court indicates Congress’s intent that an EPA waiver would allow a California regulation to disrupt the CAFE program. Section 209(b) provides only that the waiver exempts the regulations from express preemption under section 209(a). See 42 U.S.C. § 7543(b)(1). (“The Administrator shall, after notice and opportunity for public hearing, waive application of *this section* . . .” (emphasis added)). On its face, the language does not endorse regulations that present obstacles to the objectives of the EPCA, nor do the criteria considered by EPA in granting a waiver ensure that such interference will not occur.

¹¹ Merrill Lynch appears to suggest that when possible, the state statute should be preempted only to the extent that it stands as an obstacle to the federal schemes goals. 414 U.S. at 127. Defendants do not argue that some severable portion of the California regulations does not impede achieving the EPCA’s goals.

1 Section 209(b) does not provide that the regulations, once EPA grants a waiver, become
2 federal law and are thereby rendered immune from preemption by other federal statutes.
3 Defendants point out that compliance with state standards that have been granted a waiver is
4 treated as compliance with federal standards, giving them federal status. 42 U.S.C. § 7543(b)(3).
5 However, the sentence to which Defendants refer indicates that “compliance with such State
6 standards shall be treated as compliance with applicable Federal standards *for purposes of this*
7 *subchapter.*” *Id.* (emphasis added). Section 177 demonstrates that Congress also gave narrow
8 effect to other states’ adoption of regulations that receive a waiver. See 42 U.S.C. § 7507
9 (providing that “[n]otwithstanding section 7543(a) of this title,” the Clean Air Act’s express
10 preemption provision, other states may adopt standards identical to California’s (emphasis
11 added)). Hence, the statutory language explicitly disclaims any special status for the California
12 regulations under other federal statutes. The legislative history generally emphasizing the
13 breadth of California’s discretion upon receiving an EPA waiver does not provide any reason to
14 believe that the resulting regulations could stand as an obstacle to other federal schemes. See,
15 e.g., H.R. Rep. No. 95-294, at 301-02 (1977), *reprinted in* 1977 U.S.C.C.A.N. 1077, 1380-81.

16 The language of the EPCA also does not evince an intent to permit state regulations that
17 conflict with the goals of its scheme. The requirement that the Secretary “shall consider” the
18 effect of the California regulations does not indicate congressional intent to permit regulations
19 that are obstacles to the EPCA’s goals, such as ensuring vehicle safety, the economic health of
20 the industry, and consumer choice. See 42 U.S.C. § 32902(f). The parties do not discuss in
21 depth the effect of the term “consider” in the language of section 32902(f). Defendants appear to
22 read into this language a mandate that the EPCA accommodate other regulations, including those
23 granted an EPA waiver. See also Defs.’ Mot. 21:16-17 (asserting that “Congress has required
24 that NHTSA *respect* California emission standards when establishing fuel economy standards”
25 (emphasis added)). At oral argument, Defendants contended that requiring NHTSA to consider
26 the California regulations made them “part of EPCA.” Defendants urge that the requirement that
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1 NHTSA consider the California regulations amounts to Congressional authorization of such
2 regulation, regardless of their effects on the EPCA's goals.

3 However, a congressional requirement that a decision maker "consider" a factor does not
4 deserve the weight than Defendants place on it. Congress's use of the term "consider" in a
5 statute requires an actor to merely "investigate and analyze" the specified factor, but not
6 necessarily act upon it. City of Davis v. Coleman, 521 F.2d 661, 679 (9th Cir. 1975); J.H. Miles
7 & Co., Inc. v. Brown, 910 F. Supp. 1138, 1156 (E.D. Va. 1995) (regulation requiring federal
8 fishing officials to "consider" a statutory factor in setting fishing quota recommendations was not
9 a "strict dictate" and suggested officials had "some discretion" in preparing their
10 recommendation); T.S. v. Ridgefield Bd. of Educ., 808 F. Supp. 926, 931 (D. Conn. 1992)
11 (requirement under Individuals with Disabilities Education Act ("IDEA") that an independent
12 educational evaluation "must be considered" was met where an individual who reviewed the
13 evaluation read an summarized portions at a school meeting); G.D. v. Westmoreland Sch. Dist.,
14 930 F.2d 942, 947 (1st Cir.1991) (report "considered" under IDEA where it was reviewed at a
15 meeting). The language of section 32902(f) merely requires NHTSA to investigate and analyze
16 what effect the "other" regulations will have on fuel economy.

17 These definitions of "consider" comport with NHTSA's interpretation of section
18 32902(f). Responding to suggestions that the provision prevents preemption, NHTSA concluded
19 that the "EPCA's decisionmaking factor provision is neither a saving clause nor a waiver
20 provision. . . . The agency interprets that provision only to direct NHTSA to consider those State
21 standards that can otherwise be validly adopted and enforced under State and Federal law."
22 Standards for Light Trucks, 71 Fed. Reg. at 17,669. After having investigated and analyzed all of
23 the required factors, the agency is free to set the maximum feasible average fuel economy based
24 on all of the information properly before it. Even if one objective of EPCA is to set fuel
25 economy standards in a manner that takes into account the effects of California standards
26 receiving a waiver, this does not evince Congress's intent that such a standard is permitted to

1 impair the achievement of the EPCA's other objectives. See Geier, 529 U.S. at 885. The court
 2 sees no reason to interpret Congress's directive as to which information NHTSA must consider
 3 as permission for a state law to disrupt the objectives of the EPCA. Nor do Defendants cite any
 4 legislative history that furthers its reading of the "shall consider" language of section 32902(f).

5 Because nothing before the court evinces Congress's intent to permit California
 6 regulations that stand as an obstacle to the EPCA's objectives, Plaintiffs have stated a claim for
 7 EPCA preemption and the court will not grant judgment on the pleadings on this cause of action.

8 **B. Clean Air Act Preemption**

9 Plaintiffs contend that the California regulations are preempted by section 209(a) of the
 10 Clean Air Act, 42 U.S.C. § 7543(a). Section 209(a) provides that a state may not "adopt or
 11 attempt to enforce any standard relating to the control of emissions from new motor vehicles or
 12 new motor vehicle engines subject to this part." Id. Meanwhile, section 209(b) provides a means
 13 for the EPA to waive the prohibition under section 209(a) provided it makes certain findings. 42
 14 U.S.C. § 7543(b).

15 Defendants do not contend that, under section 209(a), the challenged regulations are not
 16 a "standard relating to the control of emissions from new motor vehicles." 42 U.S.C. § 7543(a).
 17 Accordingly, the regulations are preempted unless the EPA issues a waiver under section 209(b).
 18 42 U.S.C. § 7543(b). Defendants ask the court to enter judgment on the pleadings in their favor
 19 on this claim on the basis that "Plaintiffs and Plaintiff-intervenor have virtually abandoned their
 20 principal Clean Air Act claim." Defs.' Reply 4:4-5. Defendants point out that Plaintiffs have not
 21 challenged their contentions that the Clean Air Act authorizes the regulation of greenhouse gas
 22 emissions as pollutants or that the EPA has the authority to issue California a waiver. Accepting
 23 these arguments, however, does not mean that the regulations are subject to a waiver under
 24 section 209(b).¹² The EPA can still deny a waiver on the basis of a factual finding that the

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 26 ¹² In the alternative, Defendants ask the court to enter judgment against Plaintiffs'
 27 contention that the "EPA may not issue a waiver under section 209(b)(1)(C)." Defs.' Reply
 28 4:11-13. At oral argument, Defendants proposed that the court also decide at this stage that

1 regulations are not needed to meet “compelling and extraordinary conditions.”¹³ 42 U.S.C.
 2 § 7543(b)(1)(B).

3 In any event, the EPA has not waived 209(a) preemption with respect to the California
 4 regulations. Nothing in the Plaintiffs’ FAC, the Plaintiff-intervenor’s complaint, or in any other
 5 part of the record justifies granting judgment on the pleadings by speculating that the EPA will
 6 make a future factual finding that favors Defendants, the moving parties. Thus, Defendants’
 7 motion for judgment on the pleadings on this cause of action must be denied.

8 **C. Conflict with United States Foreign Policy**

9 It is beyond dispute that “at some point an exercise of state power that touches on foreign
 10 relations must yield to the National Government’s policy.” Am. Ins. Ass’n v. Garamendi, 539
 11 U.S. 396, 413 (2003). After all, it was out of “concern for uniformity in this country’s dealings
 12 with foreign nations” that the Constitution allocated the foreign relations power to the federal
 13 government. Id. (quoting Banco Nacional de Cuba v. Sabbatino, 376 U.S. 398, 427, n.25
 14 (1964)). The “executive power” vested in Article II of the Constitution provides the President
 15 the “vast share of responsibility for the conduct of our foreign relations.” Youngstown Sheet &
 16 Tube Co. v. Sawyer, 343 U.S. 579, 610-11 (1952) (Frankfurter, J., concurring). “While Congress
 17 holds express authority to regulate public and private dealings with other nations in its war and
 18 foreign commerce powers, in foreign affairs the President has a degree of independent authority
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20 EPA’s authority extends regulation of greenhouse gases. Defendants urge that such holdings are
 21 proper under the rule that a motion to dismiss “may be granted as to part of a complaint and
 22 denied as to the remainder.” See Decker v. Massey-Ferguson, Ltd., 681 F.2d 111, 115 (2d Cir.
 23 1982) (affirming the dismissal of certain claims against defendants and reversing the district
 24 court’s dismissal of other claims). Here, the court has concluded Plaintiffs have stated a claim
 for preemption under the Clean Air Act, regardless of whether the EPA has the power to issue a
 waiver authorizing the California regulations. Accordingly, the court declines at this stage to
 decide the scope of the EPA’s power.

25 ¹³ AIAM’s complaint explicitly alleges that no factual basis exists for such a finding.
 26 AIAM Compl. ¶ 62. As Judge Coyle decided in his order of October 21, 2005, the issue before
 27 the court on the Clean Air Act claim is whether section 209(a) preemption applies, not whether
 the EPA will deem a waiver of the California regulations appropriate under section 209(b)
 criteria, such as whether “compelling and extraordinary conditions” justify the regulations.

1 to act.” Garamendi, 539 U.S. at 414.

2 In Garamendi, the Supreme Court addressed whether California’s Holocaust Victim
3 Insurance Relief Act of 1999 (“HVIRA”) was preempted because it interfered with the federal
4 government’s conduct of foreign relations. Id. at 401. HVIRA required insurers doing business
5 in California to disclose details of any insurance policies issued in Europe between 1920 and
6 1945, which would be made public through a central registry. Id. at 409-10. Around the time
7 that the legislation was passed, President Clinton was attempting to negotiate with the German
8 government to develop a coordinated approach to these claims. Id. at 405. In 2000, President
9 Clinton and German Chancellor Schroder signed the German Foundation Agreement, in which
10 Germany agreed to enact legislation establishing a foundation funded by the German government
11 and German industry to compensate those injured by German companies during the Nazi era. Id.
12 In exchange, the President promised to attempt to shield Germany from litigation by filing
13 Statements of Interest in the courts, encouraging judges to defer to Foundation procedure. Id. at
14 406. Both nations also agreed that the Foundation would work with the International
15 Commission on Holocaust Era Insurance Claims to establish procedures for handling claims. Id.
16 at 407.

17 The Garamendi Court, in determining whether HVIRA was preempted under the foreign
18 affairs doctrine, considered its analysis of an Oregon probate statute in Zschernig v. Miller, 389
19 U.S. 429 (1968). The statute in Zschernig “prohibited inheritance by a nonresident alien, absent
20 showings that the foreign heir would take the property ‘without confiscation’ by his home
21 country and that American citizens would enjoy reciprocal rights of inheritance there.” Id. at
22 417. In practice, the statute encouraged state judges in Oregon probate proceedings to disparage
23 foreign governments and express anticommunist views. Id. Accordingly, the majority struck
24 down the statute because it “impair[ed] the effective exercise of the Nation’s foreign policy.” Id.
25 at 440. The majority concluded that the statute had “a direct impact upon foreign relations” and
26 potentially would “adversely affect the power of the central government to deal with those
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problems.” Id. at 441. In a concurring opinion, Justice Harlan interpreted past Supreme Court jurisprudence as establishing that “in the absence of a conflicting federal policy or violation of the express mandates of the Constitution the States may legislate in areas of their traditional competence even though their statutes may have an incidental effect on foreign relations.” Id. at 458-59 (Harlan, J., concurring).

In Garamendi, the Court decided that the majority’s and Justice Harlan’s opinions in Zschernig represented “contrasting theories of field and conflict preemption.” Garamendi, 539 U.S. at 419. The Court declined to decide which approach is correct. Id. at 419-20. Instead, the Court found that HVIRA was preempted under either approach because it would “produce something more than incidental effect in conflict with express foreign policy of the National Government.” Id. at 420. In deciding the propriety of state legislation in an areas of “their traditional competence,” the Court noted that under Justice Harlan’s view it is reasonable to “consider the strength of the state interest, judged by standards of traditional practice.”¹⁴ Id.

The parties dispute the current administration’s approach to reductions of greenhouse gas emissions. Plaintiffs focus on language in an EPA report describing the current administration’s greenhouse gas emissions strategy:

Unilateral EPA regulation of motor vehicle GHG emissions could also weaken U.S. efforts to persuade key developing countries to reduce the GHG intensity of their economies. Considering the large populations and growing economies of some developing countries, increases in their GHG emissions could quickly overwhelm the effects of GHG reduction measures in developed countries. Any potential benefit of EPA regulation could be lost to the extent other nations decided to let their emissions significantly increase in view of U.S. emission reductions. Unavoidably, climate change raises important foreign policy issues, and it is the President’s prerogative to address them.

¹⁴ The Court also suggested, but did not adopt, a complementary application of Justice Harlan’s and the Zschernig majority’s approach. Garamendi, 539 U.S. at 419 n.11. Such an approach would call for field preemption when the state legislation addressed a matter that was not a “traditional state responsibility.” Id. On the other hand, a court should strike down legislation within the state’s “traditional competence” only upon a finding of a conflict with foreign affairs of sufficient “clarity or substantiality” based on “the strength or the traditional importance of the state concern asserted.” Id.

1 Control of Emissions, 68 Fed. Reg. at 52,931 (footnote omitted).¹⁵ The report goes on to
2 conclude that “the President’s policy emphasizes international cooperation and promotes
3 working with other nations to develop an efficient and coordinated response to global climate
4 change.” *Id.* at 52,933. Plaintiffs allege that the implementation of the California regulations
5 “interferes with the ability of the United States to speak with one voice upon matters of global
6 climate change” and “diminishes the bargaining power of the United States in negotiating
7 multilateral reductions of greenhouse gases.” FAC ¶ 130.

8 Plaintiffs also cite the opinion of a district court dismissing claims seeking to abate
9 greenhouse gas emissions on a public nuisance theory as nonjusticiable political questions. *See*
10 *State of Connecticut v. Am. Elec. Power Co.*, 406 F. Supp. 2d 265 (S.D.N.Y. 2005). In
11 determining the Executive Branch’s current approach to greenhouse gas reduction, the court
12 considered the reluctance of Congress and the Executive Branch to impose formal limits on such
13 emissions. *Id.* at 269-70. It noted that Congress has focused its efforts toward researching the
14 effect of emissions, for instance, through the National Climate Program Act of 1978, 15 U.S.C.
15 § 2901 *et seq.*, and the Global Change Research Act, 15 U.S.C. §§ 2931-2938. *Id.* at 269. The
16 court also mentioned that President H. W. Bush had signed, and the senate ratified, the United
17 Nations Framework Convention on Climate Change (“UNFCCC”), “which brought together a
18 coalition of countries to work toward a coordinated approach to address the international issue of
19 global warming.” *Id.* UNFCCC member nations, and President Clinton, signed the Kyoto
20 Protocol, which called for mandatory reductions in greenhouse gas emissions. *Id.* The court
21 recognized, however, that the Senate did not approve the Protocol, rather voting 95-0 in the so-
22 called Byrd-Hagel resolution to “urge the President not to sign any agreement that would result in
23 serious harm to the economy or that did not include provisions regarding the emissions of

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25 ¹⁵ Defendants contend that, if the Supreme Court ultimately decides that the EPA
26 may not consider the effect of a state regulation on foreign affairs when it grants a waiver, then
27 Plaintiffs foreign policy preemption claim fails. Regardless of the Supreme Court’s ultimate
holding on this issue, the statement remains an expression by an executive agency of the
President’s foreign policy strategy.

1 developing nations.” Id. (citing S. 98, 105th Cong. (1997)). Congress subsequently passed
2 legislation barring the EPA from implementing the protocol. Id. (citing Pub. L. No. 105-276,
3 112 Stat. 2461, 2496 (1998); Pub. L. No. 106-74, 113 Stat. 1047, 1080 (1999); Pub. L. No.
4 106-377, 114 Stat. 1441, 1441A-41 (2000)). The court then considered President George W.
5 Bush’s opposition to the Protocol based on its exemption of developing nations, its failure to
6 address two major pollutants, and its negative impact on the United States. Id. The court
7 concluded by citing the EPA report’s focus on “international cooperation” and “coordinated
8 response” as an expression of “the policy of the current administration.” Id. at 270 (citing
9 Control of Emissions, 68 Fed. Reg. at 52,933).

10 The recent cases in which the Supreme Court has held that a state statute is preempted
11 based on United States foreign affairs concern an executive agreement or federal statute with
12 which the state legislation conflicts. See Garamendi, 539 U.S. at 421 (focusing preemption
13 inquiry on “the national position, expressed unmistakably in the executive agreements signed by
14 the President”); Crosby v. Nat’l Foreign Trade Council, 530 U.S. 363, 375-76 (2000)
15 (considering whether the challenged state law “might . . . blunt the consequences” of actions
16 available to the President pursuant to a federal statute). Here, Plaintiffs do not contend that the
17 United States’ opposition to unilateral greenhouse gas emission or its pursuit of negotiated
18 reductions is embodied in any particular executive agreement or federal statute. Rather,
19 Plaintiffs point to Executive Branch statements, the absence of national greenhouse gas
20 regulations, and the Senate’s rejection of binding emissions reductions in the Byrd-Hagel
21 resolution to establish the nature of present United States policy.

22 Plaintiffs contend that the Byrd-Hagel resolution amounts to “implied authorization” of
23 the administration’s position on negotiating emissions reductions under Youngstown. 343 U.S. at
24 635. In Youngstown, the Court held that “[w]hen the President acts pursuant to an express or
25 implied authorization of Congress, his authority is at its maximum, for it includes all that he
26 possesses in his own right plus all that Congress can delegate.” Id. Plaintiffs point out that
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1 recent Supreme Court authority provides that the scope of the President's power under
2 Youngstown determines the scope of foreign policy preemption. See Garamendi, 539 U.S. at
3 414; Crosby, 530 U.S. at 375.

4 The Byrd-Hagel resolution expressed the Senate's opposition to any protocol to or other
5 agreement regarding the UNFCCC that would:

6 (A) mandate new commitments to limit or reduce greenhouse gas
7 emissions for the Annex I Parties, unless the protocol or other
8 agreement also mandates new specific scheduled commitments to
9 limit or reduce greenhouse gas emissions for Developing Country
10 Parties within the same compliance period, or

11 (B) would result in serious harm to the economy of the United
12 States; . . .

13 S. 98, 105th Cong. (1997). While the resolution appears to speak as to what the sort of
14 agreements the Senate refuses to support, it also appears to implicitly support a Presidential
15 approach of negotiating reciprocal emissions reductions with other nations.

16 Defendants contend that the Byrd-Hagel resolution has been countermanded by a more
17 recent one, the Bingaman-Domenici resolution, calling for binding limits "on emissions of
18 greenhouse gases that slow, stop, and reverse the growth of such emissions" and that "will
19 encourage comparable action by other nations." 151 Cong. Rec. S7033 (daily ed. June 22, 2005).
20 While this later resolution expresses the Senate's sense that Congress should enact mandatory
21 emissions limits, it does not contravene the Byrd-Hagel resolution's approach to international
22 agreements. Moreover, the Bingaman-Domenici resolution does not speak to the President's
23 authority to forge international agreements, as the Byrd-Hagel resolution did. The Senate's mere
24 statement of its own intent to impose limits does not itself interfere with or express disapproval
25 of the President's efforts to negotiate limits with other countries. In any event, the Bingaman-
26 Domenici resolution does not divest the President of his "independent authority to act" on
27 matters of foreign affairs. Garamendi, 539 U.S. at 414.

28 Even if the President lacks the Senate's endorsement of his negotiation-based approach to

1 greenhouse gas emissions, he nonetheless can act pursuant to certain independent powers of his
2 office. See Youngstown, 343 U.S. at 637. In Garamendi, the Supreme Court acknowledged that
3 Presidential action pursuant to such “independent authority” in foreign affairs, such as making an
4 executive agreement, could preempt interfering state laws. 539 U.S. at 414-15, 424 n.14 (noting
5 that “the President in this case is acting without express congressional authority,” but, because
6 “the President possesses considerable independent constitutional authority to act on behalf of the
7 United States on international issues, . . . conflict with the exercise of that authority is a
8 comparably good reason to find preemption of state law”). If the President were to negotiate
9 with another nation or nations to agree to reduce greenhouse gas emissions, such an action would
10 not be “incompatible” with the Senate’s will as expressed in the Bingaman-Domenici resolution
11 to obtain mandatory emissions reductions so as to place “his power is at its lowest ebb.” See
12 Youngstown, 343 U.S. at 637. Rather, an agreement to so reduce emissions would apparently
13 further the Senate’s expressed goals of ameliorating the risks associated with such emissions.

14 The Supreme Court cases do not suggest that the absence of a statute or an executive
15 agreement is fatal to a foreign policy preemption claim. In fact, the Court’s analysis suggests that
16 such a claim is permissible. In Garamendi, though the Court addressed the preemptive effect of
17 an executive agreement, it recognized a general “executive authority to decide what that policy
18 should be” as well as authority to act independently of Congress. 539 U.S. at 414. In the field of
19 foreign policy, the President has the “lead role,” which makes it appropriate to give weight to
20 policy statements by Executive Branch officials to determine that policy. Id. at 422 & n.12
21 (considering statements of Executive Branch officials, in addition to executive agreements, to
22 determine the nature of United States foreign policy). If Executive Branch statements are
23 competent evidence of what our foreign policy is, the court sees no reason to limit preemption to
24 foreign policy as expressed in statutes or executive agreements.

25 In Crosby, the Supreme Court has preempted state law based on its potential to interfere
26 with future discretionary actions within the President’s foreign policy power. 530 U.S. at 377
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(finding preemption where state statute “undermin[ing] the President’s intended statutory authority by making it impossible for him to restrain fully the coercive power of the national economy when he may choose to take the discretionary action open to him”). In Crosby, even though the President’s discretionary powers derived from a statute, the Court did not foreclose the potential preemption of a state statute interfering with a Presidential foreign policy option on which he has not yet acted. Id. Thus, so long as the President is empowered to act to benefit United States foreign policy interests, whether through express or implied congressional authorization or through his independent authority, a state statute that excessively interferes with an action “he may choose to take” in furtherance of that interest may be preempted. See id.

Defendants contend that the UNFCCC evidences a United States policy of unilateral reductions of greenhouse gas emissions, contrary to the EPA’s account of current policy. Defendants contend that signing on to the UNFCCC committed the United States to unilaterally decrease its greenhouse gas emissions:

Each of these Parties shall adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs. These policies and measures will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions

Defs.’ RJN Ex. D at 12. Defendants point out that the UNFCCC signatories agreed to take the lead acknowledging that, as developed countries, they were responsible for the “largest share of historical and current” greenhouse gas emissions. Id. at 2. Defendants contend that the UNFCCC obligates the United States to refrain from activities that might damage the environment beyond its borders, to “protect the climate system,” and to take precautions to “anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects.” Defs.’ RJN Ex. D at 2, 9.

Defendants assert that the CAFE program under the EPCA belies Plaintiffs contention that United States policy is to eschew unilateral greenhouse gas regulation. In support,

1 Defendants quote the allegation in the FAC that “[b]y setting fuel economy standards, the
2 national government has regulated the level of greenhouse gases released by cars and trucks sold
3 in this country.” FAC ¶ 4. Plaintiffs respond that the CAFE program’s fuel economy regulations
4 only functionally regulate greenhouse gas emissions to achieve the ends specified in the EPCA,
5 which was enacted before climate change became a significant issue. Plaintiffs distinguish the
6 indirect carbon dioxide emission restrictions inherent in fuel economy from “more direct
7 regulation” of greenhouse gases, which the administration has decided to undertake through
8 multilateral agreements. Pls.’ Opp’n at 63 n.46. That the CAFE program affects carbon dioxide
9 emissions does not contradict Plaintiffs contention that current Executive Branch policy is to
10 negotiate carbon dioxide reductions with other nations. The CAFE program very well might
11 constrain the sort of agreement that the President might make to the extent a proposed agreement
12 was inconsistent with Congress’s intent in enacting the EPCA. See Youngstown, 343 U.S. at
13 637. Nevertheless, a policy of seeking out such agreements is not logically or practically
14 inconsistent with the CAFE program.

15 Defendants also cite statements by members of the State Department implying that the
16 current administration does not intend to negotiate greenhouse gas limits with developing
17 nations. Defendants provide a transcript of remarks of Dr. Harlan L. Watson, “Senior Climate
18 Negotiator and Special Representative and Alternate Head of the U.S. Delegation, Montreal,
19 Canada,” on November 29, 2005. Defs.’ RJN Ex. E. Defendants cite language from this
20 document in support of their characterization of United States policy: “the United States is
21 opposed to any such discussions under the Framework Convention. . . . We see no change in
22 current conditions that would result in a negotiated agreement consistent with the U.S.
23 approach. . . . We are not a party to the Kyoto Protocol and we do not support any such approach
24 under the Convention for future commitments.” Mot. 29:27-30:3 (citing Defs.’ RJN Ex. E).
25 Watson appears to only be discussing the United States’ opposition to certain types of
26 negotiations, specifically negotiations by the parties to the Kyoto Protocol targeted at agreeing to
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1 a “second commitment period” beginning in 2013. Defs.’ RJN Ex. E at 2. These remarks,
2 therefore, are merely reiterating that the administration opposes binding limits modeled on the
3 Kyoto approach, not that it opposes a negotiated strategy based on reciprocal greenhouse gas
4 reductions.

5 Other parts of Watson’s remarks leave open the possibility for negotiations outside of the
6 Kyoto mold. Watson points out that currently, “through bilateral and U.S.-led multilateral
7 partnerships with nearly all major developed and developing countries, we are leading a global
8 approach to achieving our shared commitments to address climate change.” Id. at 1. Dr. Watson
9 goes on to state that the United States “need[s] to pursue our international efforts in a spirit of
10 collaboration, not coercion, and with a true sense of partnership. This is especially true in our
11 relations with developing nations, which have an imperative to grow their economies and provide
12 for the welfare of their citizens.” Id. at 2.

13 Defendants’ position regarding United States foreign policy does not gain support from
14 the press briefing of Dr. Paula Dobriansky, Under Secretary of State, on December 7, 2005. See
15 Defs.’ RJN Ex. F. She expresses the same skepticism as Watson about the potential for success
16 of formalized discussions under the “Canadian proposal.” Id. at 2. Dobriansky, speaking of the
17 use of bilateral and multilateral partnerships to achieve climate change, stated that “the best way
18 forward is through different and diversified approaches that leverage these critical partnerships.”
19 Id. at 1. Dobriansky does not enunciate a United States policy of shunning negotiations with
20 developing nations regarding greenhouse gas emissions.

21 Defendants argue that, even if the California regulations interfere with the
22 administration’s policy to pursue international agreements regarding greenhouse gas emissions,
23 they cannot be preempted in light of that policy because they have been authorized by Congress.
24 In support, Defendants cite a case concerning California tax laws that were allegedly harmful to
25 United States foreign policy goals. Barclays Bank PLC v. Franchise Tax Bd., 512 U.S. 298
26 (1994). The California tax law called for a “worldwide combined reporting” method for certain
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1 multinational enterprises. Id. at 302. For three decades, Congress had been aware that foreign
2 governments were displeased with such requirements. Id. at 324. On many occasions, Congress
3 had studied state taxation of multinational enterprises and introduced numerous bills on the
4 subject. Id. at 324-25. On each occasion, Congress declined to bar the worldwide combined
5 reporting approach. Id. at 325. The Court concluded that Congress “implicitly has permitted the
6 States to use the worldwide combined reporting method.” Id. at 326.

7 Defendants contend that here Congress has explicitly granted California the power to
8 implement emissions regulations under section 209 of the Clean Air Act, providing an even
9 stronger case against preemption than the implicit permission the Supreme Court found in
10 Barclays. Defendants are hard-pressed, however, to show that section 209 demonstrates
11 Congress’s intent to permit California to implement emissions regulations even if they interfere
12 with foreign policy goals. Defendants do not contend that, as was the case in Barclays, Congress
13 has known for decades that California would impose carbon dioxide regulations that potentially
14 interfere with international greenhouse gas negotiations and has declined opportunities to
15 foreclose that approach. Presumably, Congress would not be required to draft section 209 so as
16 to explicitly preclude emissions regulations that interfere with United States foreign policy, as it
17 could rely on well-established preemption doctrine to bar such regulations. See Crosby, 530 U.S.
18 at 387-88 (“A failure to provide for preemption expressly may reflect nothing more than the
19 settled character of implied preemption doctrine that courts will dependably apply . . .”).

20 In Garamendi, the Supreme Court discussed the effect of the McCarran-Ferguson Act, 15
21 U.S.C. §§ 1011-1015, on the foreign policy preemption analysis of California’s HVIRA
22 legislation. 539 U.S. at 427-29. The Court interpreted the McCarran-Ferguson Act as limiting
23 congressional preemption under the commerce power. Id. at 428. The Court concluded,
24 nevertheless, that “a federal statute directed to implied preemption by domestic commerce
25 legislation cannot sensibly be construed to address preemption by executive conduct in foreign
26 affairs.” Id. The scope of the section 209(b) waiver seems no broader than the McCarran-

1 Ferguson Act's authorization of state regulation of insurance. Section 209(b) merely provides
2 that the explicit preemption under section 209(a) of any state motor vehicle emissions shall not
3 apply if the EPA properly grants a waiver. 42 U.S.C. § 7543(b). Defendants have pointed to no
4 basis, either in the language or legislative history of the statute, to believe that Congress, in
5 providing for a section 209(b) waiver, contemplated the effects of California emissions
6 regulations on foreign policy and intended endorse such regulations even when they interfered
7 with foreign policy goals.

8 Defendants do not contend that Plaintiffs, in alleging that the California regulations will
9 impair the President's leverage in pursuing multilateral agreements, have failed to allege
10 sufficient interference with United States foreign policy, should such a policy exist. Instead,
11 Defendants assert that preemption is only appropriate where the state statute concerns "laws or
12 conduct of foreign governments" or "foreign businesses." Defs.' Reply 22:5-6. Defendants
13 point out that the Supreme Court cases finding preemption concern state laws targeting foreign
14 entities. See Zschernig, 389 U.S. at 430-31, 440 (probate statute affecting the rights of
15 nonresident aliens and requiring a judicial evaluation that resulted in criticism foreign
16 governments); Crosby, 530 U.S. at 376 (statute exerting economic pressure on the Burmese
17 political regime); Garamendi, 539 U.S. at 423-24 (disclosure requirements designed to apply
18 economic pressure to insurance companies that did business in Europe during World War II).

19 Defendants focus on language in Garamendi that they assert precludes preemption of a
20 generally applicable domestic regulation: "[Q]uite unlike a generally applicable 'blue sky' law,
21 HVIRA effectively singles out only policies issued by European companies, in Europe, to
22 European residents, at least 55 years ago." Garamendi, 539 U.S. at 425-26. Reading this
23 sentence in context, however, indicates that it does not evince the Court's intent to exclude
24 generally applicable laws from conflict preemption. Id. Rather, the sentence comes in the
25 context of an analysis of the degree of the state's interest in enforcement of the statute. Id. at
26 425. The state had contended that the statute's disclosure requirements merely facilitated

1 evaluating corporate reliability. Id. at 425-26. The Court found that the statute's limitation of
 2 the disclosure requirement to certain companies' sales to certain types of customers "raises great
 3 doubt" as to the validity of the state's expressed purpose. Id. at 426. In other words, because
 4 HVIRA's disclosure requirements were not generally applicable, the Court questioned their
 5 furtherance of the state's interests in corporate reliability. Id. The Court did not speak to
 6 whether preemption generally turned on the breadth of the state regulation.

7 Nothing in the Supreme Court's foreign policy preemption jurisprudence forecloses the
 8 possibility of preemption of a generally applicable law that interferes with foreign policy. The
 9 focus is on whether the practical effect of the state law is to disturb foreign relations or impair a
 10 proper exercise of Presidential authority. See Crosby, 530 U.S. at 375; Zschernig, 389 U.S. at
 11 440. Plaintiffs have demonstrated that current Executive Branch policy is to negotiate with other
 12 nations to reach agreements regarding greenhouse gas emissions reductions. They have alleged
 13 that the California regulations, by unilaterally reducing such emissions, potentially undercut the
 14 Executive's ability to pursue such agreements. Accordingly, Plaintiffs have stated a claim for
 15 preemption of the regulations based on foreign policy.

16 **D. Dormant Commerce Clause**

17 By its terms, the Commerce Clause authorizes Congress to "regulate Commerce . . .
 18 among the several States." U.S. Const., art. 1, § 8, cl. 3. The Supreme Court has interpreted the
 19 clause to prohibit states from unduly interfering with interstate commerce absent congressional
 20 permission. See, e.g., Raymond Motor Transp., Inc. v. Rice, 434 U.S. 429, 441 (1978); Pike v.
 21 Bruce Church, Inc., 397 U.S. 137, 142 (1970). The Commerce Clause does not prohibit every
 22 exercise of state power that affects interstate commerce. Gravquick A/S v. Trimble Navigation
 23 Int'l, 323 F.3d 1219, 1224 (9th Cir. 2003). This is because, "[i]f the law 'regulates
 24 even-handedly to effectuate a legitimate local public interest, and its effects on interstate
 25 commerce are only incidental,' then the statute must be upheld 'unless the burden imposed on
 26 such commerce is clearly excessive in relation to the putative local benefits.'" Id. (quoting Pike,

1 397 U.S. at 142).

2 Plaintiffs' Dormant Commerce Clause claim does not allege that California's regulations
3 discriminate against out-of-state interests or directly regulate interstate commerce. See
4 Brown-Forman Distillers Corp. v. N.Y. State Liquor Auth., 476 U.S. 573, 579 (1986); NCAA v.
5 Miller, 10 F.3d 633, 638 (9th Cir. 1993). Instead, Plaintiffs allege that the regulations are
6 impermissible because they burden "the production and sale of new motor vehicles" while
7 providing "no local environmental benefit, or insubstantial benefits at best." FAC ¶¶ 135, 136.

8 Defendants argue that, if the EPA grants the California regulations a waiver, they cannot
9 violate the Dormant Commerce Clause because they will have been congressionally authorized.
10 Because the Commerce Clause is a grant of authority to Congress, it does not restrict Congress's
11 authority to regulate interstate commerce as it sees fit. W. & S. Life Ins. Co. v. State Bd. of
12 Equalization, 451 U.S. 648, 652 (1981). Accordingly, Congress may authorize states to restrict
13 the flow of interstate commerce in a manner that they would not otherwise enjoy. Id. "If
14 Congress ordains that the States may freely regulate an aspect of interstate commerce, any action
15 taken by a State within the scope of the congressional authorization is rendered invulnerable to
16 Commerce Clause challenge." Id. at 652-53; White v. Mass. Council of Constr. Employers, 460
17 U.S. 204, 213 (1983) ("Where state or local government action is specifically authorized by
18 Congress, it is not subject to the Commerce Clause even if it interferes with interstate
19 commerce."). The Supreme Court has set a rigorous standard for finding congressional intent to
20 authorize state laws that violate the Commerce Clause. "Congress must be 'unmistakably clear'
21 before we will conclude that it intended to permit state regulation which would otherwise violate
22 the dormant Commerce Clause." C&A Carbone, Inc. v. Town of Clarkstown, 511 U.S. 383, 408
23 (1994) (O'Connor, J., concurring) (quoting South-Central Timber Dev., Inc. v. Wunnicke, 467
24 U.S. 82, 91 (1984)). Courts may look to the language of the relevant statute and the legislative
25 history to find this intent. Sporhase v. Nebraska ex rel. Douglas, 458 U.S. 941, 960 (1982). The
26 state bears the burden of demonstrating this intent. Wyoming v. Oklahoma, 502 U.S. 437, 458

1 (1992).

2 It is undisputed that, on its face, Clean Air Act section 209(b) authorizes California to
3 implement emissions regulations upon receiving an EPA waiver. The terms of section 209(b)
4 indicate that it only shields such regulations from “application of this section,” referring to the
5 broad preemption under section 209(a). See 42 U.S.C. § 7543. Defendants point instead to
6 legislative history to demonstrate Congress’s intent to immunize California regulations from a
7 Dormant Commerce Clause challenge. They contend that when Congress conferred on
8 California the authority to set standards applicable to automobile manufacturers selling cars in
9 California, it knew that California would regulate a significant aspect of interstate commerce.

10 The District of Columbia Circuit summarized the history of California’s Clean Air Act
11 waiver in Motor & Equipment Manufacturers Association v. EPA, 627 F.2d 1095, 1109-10 (D.C.
12 Cir. 1979). The debate in the Senate over granting California a broad waiver “sharpened the
13 differences between the states, which wanted to preserve their traditional role in regulating motor
14 vehicles, and the manufacturers, which wanted to avoid the economic disruption latent in having
15 to meet fifty-one separate sets of emissions control requirements.” Id. at 1109. As the Senate
16 Committee presenting the bill acknowledged, “[t]he auto industry . . . was adamant that the
17 nature of their manufacturing mechanism required a single national standard in order to eliminate
18 undue economic strain on the industry.” Id. (citing S. Rep. No. 90-403, 33 (1967)). “Thus the
19 Committee that formulated the waiver provision understood the costs involved in making an
20 exception” but reported that the drawbacks of the waiver were balanced by the “benefits for the
21 Nation to be derived from permitting California to continue its experiments in the field of
22 emissions control . . . and the benefits for the people of California to be derived from letting that
23 State improve on ‘its already excellent program’ of emissions control.” Id. at 1109-10.

24 The House also considered the far-reaching economic implications of the waiver
25 provision. The House Committee was so concerned “that the separate administration of two
26 different sets of emission regulations would unduly burden the industry,” that it amended the
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1 waiver provision to make the Secretary's action permissive, rather than mandatory. Id. at 1121
2 (citing H.R. Rep. No. 90-728, 21-22 (1967)). On the floor of the House, the bill was amended to
3 replace the House Committee language and revert to that of the original Senate proposal. Id.
4 (citing 113 Cong. Rec. 30975 (1967) (remarks of Rep. Moss)). The House ultimately adopted
5 the amendment, agreeing with the Senate to place the burden on those "on those who allege, in
6 effect, that the national program is adequate to California's needs." Id.

7 The legislative history makes clear that both the House and the Senate considered that the
8 California regulations under the waiver would substantially burden interstate commerce.
9 Nevertheless, realizing the benefits for California and for the nation from allowing the state
10 broad authority, Congress enacted the waiver anyway. One judge in this district and a California
11 Court of Appeal have concluded that Congress intended regulations that receive a section 209(b)
12 waiver to be immune from Dormant Commerce Clause scrutiny. Oxygenated Fuels Ass'n v.
13 Davis, 163 F. Supp. 2d 1182, 1188 (E.D. Cal. 2001), *aff'd*, 331 F.3d 665 (9th Cir. 2003) (holding
14 that Congress's authorization of California's regulation of fuels and fuel additives upon receiving
15 a section 209(b) waiver rendered the state law "not subject to the Commerce Clause" (quoting
16 White, 460 U.S. at 213)); People ex rel. State Air Res. Bd. v. Wilmshurst, 68 Cal. App. 4th 1332,
17 1345 (1999) (Congress's intent to "allow California to forge emissions standards at variance with
18 the rest of the United States" meant that a California regulation receiving an EPA waiver was not
19 vulnerable to a Commerce Clause challenge (citing Motor and Equip. Mfrs. Ass'n, 627 F.2d at
20 1128.)).

21 Plaintiffs do not take issue with Defendants' characterization of the legislative history of
22 section 209(b). Plaintiffs do not dispute that, at the time Congress passed the waiver provision, it
23 intended to permit California, with EPA approval, to implement regulations burdening interstate
24 commerce. Plaintiffs contend instead that, in deciding whether Congress intended to permit the
25 California regulations even if they burden interstate commerce, the court should also consider the
26 extent to which the EPCA demonstrates a congressional intent to protect interstate commerce in
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1 vehicle production from state fuel economy regulation. Plaintiffs point to the express preemption
2 provision, 49 U.S.C. § 32919(a), as well as other provisions requiring administration of the
3 CAFE program in a manner that does not economically harm the automobile manufacturing
4 sector. See 49 U.S.C. §§ 32913, 32916. Plaintiffs contend that the holdings of S. Life Ins. Co.
5 and White do not apply where there is “no clear expression of Congressional intent to approve
6 any type of state regulation.” Pls.’ Opp’n 66:9-11.

7 Because they do not dispute the District of Columbia Circuit’s interpretation of the
8 legislative history of the Clean Air Act, Plaintiffs must find in the EPCA Congress’s intent to
9 revoke the permission to burden interstate commerce that it had previously given California. The
10 EPCA sections to which Plaintiffs cite do not evince such congressional intent. Plaintiffs point
11 to 42 U.S.C. § 32913, which concerns civil penalties for failing to comply with requirements
12 under the EPCA. It authorizes the Secretary of Transportation to reduce such a penalty to the
13 extent “necessary to prevent a substantial lessening of competition.” 42 U.S.C. § 32913.
14 Plaintiffs also cite a requirement that the Secretary, after providing a manufacturer an exemption
15 from “the requirement of separate calculations” should evaluate the economic effect of such an
16 exemption. 42 U.S.C. § 32916. Neither of these provisions illuminates Congress’s intent
17 regarding the economic effects of regulations waived under Clean Air Act section 209(b). Nor
18 does the EPCA’s express preemption provision, 42 U.S.C. § 32919(a), explicitly or implicitly
19 bear on Congress’s belief that the benefits of more stringent California emissions regulations
20 justify a burden on commerce.¹⁶ Taken together in light of the legislative history of section
21 209(b), the EPCA provisions that Plaintiffs cite do not contravene Congress’s “unmistakably
22 clear” permission to California to burden interstate commerce. See C&A Carbone, 511 U.S. at
23 408. Accordingly, Plaintiffs do not state a claim under the Dormant Commerce Clause, making
24 judgment on the pleadings for Defendants appropriate.

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26 ¹⁶ Of course, it is undisputed that should the California regulations be subject to the
27 EPCA’s preemption provision, they will be barred.

E. Sherman Act

In their opening brief, Defendants moved for judgment on the pleadings on Plaintiffs' claim under the Sherman Act on the basis that they had failed to state a facial preemption challenge. In their opposition brief, Plaintiffs concede that they have not stated a claim for a facial challenge to the California regulations. Pls.' Opp'n 67:21-22. Instead, they seek to "prove specific anticompetitive effects that trigger preemption under the Sherman Act." *Id.* In their reply, Defendants contend that Plaintiffs have failed to state a claim for such an as-applied challenge and, in the alternative, that such a claim is unripe.

Under section 1 of the Sherman Act, "[e]very contract, combination in the form of trust or otherwise, or conspiracy, in restraint of trade or commerce among the several States, or with foreign nations," is illegal. 15 U.S.C. § 1. To establish a section 1 violation, a plaintiff must demonstrate three elements:

(1) an agreement, conspiracy, or combination among two or more persons or distinct business entities; (2) which is intended to harm or unreasonably restrain competition; and (3) which actually causes injury to competition, beyond the impact on the claimant, within a field of commerce in which the claimant is engaged (i.e., "antitrust injury").

McGlinchy, 845 F.2d at 811. Where two parties to an alleged conspiracy actually constitute a "single entity," they are immune from section 1 liability, as the "company cannot conspire with itself." *Freeman v. San Diego Ass'n of Realtors*, 322 F.3d 1133, 1147 (9th Cir. 2003) (citing *Copperweld Corp. v. Independence Tube Corp.*, 467 U.S. 752, 769 (1984)). "Where there is substantial common ownership, a fiduciary obligation to act for another entity's economic benefit or an agreement to divide profits and losses, individual firms function as an economic unit and are generally treated as a single entity." *Id.*

The FAC alleges that the California regulations may lead to price fixing. FAC ¶ 143. This is because the regulations, in some cases, require companies with a ten percent or greater overlap in ownership, but which are not one economic unit, to jointly demonstrate compliance

1 with the greenhouse gas emissions limits. Id. The FAC alleges that manufacturers control the
2 mix of vehicles sold by raising and lowering prices to influence demand for particular vehicle
3 groups or models. Id. In order to control the aggregate emissions of the vehicles sold, the FAC
4 alleges, “the two manufacturers will need to coordinate the sale of vehicles according to their fuel
5 economy.” Id. This will require, according to the FAC, the exchange of production, supply, and
6 price information, which could ultimately result in price fixing. Id.

7 Generally, the Sherman Act does not constrain “a state or its officers or agents from
8 activities directed by its legislature.” Parker v. Brown, 317 U.S. 341, 350-51 (1943). This is
9 because the Sherman Act does not evince Congress’s intent to “nullify a state’s control over its
10 officers and agents.” Id. at 351. Consequently, the Parker Court decided, based on principles of
11 federalism and state sovereignty, that the acts of a state’s legislative power or “official action
12 directed by a state” are not subject to Sherman Act scrutiny. Id. A state statute may, however, be
13 preempted where “there exists an irreconcilable conflict between the federal and state regulatory
14 schemes.” Rice v. Norman Williams Co. (Rice), 458 U.S. 654, 659 (1982).

15 Rice concerned the enforceability of a state scheme involving licensing of beverage
16 importers. Id. at 656-57. The Court held that it was irrelevant to the inquiry into the validity of
17 the statute whether it “might have an anticompetitive effect when applied in concrete factual
18 situations.” Id. A consideration of the effects of a state statute may be relevant to determining
19 whether a private individual is entitled to the “state action” exemption to Sherman Act liability.
20 See Cal. Retail Liquor Dealers Ass’n v. Midcal Aluminum, 445 U.S. 97, 103 (1980) (citing
21 Parker, 317 U.S. at 351). Plaintiffs do not present any authority, and the court is aware of none,
22 suggesting that anticompetitive effects short of “irreconcilable conflict” are grounds for
23 preemption of a state statute.¹⁷ See Rice, 458 U.S. at 659. To the contrary, only “[w]hen the
24

25 ¹⁷ Plaintiffs’ attempts to resuscitate this claim, both in their opposition brief and at
26 oral argument, centered on presenting authority indicating that a preenforcement as-applied
27 challenge to a state statute is generally permissible. See Compassion in Dying v. Washington,
79 F.3d 790, 798 (9th Cir. 1996). Such authority is unhelpful to Plaintiffs as they have not
demonstrated any statutory basis for preemption of the California regulations under the Sherman

1 plaintiff challenges the facial validity of a statute or ordinance, preemption principles come into
 2 play. Where, however, the plaintiff alleges that action taken pursuant to legislation constitutes an
 3 antitrust violation, preemption principles are not implicated, while the state action doctrine can
 4 provide protection.” 3 Julian O. von Kalinowski et al., Antitrust Laws and Trade Regulation
 5 § 49.06[2] (2d ed. 2004).

6 Preemption based on “irreconcilable conflict” under Rice represents an exception to the
 7 well-established rule that a state’s actions are exempt from section 1 scrutiny. See 458 U.S. at
 8 659. Plaintiffs do not point to any other grounds to invalidate the California regulations. Thus,
 9 while, “specific anticompetitive effects” of the California regulations might ameliorate the
 10 liability of manufacturers forced to engage in anticompetitive activities to comply with them,
 11 principles of federalism and state sovereignty preclude invalidating all or part of the statute based
 12 on such effects. Because Plaintiffs concede that Rice preemption of the regulations is
 13 inappropriate and no other grounds for Sherman Act preemption are before the court, the court
 14 grants judgment on the pleadings for Defendants on this claim.

15 **F. Global Warming Science Discovery**

16 In its order issued September 11, 2006, the court granted Defendants’ motion for
 17 reconsideration with respect to certain discovery orders of the Magistrate Judge. The court
 18 concluded, in the section entitled “Global Warming,” that certain document requests¹⁸ were
 19 permissible because they were likely to lead to the production of evidence relevant to Plaintiffs’
 20 Dormant Commerce Clause challenge, on which judgment on the pleadings has now been
 21 granted. See Fed. R. Civ. P. 26(b)(1); Fed. R. Evid. 401. In opposing the motion for
 22 reconsideration, Defendants had also contended that the document requests were permissible to
 23 seek evidence refuting AIAM’s claim that EPA cannot find, under 42 U.S.C. § 7543(b)(1)(B),

24 _____
 25 Act.

26 ¹⁸ These requests include those designated GM 22/DCC 21/AAM 20, GM 23/DCC
 27 22/AAM 21, GM 25/DCC 24, GM 26/DCC 25/AAM 24, GM-DCC-AAM 8, 9, 10 and 11, GM
 20/DCC-AAM 19, GM 14, and GM 15/DCC-AAM 14.

“compelling and extraordinary conditions” justifying a waiver. See AIAM Compl. ¶ 62. As Judge Coyle made clear in his order of October 21, 2005, whether EPA will ultimately decide to grant the California regulations a waiver is not properly before this court. Accordingly, the court finds that, notwithstanding any prior order, document requests that seek evidence about the science of global warming are not, on that basis, reasonably calculated to lead to evidence admissible in this action.

CONCLUSION AND ORDER

For the reasons stated in the above Memorandum Opinion, IT IS HEREBY ORDERED that:

1. Defendants’ motion for JUDGMENT ON THE PLEADINGS is DENIED with respect to the claims for EPCA preemption, EPA preemption, and foreign policy preemption;
2. Defendants’ motion for JUDGMENT ON THE PLEADINGS is GRANTED with respect to the Dormant Commerce Clause and Sherman Act claims; and
3. Notwithstanding any prior order of this court, Plaintiffs need not produce documents responsive to requests designated GM 22/DCC 21/AAM 20, GM 23/DCC 22/AAM 21, GM 25/DCC 24, GM 26/DCC 25/AAM 24, GM-DCC-AAM 8, 9, 10 and 11, GM 20/DCC-AAM 19, GM 14, and GM 15/DCC-AAM 14.

IT IS SO ORDERED.

Dated: September 22, 2006
0m8i78

/s/ Anthony W. Ishii
UNITED STATES DISTRICT JUDGE

The WHITE HOUSE

BRIEFINGS & STATEMENTS

STATEMENT BY THE PRESIDENT

The White House

June 12, 2025

Today, I signed into law (1) H.J. Res. 87, “Joint Resolution providing congressional disapproval under chapter 8 of title 5, United States Code, of the rule submitted by the Environmental Protection Agency relating to ‘California State Motor Vehicle and Engine Pollution Control Standards; Heavy-Duty Vehicle and Engine Emission Warranty and Maintenance Provisions; Advanced Clean Trucks; Zero Emission Airport Shuttle; Zero-Emission Power Train Certification; Waiver of Preemption; Notice of Decision’”; (2) H.J. Res. 88, “Joint Resolution providing congressional disapproval under chapter 8 of title 5, United States Code, of the rule submitted by the Environmental Protection Agency relating to ‘California State Motor Vehicle and Engine Pollution Control Standards; Advanced Clean Cars II; Waiver of Preemption; Notice of Decision’”; and (3) H.J. Res. 89, “Joint Resolution providing congressional disapproval under chapter 8 of title 5, United States Code, of the rule submitted by the Environmental Protection Agency relating to ‘California State Motor Vehicle and Engine and Nonroad Engine Pollution Control Standards; The ‘Omnibus’ Low NOX Regulation; Waiver of Preemption; Notice of Decision’”.

These bipartisan measures prevent California’s attempt to impose a nationwide electric vehicle mandate and to regulate national fuel economy by regulating carbon emissions. Because of the joint resolutions I signed today, California’s Advanced Clean Cars II, Advanced Clean Trucks, and Omnibus Low NOX programs are fully and expressly preempted by the Clean Air Act and cannot be implemented.

Preemption of these programs is essential to preserving the Constitution’s allocation of power both among the States and between the States and the Federal Government. It is the Federal Government, not States, that should establish vehicle emissions standards given the inherently interstate nature of air quality; a patchwork of State vehicle

regulations on this subject is unworkable. Our Constitution does not allow one State special status to create standards that limit consumer choice and impose an electric vehicle mandate upon the entire Nation.

As the Congress's joint resolutions make clear, California's attempts to impose an electric vehicle mandate, regulate national fuel economy, and regulate greenhouse gas emissions are not eligible for waivers of preemption under section 209 of the Clean Air Act. This provision of the Clean Air Act authorizes the Environmental Protection Agency (EPA) to grant waivers to California to address only compelling and extraordinary localized issues. It can never again be misused to regulate greenhouse gas emissions, which inherently do not have localized effects, much less compelling and extraordinary local effects, or vehicle emissions across the Nation.

Under the Congressional Review Act, the EPA cannot approve any future waivers that are "substantially the same" as those disapproved in the joint resolutions. The core of the waivers at issue are their authorization of California to regulate greenhouse gas and NOX emissions from internal combustion engines and to impose what amounts to an electric vehicle mandate across the Nation. Accordingly, the joint resolutions prohibit the EPA from approving future waivers for California that would impose California's policy goals across the entire country and violate fundamental constitutional principles of federalism, ending the electric vehicle mandate for good.

DONALD J. TRUMP

THE WHITE HOUSE,
June 12, 2025.

5 USC 801: Congressional review

Text contains those laws in effect on November 18, 2025

From Title 5-GOVERNMENT ORGANIZATION AND EMPLOYEES

PART I-THE AGENCIES GENERALLY

CHAPTER 8-CONGRESSIONAL REVIEW OF AGENCY RULEMAKING

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§801. Congressional review

(a)(1)(A) Before a rule can take effect, the Federal agency promulgating such rule shall submit to each House of the Congress and to the Comptroller General a report containing-

- (i) a copy of the rule;
- (ii) a concise general statement relating to the rule, including whether it is a major rule; and
- (iii) the proposed effective date of the rule.

(B) On the date of the submission of the report under subparagraph (A), the Federal agency promulgating the rule shall submit to the Comptroller General and make available to each House of Congress-

- (i) a complete copy of the cost-benefit analysis of the rule, if any;
- (ii) the agency's actions relevant to sections 603, 604, 605, 607, and 609;
- (iii) the agency's actions relevant to sections 202, 203, 204, and 205 of the Unfunded Mandates Reform Act of 1995; and
- (iv) any other relevant information or requirements under any other Act and any relevant Executive orders.

(C) Upon receipt of a report submitted under subparagraph (A), each House shall provide copies of the report to the chairman and ranking member of each standing committee with jurisdiction under the rules of the House of Representatives or the Senate to report a bill to amend the provision of law under which the rule is issued.

(D) For any rule submitted under subparagraph (A), if the Federal agency promulgating the rule, in whole or in part, revokes, suspends, replaces, amends, or otherwise makes the rule ineffective, or the rule is made ineffective for any other reason, the Federal agency shall submit to the Comptroller General a report containing-

- (i) the title of the rule;
- (ii) the Federal Register citation for the rule, if any;
- (iii) the date on which rule was submitted to the Comptroller General; and
- (iv) a description of the provisions of the rule that are being revoked, suspended, replaced, amended, or otherwise made ineffective.

(2)(A) The Comptroller General shall provide a report on each major rule to the committees of jurisdiction in each House of the Congress by the end of 15 calendar days after the submission or publication date as provided in section 802(b)(2). The report of the Comptroller General shall include an assessment of the agency's compliance with procedural steps required by paragraph (1)(B).

(B) Federal agencies shall cooperate with the Comptroller General by providing information relevant to the Comptroller General's report under subparagraph (A).

(3) A major rule relating to a report submitted under paragraph (1) shall take effect on the latest of-

- (A) the later of the date occurring 60 days after the date on which-
 - (i) the Congress receives the report submitted under paragraph (1); or
 - (ii) the rule is published in the Federal Register, if so published;

(B) if the Congress passes a joint resolution of disapproval described in section 802 relating to the rule, and the President signs a veto of such resolution, the earlier date-

- (i) on which either House of Congress votes and fails to override the veto of the President; or
- (ii) occurring 30 session days after the date on which the Congress received the veto and objections of the President; or

(C) the date the rule would have otherwise taken effect, if not for this section (unless a joint resolution of disapproval under section 802 is enacted).

(4) Except for a major rule, a rule shall take effect as otherwise provided by law after submission to Congress under paragraph (1).

(5) Notwithstanding paragraph (3), the effective date of a rule shall not be delayed by operation of this chapter beyond the date on which either House of Congress votes to reject a joint resolution of disapproval under section 802.

(b)(1) A rule shall not take effect (or continue), if the Congress enacts a joint resolution of disapproval, described under section 802, of the rule.

(2) A rule that does not take effect (or does not continue) under paragraph (1) may not be reissued in substantially the same form, and a new rule that is substantially the same as such a rule may not be issued, unless the reissued or new rule is specifically authorized by a law enacted after the date of the joint resolution disapproving the original rule.

(c)(1) Notwithstanding any other provision of this section (except subject to paragraph (3)), a rule that would not take effect by reason of subsection (a)(3) may take effect, if the President makes a determination under paragraph (2) and submits written notice of such determination to the Congress.

(2) Paragraph (1) applies to a determination made by the President by Executive order that the rule should take effect because such rule is-

- (A) necessary because of an imminent threat to health or safety or other emergency;
- (B) necessary for the enforcement of criminal laws;
- (C) necessary for national security; or
- (D) issued pursuant to any statute implementing an international trade agreement.

(3) An exercise by the President of the authority under this subsection shall have no effect on the procedures under section 802 or the effect of a joint resolution of disapproval under this section.

(d)(1) In addition to the opportunity for review otherwise provided under this chapter, in the case of any rule for which a report was submitted in accordance with subsection (a)(1)(A) during the period beginning on the date occurring-

- (A) in the case of the Senate, 60 session days, or
- (B) in the case of the House of Representatives, 60 legislative days,

before the date the Congress adjourns a session of Congress through the date on which the same or succeeding Congress first convenes its next session, section 802 shall apply to such rule in the succeeding session of Congress.

(2)(A) In applying section 802 for purposes of such additional review, a rule described under paragraph (1) shall be treated as though-

- (i) such rule were published in the Federal Register (as a rule that shall take effect) on-
 - (I) in the case of the Senate, the 15th session day, or
 - (II) in the case of the House of Representatives, the 15th legislative day,

after the succeeding session of Congress first convenes; and

- (ii) a report on such rule were submitted to Congress under subsection (a)(1) on such date.

(B) Nothing in this paragraph shall be construed to affect the requirement under subsection (a)(1) that a report shall be submitted to Congress before a rule can take effect.

(3) A rule described under paragraph (1) shall take effect as otherwise provided by law (including other subsections of this section).

(e)(1) For purposes of this subsection, section 802 shall also apply to any major rule promulgated between March 1, 1996, and the date of the enactment of this chapter.

(2) In applying section 802 for purposes of Congressional review, a rule described under paragraph (1) shall be treated as though-

- (A) such rule were published in the Federal Register on the date of enactment of this chapter; and
- (B) a report on such rule were submitted to Congress under subsection (a)(1) on such date.

(3) The effectiveness of a rule described under paragraph (1) shall be as otherwise provided by law, unless the rule is made of no force or effect under section 802.

(f) Any rule that takes effect and later is made of no force or effect by enactment of a joint resolution under section 802 shall be treated as though such rule had never taken effect.

(g) If the Congress does not enact a joint resolution of disapproval under section 802 respecting a rule, no court or agency may infer any intent of the Congress from any action or inaction of the Congress with regard to such rule, related statute, or joint resolution of disapproval.

(Added Pub. L. 104-121, [title II, §251, Mar. 29, 1996](#), 110 Stat. 868 ; amended Pub. L. 118-5, [div. B, title III, §270, June 3, 2023](#), 137 Stat. 33 ; Pub. L. 118-97, [§2, Oct. 1, 2024](#), 138 Stat. 1573 .)

AMENDMENT OF SUBSECTION (A)(1)(D)

Pub. L. 118-97, §2(b), Oct. 1, 2024, 138 Stat. 1574 , provided that, effective 6 years after Oct. 1, 2024, subsection (a)(1) of this section is amended by striking subparagraph (D). See 2024 Amendment note below.

EDITORIAL NOTES

REFERENCES IN TEXT

Sections 202, 203, 204, and 205 of the Unfunded Mandates Reform Act of 1995, referred to in subsec. (a)(1)(B)(iii), are classified to sections 1532, 1533, 1534, and 1535, respectively, of Title 2, The Congress.

The date of the enactment of this chapter, referred to in subsec. (e)(1), (2), is the date of the enactment of Pub. L. 104–121, which was approved Mar. 29, 1996.

AMENDMENTS

2024-Subsec. (a)(1)(D). Pub. L. 118–97, §2(b), struck out subpar. (D) which required Federal agencies to submit to the Comptroller General a report on rules that are revoked, suspended, replaced, amended, or otherwise made ineffective.

Pub. L. 118–97, §2(a), added subpar. (D).

2023-Subsec. (a)(2)(A). Pub. L. 118–5, §§268, 270, temporarily inserted ", and shall in addition include an assessment of the agency's compliance with such requirements of the Administrative Pay-As-You-Go Act of 2023 as may be applicable" after "compliance with procedural steps required by paragraph (1)(B)". See Termination Date of 2023 Amendment note below.

STATUTORY NOTES AND RELATED SUBSIDIARIES

EFFECTIVE DATE OF 2024 AMENDMENT

Pub. L. 118–97, §2(b), [Oct. 1, 2024](#), 138 Stat. 1574 , provided that the amendment made by section 2(b) is effective on the date that is 6 years after Oct. 1, 2024.

TERMINATION DATE OF 2023 AMENDMENT

Amendment by Pub. L. 118–5 expires on Dec. 31, 2024, see section 268 of Pub. L. 118–5, set out in a Statutory Administrative Pay-As-You-Go note under section 551 of this title.

EFFECTIVE DATE

Pub. L. 104–121, [title II, §252, Mar. 29, 1996](#), 110 Stat. 874 , provided that: "The amendment made by section 351 [probably means section 251, enacting this chapter] shall take effect on the date of enactment of this Act [Mar. 29, 1996]."

SHORT TITLE

This chapter is popularly known as the "Congressional Review Act".

TRUTH IN REGULATING

Pub. L. 106–312, [Oct. 17, 2000](#), 114 Stat. 1248 , as amended by Pub. L. 108–271, [§8\(b\), July 7, 2004](#), 118 Stat. 814 , provided that:

"SECTION 1. SHORT TITLE.

"This Act may be cited as the 'Truth in Regulating Act of 2000'.

"SEC. 2. PURPOSES.

"The purposes of this Act are to-

"(1) increase the transparency of important regulatory decisions;

"(2) promote effective congressional oversight to ensure that agency rules fulfill statutory requirements in an efficient, effective, and fair manner; and

"(3) increase the accountability of Congress and the agencies to the people they serve.

"SEC. 3. DEFINITIONS.

"In this Act, the term-

"(1) 'agency' has the meaning given such term under section 551(1) of title 5, United States Code;

"(2) 'economically significant rule' means any proposed or final rule, including an interim or direct final rule, that may have an annual effect on the economy of \$100,000,000 or more or adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or State, local, or tribal governments or communities; and

"(3) 'independent evaluation' means a substantive evaluation of the agency's data, methodology, and assumptions used in developing the economically significant rule, including-

"(A) an explanation of how any strengths or weaknesses in those data, methodology, and assumptions support or detract from conclusions reached by the agency; and

"(B) the implications, if any, of those strengths or weaknesses for the rulemaking.

"SEC. 4. PILOT PROJECT FOR REPORT ON RULES.

"(a) IN GENERAL.-

"(1) REQUEST FOR REVIEW.-When an agency publishes an economically significant rule, a chairman or ranking member of a committee of jurisdiction of either House of Congress may request the Comptroller General of the United States to review the rule.

"(2) REPORT.-The Comptroller General shall submit a report on each economically significant rule selected under paragraph (4) to the committees of jurisdiction in each House of Congress not later than 180 calendar days after a committee request is received. The report shall include an independent evaluation of the economically significant rule by the Comptroller General.

"(3) INDEPENDENT EVALUATION.-The independent evaluation of the economically significant rule by the Comptroller General under paragraph (2) shall include-

"(A) an evaluation of the agency's analysis of the potential benefits of the rule, including any beneficial effects that cannot be quantified in monetary terms and the identification of the persons or entities likely to receive the benefits;

"(B) an evaluation of the agency's analysis of the potential costs of the rule, including any adverse effects that cannot be quantified in monetary terms and the identification of the persons or entities likely to bear the costs;

"(C) an evaluation of the agency's analysis of alternative approaches set forth in the notice of proposed rulemaking and in the rulemaking record, as well as of any regulatory impact analysis, federalism assessment, or other analysis or assessment prepared by the agency or required for the economically significant rule; and

"(D) a summary of the results of the evaluation of the Comptroller General and the implications of those results.

"(4) PROCEDURES FOR PRIORITIES OF REQUESTS.-The Comptroller General shall have discretion to develop procedures for determining the priority and number of requests for review under paragraph (1) for which a report will be submitted under paragraph (2).

"(b) AUTHORITY OF COMPTROLLER GENERAL.-Each agency shall promptly cooperate with the Comptroller General in carrying out this Act. Nothing in this Act is intended to expand or limit the authority of the Government Accountability Office.

"SEC. 5. AUTHORIZATION OF APPROPRIATIONS.

"There are authorized to be appropriated to the Government Accountability Office to carry out this Act \$5,200,000 for each of fiscal years 2000 through 2002.

"SEC. 6. EFFECTIVE DATE AND DURATION OF PILOT PROJECT.

"(a) EFFECTIVE DATE.-This Act and the amendments made by this Act shall take effect 90 days after the date of enactment of this Act [Oct. 17, 2000].

"(b) DURATION OF PILOT PROJECT.-The pilot project under this Act shall continue for a period of 3 years, if in each fiscal year, or portion thereof included in that period, a specific annual appropriation not less than \$5,200,000 or the pro-rated equivalent thereof shall have been made for the pilot project.

"(c) REPORT.-Before the conclusion of the 3-year period, the Comptroller General shall submit to Congress a report reviewing the effectiveness of the pilot project and recommending whether or not Congress should permanently authorize the pilot project."