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Carbon Return on Investment for Electrified Vehicles

Executive Summary

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COORDINATING RESEARCH COUNCIL, INC.
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Carbon Return on Investment for Electrified Vehicles

Introduction

The Sustainable Mobility Committee of CRC supported research by the National Renewable Energy Laboratory that was published in a separate report: "Analyzing Potential Greenhouse Gas Emissions Reductions from Plug-in Electric Vehicles". The following Executive Summary was authored by the Committee to highlight key findings from the study report that address the research objective of evaluating the carbon return on investment (CROI) for a variety of battery sizes in different vehicle electrification strategies and in different vehicle usage applications in the US light-duty vehicle market.

Executive Summary

Battery and electrification technologies have the potential to greatly reduce vehicular greenhouse gas (GHG) emissions. For instance, a battery electric vehicle (BEV) generates zero tailpipe emissions, but will have GHG emissions associated with production of the vehicle including its battery, and with any carbon-emitting electricity sources used to charge the vehicle. This study explores the GHG reduction benefits of different plug-in electric vehicle (PEV) designs in the context of factors such as electricity production mix, per-vehicle battery requirements, and varying battery supply scenarios. The analyses focus on the U.S. light-duty vehicle (LDV) market, which accounts for nearly 60% of U.S. transportation sector GHG emissions—over twice as much as the next largest contributing transportation sub-sector (EPA, 2022).

The research first quantifies each of the factors contributing to vehicle life cycle GHG emissions and their variability. This includes assembling detailed data on battery production, vehicle manufacturing, driving patterns, local climate, electric grid evolution, electric vehicle charging behavior, vehicle type and class, and both current and projected future vehicle attributes. The study then examines vehicle-level life cycle GHG emissions for a range of powertrain configurations. This portion of the research effort takes a stochastic analytical approach and incorporates various scenarios for key contributing factors to account for uncertainty and variability—for example, relating to varying assumptions for penetration of renewable energy into the electric grid. The evaluation additionally employs spatially and temporally resolved analysis of vehicle operation, building upon hourly electric grid operation and hourly electric vehicle charging probability for every year of a vehicle's life, and spanning different regions across the U.S. This enables the analysis to account for spatial and temporal heterogeneity of key factors that influence life cycle GHG emissions.

Figure ES 1 summarizes the range of estimated GHG emission reductions for PEVs relative to comparable internal combustion engine vehicles (ICEVs) on a per-vehicle basis. The assessment considers a 15-year vehicle lifetime and examines model years 2025 and 2040, which translates into an analysis time horizon spanning calendar years 2025 through 2055. Considering all evaluated scenarios and representative PEVs in different model years, the analyses indicate that plug-in hybrid electric vehicles (PHEVs) may reduce life cycle GHG emissions by 52%-73%, and that BEVs may achieve 54%-84% reduction, compared to ICEVs. Even for a given vehicle type and model year, the estimated GHG emissions reductions can vary widely, by as much as 10%-30%. Factors contributing to the range of results include varying input scenarios for temporal electric grid evolution, spatial heterogeneity of regional electric grid characteristics, PEV charging behavior, and evolution of high voltage (HV) battery chemistry mix and manufacturing processes.

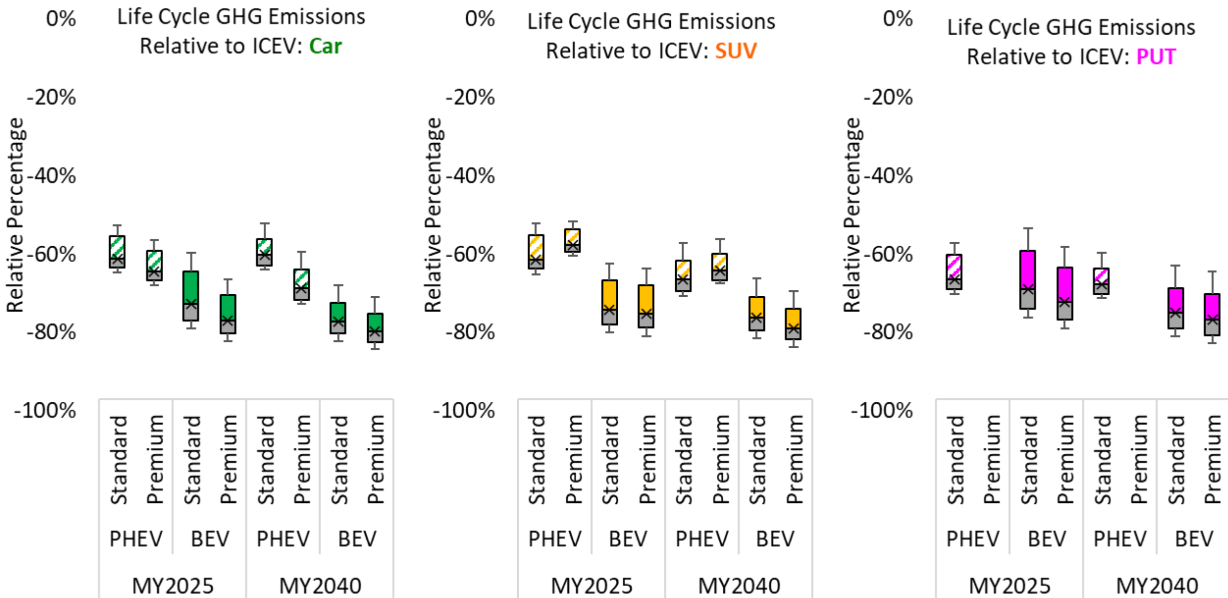

Figure ES 1. Per-vehicle percentage reduction in life cycle GHG emissions for PHEVs (crosshatch pattern) and BEVs (solid pattern) relative to comparable ICEVs. Results shown for car (left), sport utility vehicle (middle), and pickup truck (right). Vehicle attributes derived from another study via sales-weighting the most expensive 20% (premium) and the remaining 80% (standard) in each vehicle type and powertrain category. The lower and upper boxes are the respective 25th to 75th percentiles from the stochastic analyses, with median in the middle. The lower and upper error bars indicate the 10th and 90th percentiles, respectively.

Detailed findings from the HV battery analyses indicate that life cycle carbon intensity can vary significantly depending on cathode chemistry, manufacturing location, and manufacturing year. Battery production carbon intensity for NMC (Lithium Nickel-Cobalt-Manganese Oxide) range from 55 to 77 kg CO_2e per kWh, if manufactured in the U.S. in 2023, versus 31–34 kg CO_2e per kWh for LFP (Lithium Iron Phosphate) and 59–75 kg CO_2e per kWh for NCA (Lithium Nickel-Cobalt-Aluminum Oxide). By 2040, all things equal, the projected carbon intensities are 46–69 kg CO_2e per kWh for NMC, 26–38 for LFP, and 49–67 for NCA. When accounting for batteries manufactured in different countries, the overall HV battery production carbon intensity estimates range from 25 to 95 CO_2e per kWh by 2040 (aggregated based on production volume).

The individual vehicle-level analyses in the report conclude by exploring ways to define "carbon return on investment" (CROI) metrics—such as through normalizing the life cycle carbon savings of a PEV versus an ICEV by the incremental battery content (in kWh) of the PEV's battery, calculated using the equation below. Figure ES 2 shows the CROI results for standard (top) and premium (bottom) vehicles—which have units of $kgCO_2e/kWh$. While BEVs achieve greater overall per-vehicle GHG reductions, these results show that PHEVs achieve a 3.2-6.5 times higher ratio of PEV vs. ICEV GHG savings relative to the incremental energy capacity of the PEV's battery.

$$CROI = \frac{GHG_{ICEV} - GHG_{xEV}}{BattCap_{xEV} - BattCap_{ICEV}}$$

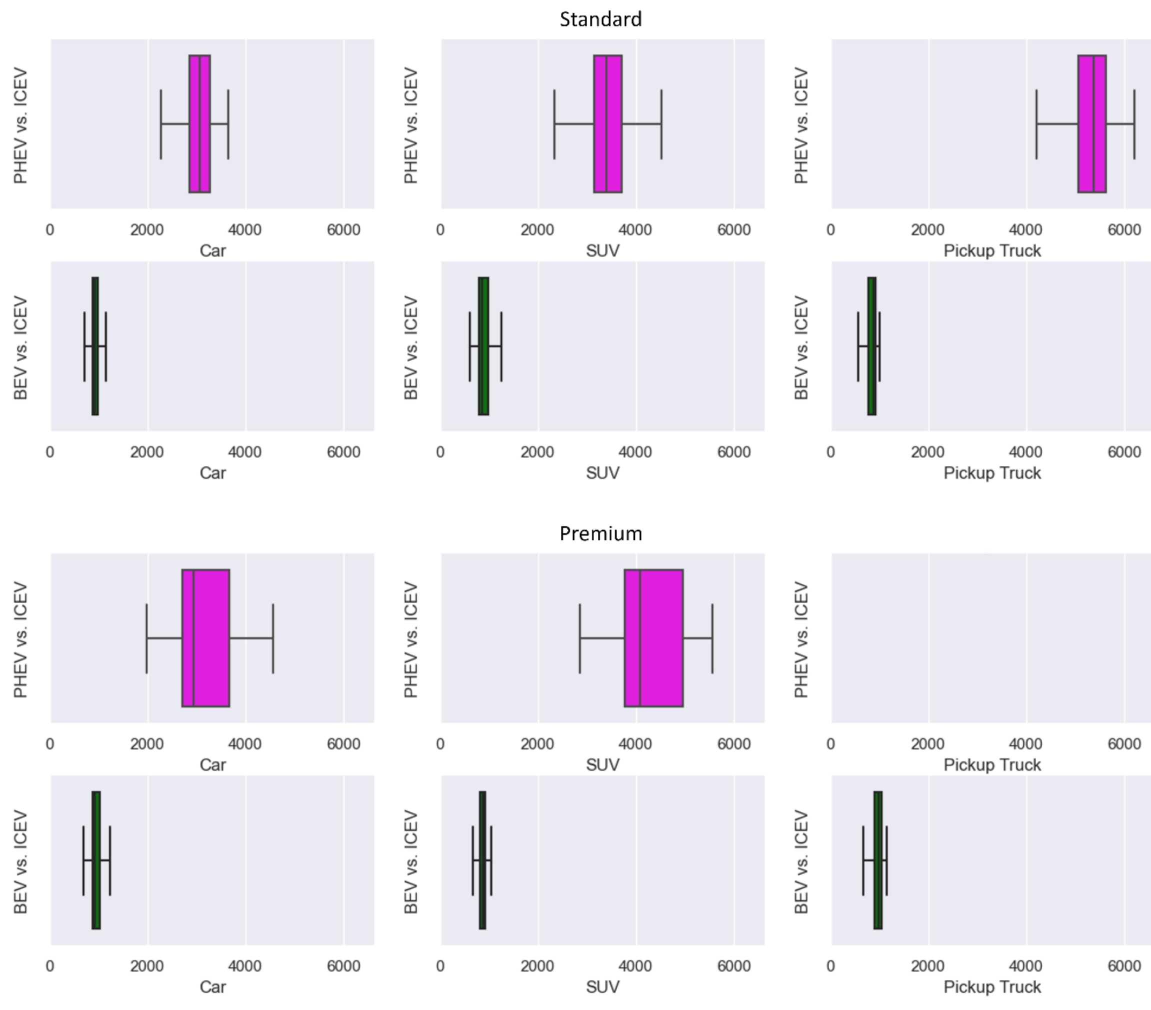

Figure ES 2. CROI results for standard (top) and premium (bottom) vehicles—CROI units are kg CO_2e per kWh for this approach.

Another way to look at CROI is to normalize the life cycle carbon savings of a PEV versus an ICEV by the incremental cost of the PEV's battery (in dollars) as shown in the equation below. Figure ES 3 shows that PHEVs achieve a higher ratio of PEV vs. ICEV GHG savings relative to battery cost. While BEVs achieve greater overall per-vehicle GHG emissions reductions, these results show that the analyzed PHEVs achieve a 2-4 times higher ratio of GHG savings relative to the battery cost.

$$CROI_3 = \frac{GHG_{ICEV} - GHG_{xEV}}{BattCost_{xEV} - BattCost_{ICEV}}$$

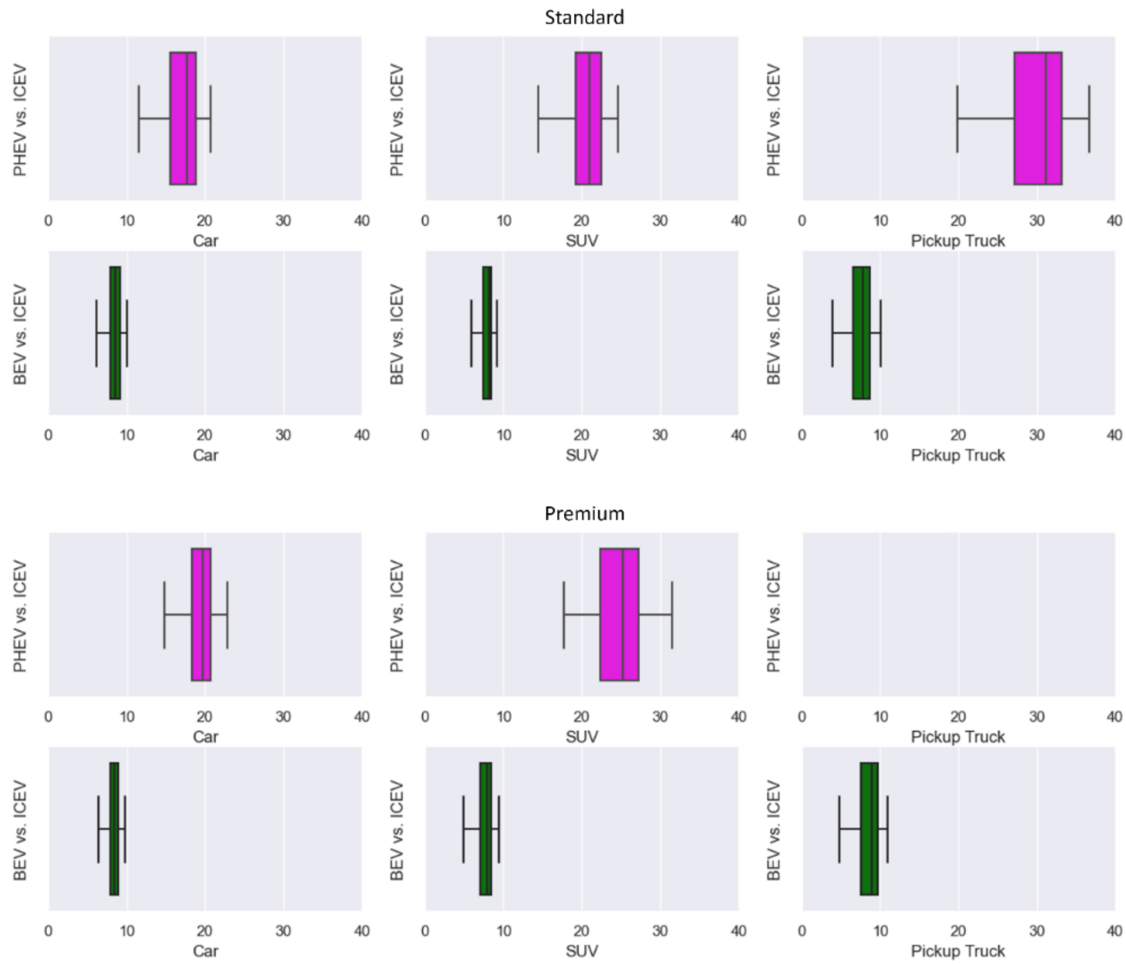

Figure ES 3. $CROI_3$ results for standard (top) and premium (bottom) vehicles—which have units of kg CO2e per dollar for this formulation.

Recognizing that the aggregate GHG emissions benefits for a given PEV depend both on its vehicle-level carbon reduction potential and on how widely it penetrates the market, the analysis additionally evaluated how different growth rates of battery availability could constrain the theoretical adoption and overall GHG emissions benefits for different PEVs. The precursor step to the theoretical analysis of replacing all new U.S. LDVs with a given type of PEV is thus to establish a range of prospective growth scenarios for the quantity of batteries available to support the U.S. LDV market. Irrespective of the extent to which PEV and/or battery imports may contribute to future U.S. LDV sales, a reference scenario growth rate of batteries available to new U.S. LDVs is assumed to match the growth rate of total capacity levels for existing and currently announced battery manufacturing facilities in the U.S. and Canada. Acknowledging multiple significant uncertainties, higher and lower sensitivity scenarios are established by respectively scaling the reference scenario up by 20% and down by 50%. A crossover SUV with representative sales-weighted characteristics is chosen as the basis for all powertrain options to streamline the theoretical national-level analyses.

Figure ES 4 shows the aggregate theoretical carbon emissions results for each powertrain type considered to replace all new U.S. LDVs over three different analysis years for the reference battery growth scenario. Note that the percentage next to each PEV label along the x-axis indicates the proportion of new U.S. LDV sales that the PEV type could satisfy given the scenario's assumed battery availability constraints. This analysis also assumes that all vehicles are at least a hybrid electric vehicle (HEV). Whenever the assumed battery availability is insufficient to replace all new U.S. LDVs with the given PEV, the analysis calculates carbon emissions from an alternative HEV used to cover the remaining new LDVs and adds these to the national-level emissions estimate for the examined PEV. To highlight when this occurs, the percentage of new vehicles assumed to be filled in by the alternative HEV is included just above the alternative HEV gasoline bar segment. At the top of each bar stack, whiskers additionally show result sensitivities under different combinations of grid and battery manufacturing scenario assumptions—for which the range of grid mix assumptions account for most of the variation.

The results in Figure ES 4 reinforce observations from the per-vehicle analysis that HEVs reduce carbon emissions relative to conventional vehicles, PHEVs reduce emissions further, and BEVs reduce emissions the furthest (provided sufficient battery availability). The 2025 results indicate that battery availability in the reference scenario would be insufficient to immediately replace all new U.S. LDVs with long-range BEVs, resulting in substantial numbers of supplementary alternative HEVs needed. That said, given that PHEVs and BEVs of all ranges combined to make up roughly 9% of new LDV sales in 2023 (EIA, 2024), it is unrealistic to expect complete changeover of all new U.S. LDVs to PEVs in 2025. On the other hand, the farther out reference scenario results in 2032 and in 2040 indicate sufficient battery availability for full replacement of new U.S. LDV sales with any of the indicated types of PEVs. For those farther out years, the BEV configurations tend to show the lowest overall carbon emissions, with the shorter range BEVs edging out the longer-range options due to having lower battery manufacturing carbon emissions.

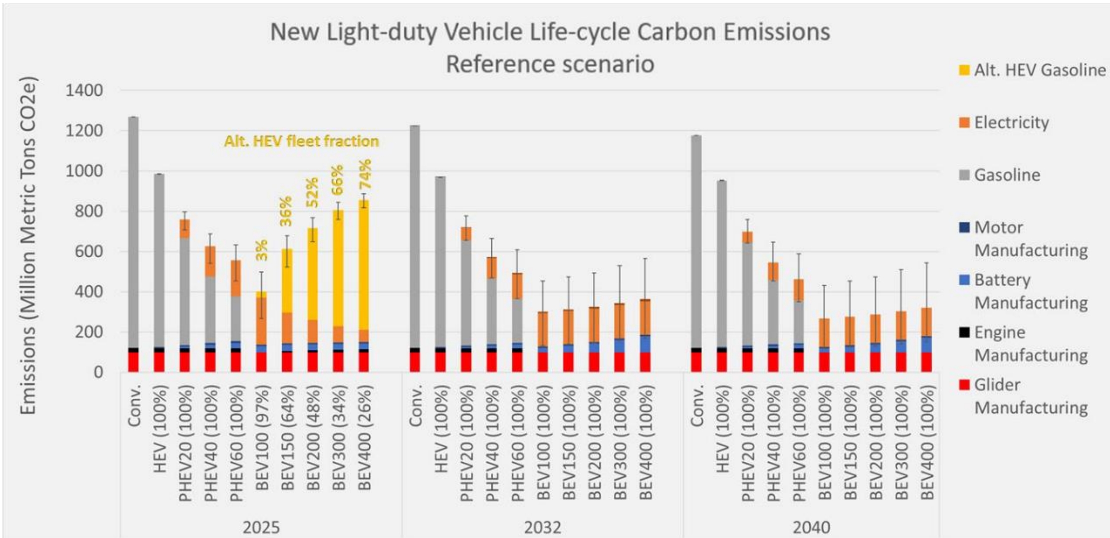

Figure ES 4. Theoretical national-level carbon emissions by powertrain under the reference battery growth scenario.

The results for the low battery availability scenario in Figure ES 5 show substantially more variation from the results for the reference scenario in Figure ES 4. Notably, the lower assumed battery growth results in more significant needs for alternative HEVs, including for several future year PEV cases. The theoretical lowest carbon vehicles in 2032 and 2040 remains the short-range BEVs, but particularly in 2032, the GHGs of longer-range BEV scenario deviate further from the short-range BEVs' theoretical minimum carbon emissions due to now having substantive carbon emissions from alternative HEV gasoline consumption. Under this assumed 2032 battery availability, the BEV300 plus alternative HEV theoretical carbon emissions are comparable to those for the PHEV40—both over a 50% reduction relative to the conventional vehicle case. Furthermore, in this same scenario, the PHEV60 provides further reductions over the BEV300 due to increased battery range over the PHEV40.

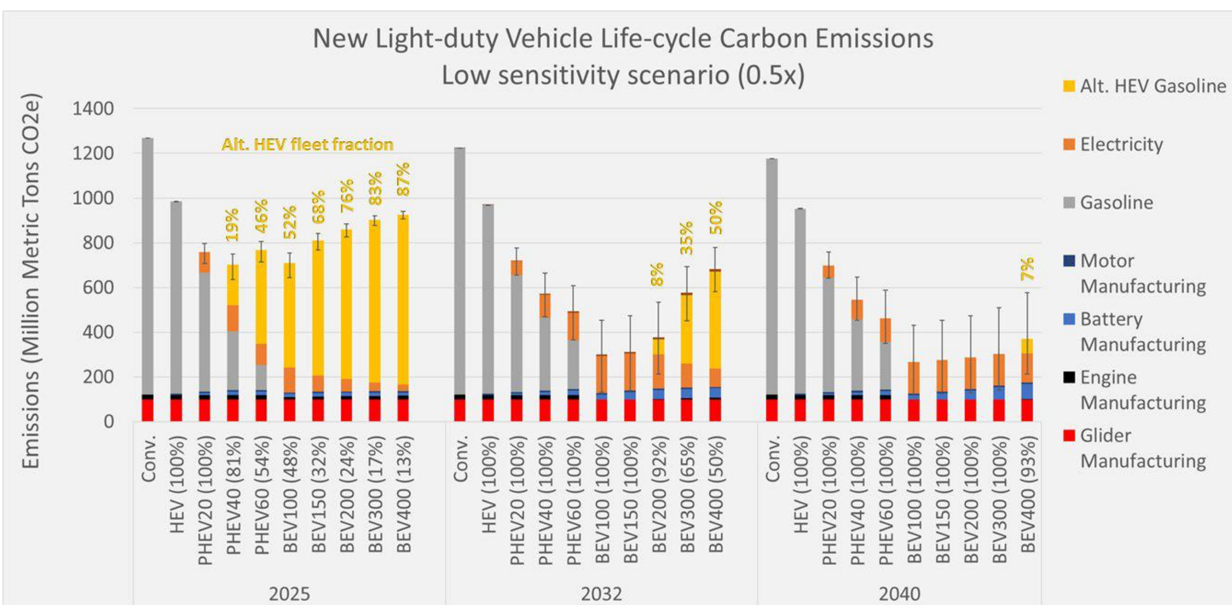

Figure ES 5. Theoretical national-level carbon emissions by powertrain under the low battery availability scenario.

Limitations for the national-level analyses include the acknowledgement that monolithic replacement of all new U.S. LDVs by a single type of PEV is not realistic—particularly in the near term—and that utility and marketability constraints are not considered (e.g., short-range BEVs are recognized to have significant market penetration barriers due to such constraints). Extension of this work incorporating realistic market dynamics modeling would give further insights on the combinations of vehicle GHG reductions and large-scale marketability that minimize overall GHG emissions under different battery growth scenarios. Given the criticality of battery availability to enable the deepest theoretical decarbonization outcomes, the current work underscores the importance of ongoing investments and actions to continue expanding growth of battery production and to mitigate potential supply chain bottlenecks. This includes efforts to identify and gain access to additional sources of critical minerals, and to pursue increased resilience through a diversity of potential battery chemistry options complement to lithium-ion battery supplies.

Although complete replacement of all new U.S. LDVs with PEVs may not be feasible in the near term, maximizing market penetration across a range of PEV designs would achieve significant GHG reduction benefits. This observation aligns with the minimum battery size of 7 kWh in current federal incentives, which covers a range of PHEVs as well as BEVs. Furthermore, while replacing new U.S. LDVs with PEVs achieves the best GHG emissions outcome, if those vehicles not replaced with PEVs are at least replaced with HEVs, there will be significantly greater GHG emissions savings than if those vehicles remain ICEVs—which is the status quo for over 80% of current LDV sales (EIA, 2024).