Analyzing Potential Greenhouse Gas Emissions Reductions from Plug-In Electric Vehicles: Report for CRC Project, “Carbon Return on Investment for Electrified Vehicles”

Supported by Coordinating Research Council (CRC) Project SM-E-20

Dong-Yeon Lee, Nevi Cahya Winofa, Jasmine Pattany, Aaron Brooker, Tapajyoti Ghosh, and Jeffrey Gonder

National Renewable Energy Laboratory

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List of Acronyms

ADOPT	Automotive Deployment Options Projection Tool
BEV	battery-electric vehicle
CCS	carbon capture and sequestration
CO_2e	carbon dioxide equivalent
CROI	carbon return on investment
DCFC	direct-current fast charging
EPA	U.S. Environmental Protection Agency
EVI-Pro	Electric Vehicle Infrastructure – Projection Tool
FTA	Free Trade Agreement
GEA	Generation and Emission Assessment (GEA)
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
HV	high voltage
HVAC	heating, ventilating, and air conditioning
ICEV	internal combustion engine vehicle
IRA	Inflation Reduction Act
LD	light duty
LDV	light-duty vehicle
LFP	lithium iron phosphate (type of lithium battery chemistry)
LiAISON	Life cycle Analysis Integration into Scalable Open-source Numerical models
LIBRA	Lithium-Ion Battery Resource Assessment
MY	model year
NCA	nickel-cobalt-aluminum oxide (type of lithium battery chemistry)
NERC	North American Electric Reliability Corporation
NG	natural gas
NMC	nickel-manganese-cobalt oxide (type of lithium battery chemistry)
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PUT	pickup truck
TDA	Transportation Decarbonization Analysis
TOU	time of use

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Executive Summary

Investment in battery and electrification technologies has the potential to greatly reduce vehicular greenhouse gas (GHG) emissions, as a battery-electric vehicle (BEV) will have zero tailpipe emissions. However, there will be 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 market growth 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, plus current and estimated 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, due 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 each region across the country. 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. Figure ES 2 illustrates the evolution of GHG emission reductions over vehicle lifetime for one of the scenarios considered (i.e., the baseline scenario MY2025 SUV), of which the values in the 15th year are used in Figure ES 1. 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. 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 longitudinal 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.

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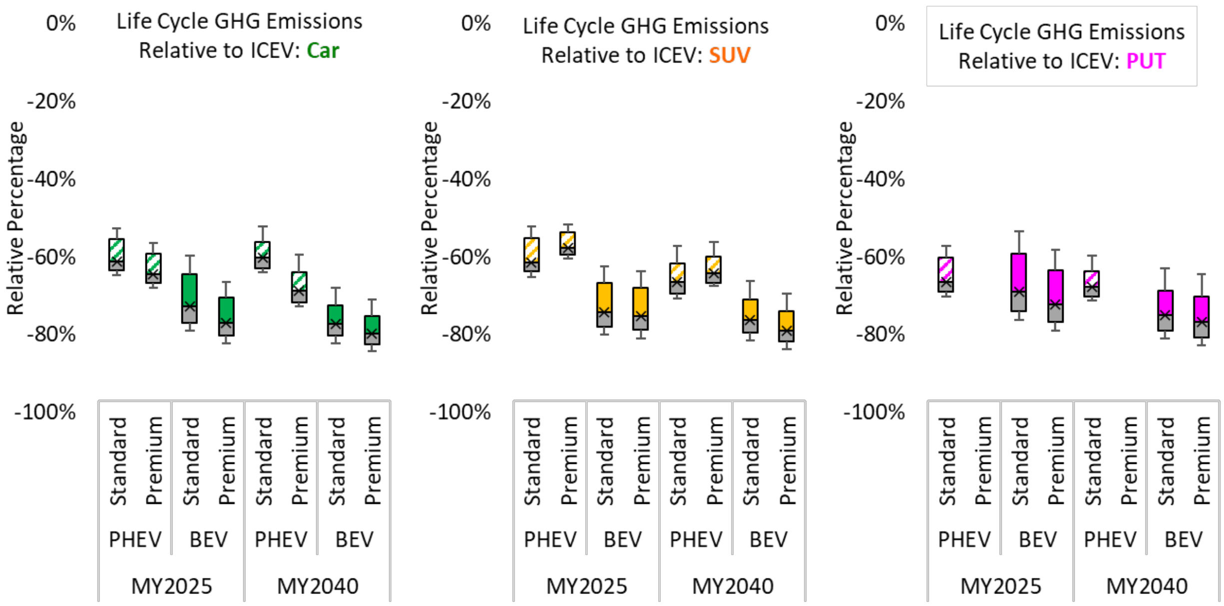

Figure ES 1. Per-vehicle percentage reduction in life cycle GHG emissions for PHEVs (crosshatch pattern) and BEVs (solid pattern) relative to comparable ICEVs. Results shown for car (left), SUV (middle), and pickup truck (right). Vehicle attributes derived from another study via sales-weighting the most 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.

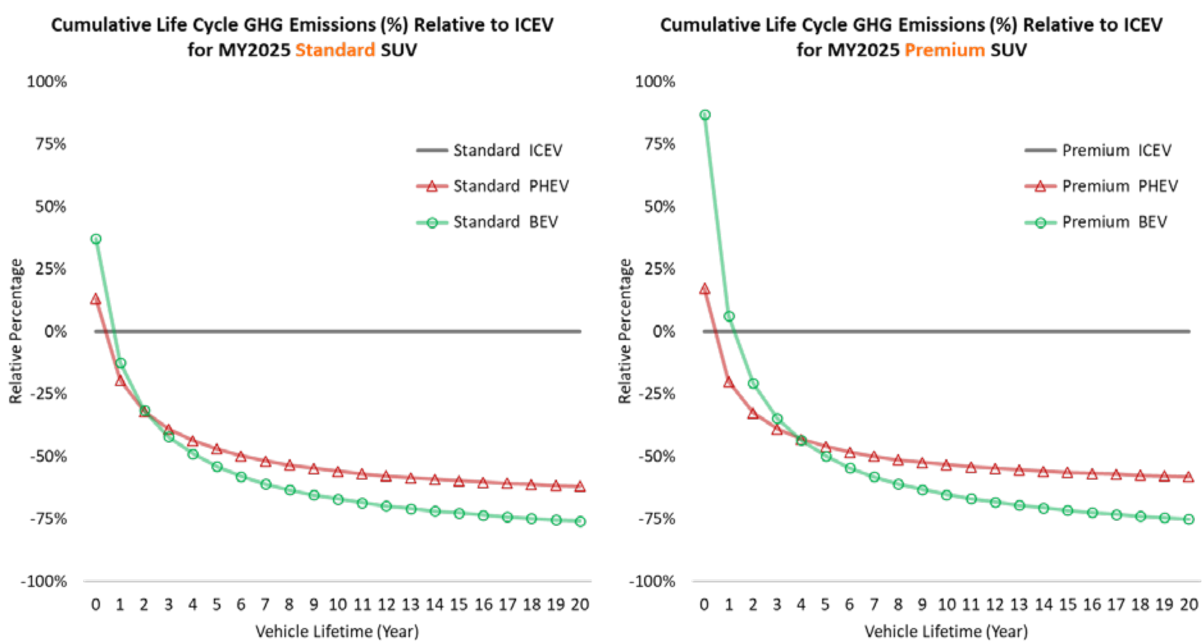

Figure ES 2. Cumulative life cycle GHG emissions relative to ICEV for the baseline scenario MY2025 SUV (with PHEV electric range ~28-38 mi and BEV electric range ~270-350 mi between the standard and premium configurations).

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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-Manganese-Cobalt 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 energy content of the PEV's battery. This exploration indicates that while BEVs consistently show the largest individual vehicle carbon reduction potential, PHEVs consistently show higher CROI values. 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 next portion of the analysis evaluates 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 3 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. LDVs that could become that type of PEV given the scenario's assumed battery availability constraints. 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 further highlight when this occurs, a percentage number is included just above the alternative HEV gasoline bar segment to indicate the proportion of new vehicles assumed to be filled in by the alternative HEV. 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 3 reinforce observations from the per-vehicle analysis that HEVs reduce carbon emissions relative to conventional vehicles, PHEVs reduce emissions further, and BEVs

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reduce emissions the furthest (provided sufficient battery availability). The 2025 results indicate that battery availability that year 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), and that the official goal is to reach 50% combined PEV and fuel cell vehicle sales by 2030 (White House 2021), there are certainly considerations beyond battery growth rate that make it 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.

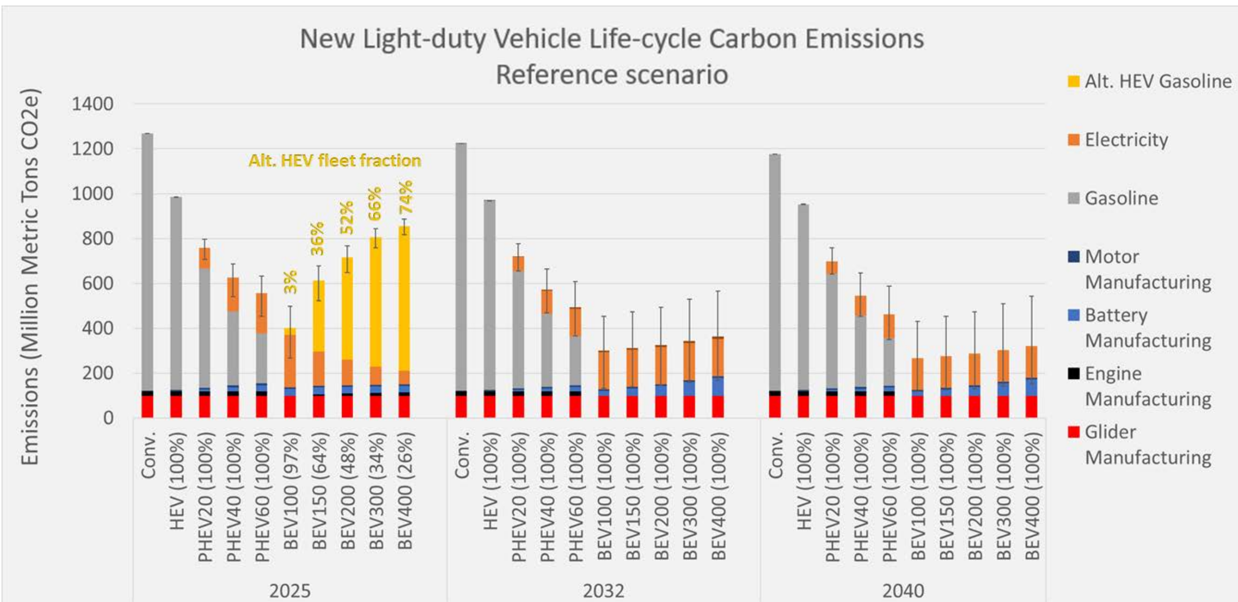

Figure ES 3. Theoretical national-level carbon emissions by powertrain under the reference battery growth scenario (which aligns with the growth rate of total capacity levels for existing and currently announced battery manufacturing facilities in the U.S. and Canada).

The analyses conducted across the reference along with the high and the low sensitivity scenarios highlight the significant impact of the battery growth assumptions on the theoretical analyses for replacing all new U.S. LDVs with a given type of PEV. To underscore this, Figure ES 4 plots the potential carbon emissions reduction for three example powertrains from both the reference and the low sensitivity battery growth scenarios against the assumed GWh/year constraint at each analyzed year. Note that the results in the right half of the figure remain relatively unchanged since each of the PEVs can achieve full theoretical replacements of new U.S. LDVs once the assumed battery constraint exceeds ~1,500 GWh/year (which is also why including results from the high sensitivity battery growth scenario would add little value to the plot). The little variation that exists beyond ~1,500 GWh/year is simply an artifact of the different grid mix assumptions in the varying analysis years (e.g., 2032 versus 2040) associated with different scenario datapoints.

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Under such conditions of sufficient battery availability, BEVs achieve the lowest national-level GHG emissions outcomes (as in the per-vehicle analysis), with relatively consistent results across BEVs of different ranges—though with short-range BEVs achieving the absolute lowest theoretical carbon emissions results. Under moderately constrained battery availability assumptions, short-range BEVs show significantly more pronounced theoretical GHG emissions advantage (though are acknowledged to have questionable large-scale market potential). Under the nearest-term and most constrained battery availability assumptions, each of the PEV configurations in Figure ES 4 would need to combine with some proportion of alternative HEVs to fully replace new U.S. LDVs. Under these assumptions, the depths of GHG emissions reductions are more limited than when battery availability is greater, and the theoretical minimum GHG emissions outcomes are comparable between PHEVs and short-range BEVs.

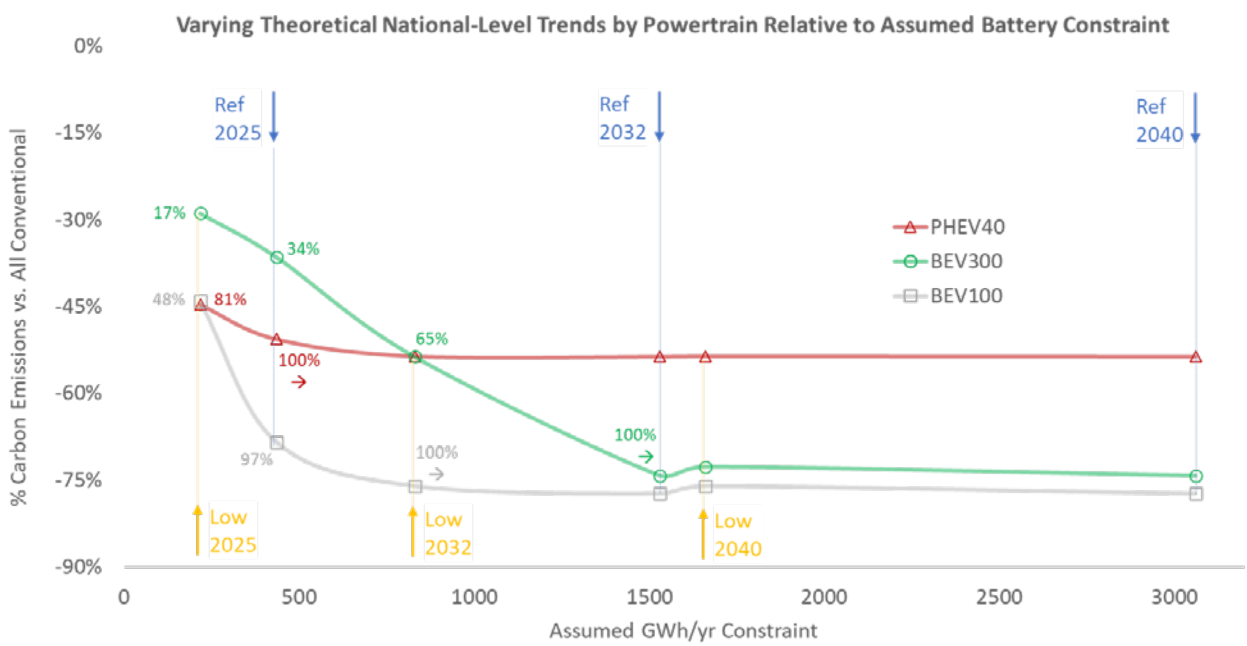

Figure ES 4. Summarized impact of battery availability on theoretical national-level carbon emissions reduction for three powertrains—drawn from the reference ("Ref") and the lower sensitivity ("Low") battery growth scenario analyses. The small font percentages next to the plotted points indicate the fraction of new U.S. LDV sales that could be that powertrain at each assumed GWh/year constraint (while allowing the remainder of the fleet to be HEVs). Once 100% of new U.S. LDV sales could become the given type of powertrain, points at higher assumed GWh/year availability levels are no longer labeled.

Limitations for the national-level analyses include the acknowledgement that monolithic replacement of all new U.S. LDVs by a single type of PEV may not be 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 best combinations of vehicle GHG reductions and large-scale marketability to 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

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battery growth 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—including the development of novel technologies such as sodium-ion, which may help as a viable complement to lithium-ion battery supplies.

Though complete replacement of all new U.S. LDVs with PEVs may not be feasible in the next couple of years, 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).

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1 Introduction

Investment in battery and electrification technologies has the potential to greatly reduce vehicular greenhouse gas (GHG) emissions, as a battery electric vehicle (BEV) will have zero tailpipe emissions. However, there will be GHG emissions associated with production of the vehicle including its battery, and with any carbon-emitting electricity sources used to charge the vehicle. In the context of material accessibility and supply chain challenges that may restrict the rate of increasing battery availability, technologies such as plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) can also reduce GHG emissions relative to conventional internal combustion engine vehicles (ICEVs) with progressively lower per-vehicle battery requirements.

This study explores the GHG reduction benefits of different vehicle designs in the context of the per-vehicle battery requirements and varying overall battery availability growth 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 focuses on inventorying the factors contributing to vehicle life cycle GHG emissions and their variability. These factors are then used to analyze the relative carbon reduction benefits of different vehicle designs and electrification levels. Note that electrified vehicles may include HEVs, PHEVs, and BEVs—though only the latter two (collectively referred to as plug-in electric vehicles, or PEVs) can have zero tailpipe emissions. After establishing a range of prospective battery availability growth scenarios, the project expands the vehicle-level analysis to the national fleet level. Under the initial phase of work included in this report, the national-level analysis focuses on identifying the configuration of the theoretically lowest carbon PEV if all available batteries under a given scenario are used to replace all new U.S. LDVs with a single type of PEV. Though not included in the current phase of work, potential future extension incorporating realistic market dynamics modeling would give further insights on the best combinations of vehicle GHG reductions and large-scale marketability to minimize overall GHG emissions under different battery availability scenarios.

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2 Data and Method for Life Cycle GHG Emissions Estimation

This chapter first defines the scope, system boundary, and functional unit for the estimation of life cycle GHG emissions. The framework for life cycle GHG emissions estimation is also presented to illustrate the overall data flow and integration. The vehicle-level assessment in Chapter 3 adopts a stochastic analytical approach to account for uncertainty and variability, for which this chapter describes different scenarios and assumptions around key input parameters, focusing on vehicle attributes, carbon intensity of high voltage battery production, vehicle operation, and electric grid evolution.

2.1 Scope, System Boundary, and Functional Unit

As this study is focused on U.S. LDV carbon emissions, the environmental impact category is limited to GHG emissions, which are characterized as carbon dioxide equivalent (CO_2e) in metric ton (or tonne), based on 100-year global warming potentials (GWP) from the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC 2023). For simplicity, carbon emissions and GHG emissions are used interchangeably in this study. The functional unit is emissions over each mile of vehicle travel (CO_2e per mile), without considering the number of passengers (e.g., CO_2e per passenger-mile traveled) or total mass transported (e.g., CO_2e per kg-mile traveled).

Vehicle powertrain technologies in this study include ICEV, HEV, PHEV, and BEV. The per-vehicle analysis 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. The vehicle attributes for each powertrain technology and model year derive from a separate Transportation Decarbonization Analysis (TDA) project (Brooker, Yang and Gonder 2024). The TDA project estimated future evolution of vehicle characteristics and sales for the full diversity of the U.S. LDV fleet. These have been aggregated into representative characteristics for three vehicle type categories: cars/sedans, SUVs, and pickup trucks (PUTs), while differentiating standard vs. premium class. This is done through sales weighting the attributes for the highest priced 20% of individual vehicles in each category (for premium) and likewise for the lowest priced 80% of individual vehicles in each category (for standard). The resulting future attributes for each powertrain type in each of these vehicle categories are available from the Automotive Deployment Options Projection Tool (ADOPT) website in 5-year increments out to 2050, though just the attribute cases for 2025 and for 2040 are leveraged for this study (NREL 2023a).

In addition to the various technology- and time-related elements, as illustrated in Figure 1, the study scope includes raw materials extraction, transportation, and processing; vehicle and parts manufacturing and assembly; vehicle operation and maintenance; fuel production, transmission, distribution, and transportation; and vehicle and parts end-of-life. The system boundary excludes the construction, operation, maintenance, and end-of-life of roadways, charging infrastructure, and other transportation assets, assuming that the overall impact of those components on comparative life cycle GHG emissions between different vehicle technologies is not significant. Indirect GHG emissions associated with financial services and/or insurance are also excluded from the analysis.

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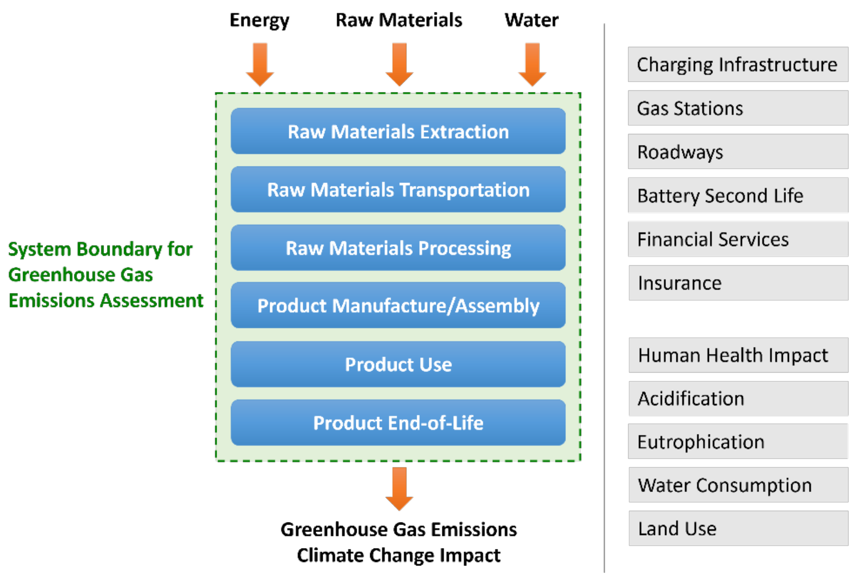

Figure 1. System boundary – adapted from (Lee, Thomas and Brown 2013) (Lee and Thomas 2017).

Regarding the end-of-life stage, this study does not consider cases where some vehicle parts are repurposed and used for another product or service. The life cycle assessment in this report would thus be characterized as cradle-to-grave rather than cradle-to-cradle. For instance, the analysis does not account for potential repurposing of a BEV's high-voltage (HV) battery for stationary energy storage applications following retirement after exhausting its useful life for vehicular application. As detailed later, however, the potential for recycled HV batteries to become a substantial raw material resource in the future is accounted for within the range of scenarios considered for how GHG emissions from battery manufacturing may evolve over time.

2.2 Life Cycle GHG Emissions Estimation Framework

Figure 2 shows the overall data flow and framework adopted for the per-vehicle life cycle GHG emissions estimation. In general, the analysis relies on a stochastic approach to account for uncertainty and variation of input parameters and scenarios.

The first part of the analysis considers manufacturing and assembly of the vehicle and parts (body, chassis, tires, etc., except for the HV battery in electrified vehicles) as well as their replacements (tires, engine oils, etc.) over the vehicle lifetime. Here, manufacturing and assembly also includes upstream processes such as raw materials extraction/processing and transportation, as well as downstream end-of-life components. To estimate life cycle GHG emissions for these components, the analysis employs the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (ANL, GREET 2023).

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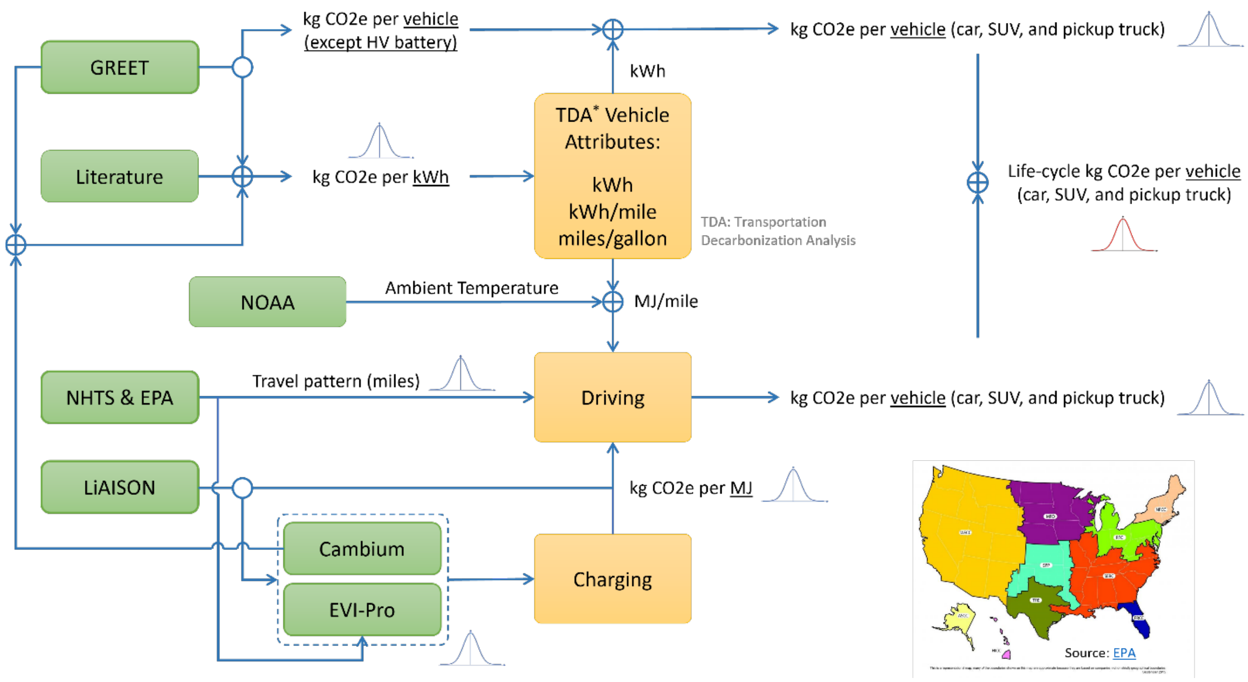

Figure 2. Framework for per-vehicle life cycle (cradle-to-grave) GHG emissions accounting. The circles with plus signs in the figure indicate inputs from multiple sources coming together for use in the downstream calculation.

Regarding production of the HV battery (distinct from the low-voltage battery used for auxiliary loads), life cycle GHG intensity is estimated on a per-kWh basis via literature review discussed in a later section. This allows incorporation of different battery capacity assumptions for different vehicle types, classes, and model years (Figure 3), which will lead to different total GHG emissions per battery pack or vehicle. Battery capacity values in Figure 3 derive from the aforementioned TDA project (NREL 2023a; Brooker, Yang, and Gonder 2024). These battery size assumptions translate into 30 to 80 miles of electric range for PHEVs and 200 to 400 miles for BEVs; further characteristics for the range of vehicles included in the stochastic analyses are provided in Section 2.3.

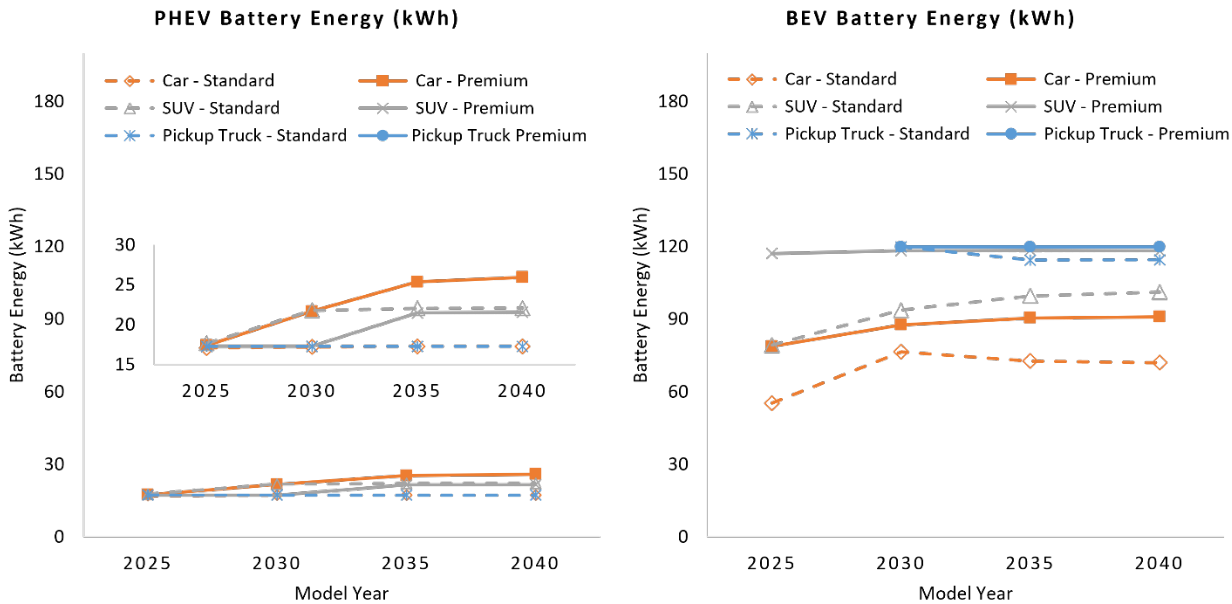

Figure 3. HV battery energy by model year – PHEV (left, including zoomed-in inset) and BEV (right). (NREL 2023a; Brooker, Yang, and Gonder 2024).

The remaining life cycle GHG emissions accounting comprises vehicle operation (i.e., driving and charging). For vehicle driving, the study again leverages TDA's baseline vehicle energy efficiency values that vary with vehicle type, class, and model year (NREL 2023a; Brooker, Yang, and Gonder 2024). Vehicle energy use is also affected by ambient temperature and corresponding heating, ventilating, and air-conditioning (HVAC) load, which is known to disproportionally influence electric vehicles compared to internal combustion engine counterparts (AAA 2019) (Lee, Elgowainy and Vijayagopal 2019). For ambient temperatures, the analysis utilizes NOAA's county-by-county annual average temperature data (NOAA 2023b) – see Figure 4 for example. In short, baseline electric vehicle energy efficiency (or energy consumption rate) is adjusted as a function of ambient temperature, using temperature correction factors from the Electric Vehicle Infrastructure for Road Trips (EVI-RoadTrip) model (NREL 2023d) that is discussed in a later section.

From the vehicle energy consumption rates (e.g., MJ/mile), total GHG emissions for driving are calculated from the total distance traveled (miles) and life cycle GHG intensity of fuels consumed (kg CO2e per MJ). Vehicle lifetime travel distance is based on the latest vehicle emissions regulatory analysis data (EPA 2023c). For PEVs, GHG emissions related to electricity consumption heavily depend on electricity source and charging pattern (e.g., time of the day). This study relies on NREL's Cambium (NREL 2023b) for the former (electricity source from 2023 to 2055) and the Electric Vehicle Infrastructure – Projection (EVI-Pro) tool (NREL 2023c) for the latter (charging pattern).

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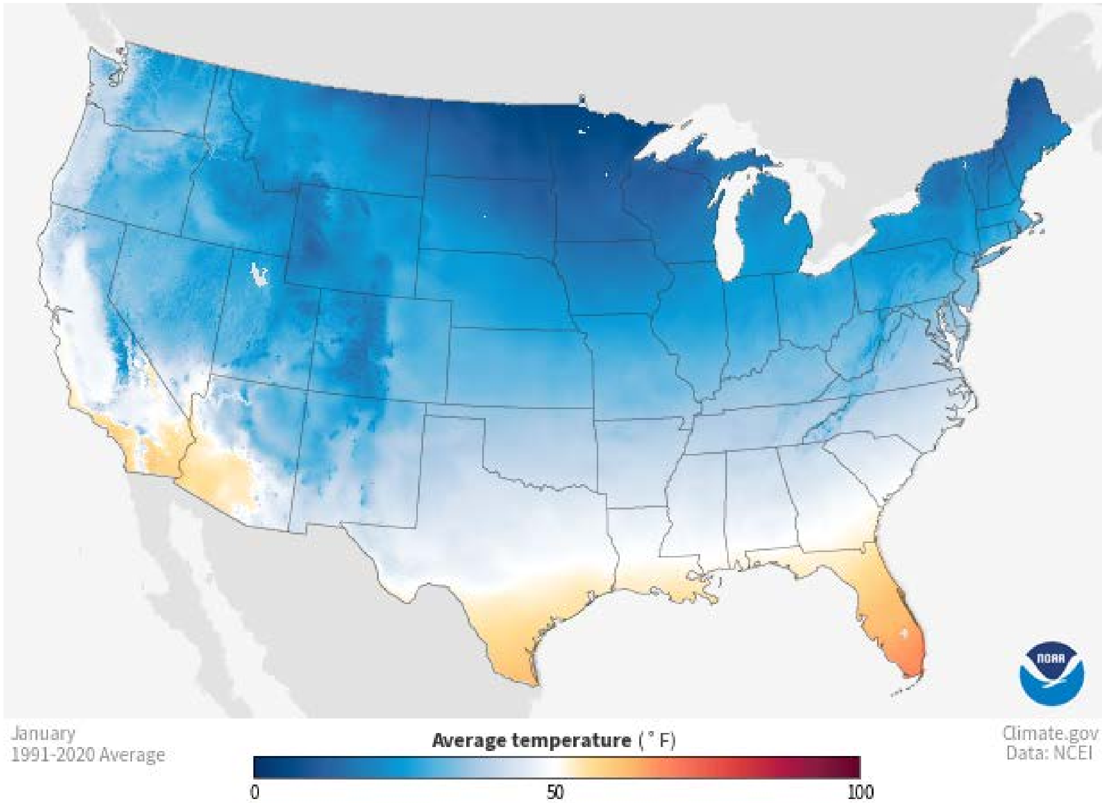

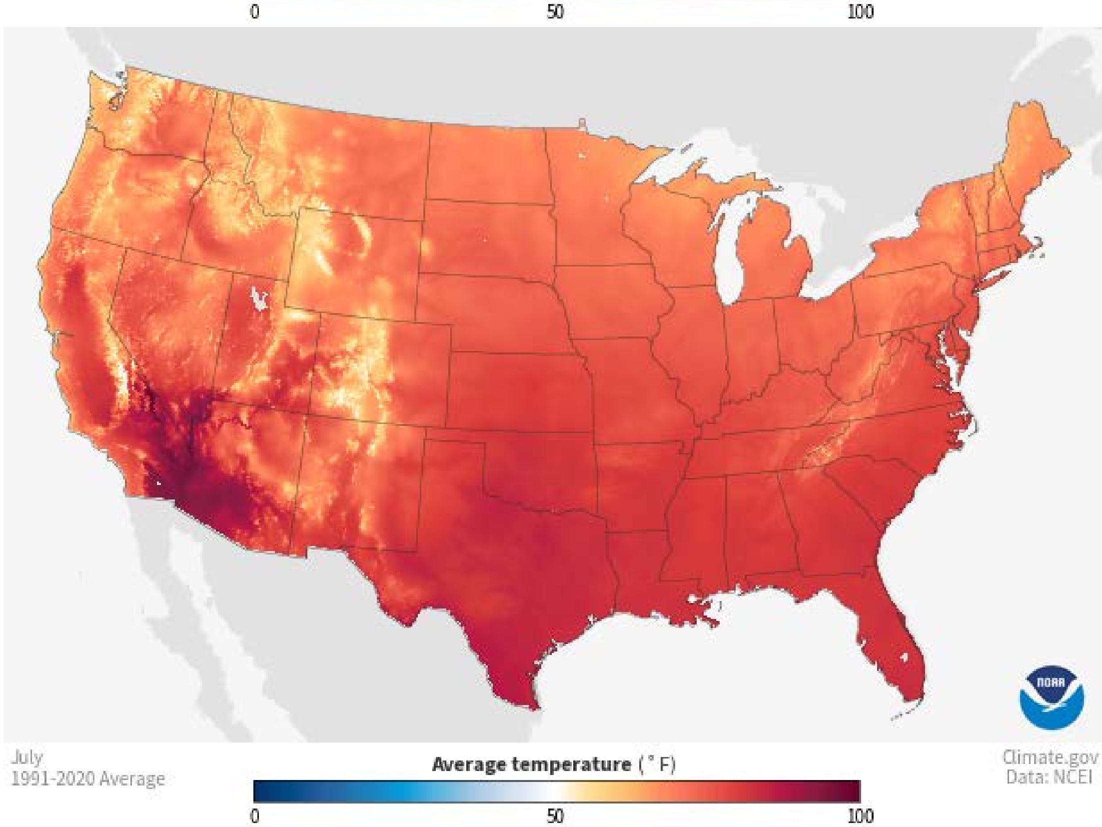

Figure 4. 1991-2020 Monthly average temperature for January (top) and July (bottom) (NOAA 2023a).

Life cycle Analysis Integration into Scalable Open-source Numerical models (LiAISON) (Lamers, et al. 2023) performs prospective life cycle GHG assessment for fuels used in conventional vehicles and power supply for electric vehicles. This framework uses predictive information from integrated assessment models (IAMs) to determine how important industrial sectors will change in the future (production, efficiency, type, etc.). This information is used to create updated life cycle inventory databases for performing prospective life cycle assessment. See Appendix section A.1 for relevant data from LiAISON.

Using LiAISON, GHG intensity of gasoline is obtained from cradle to pump. This includes raw material extraction, processing, and distribution, as well as fuel production facility construction, maintenance, and operation Similarly, electricity production GHG emissions are obtained from cradle to plug for different generation technologies. These are aggregated into regional electricity mixes using generation data (from Cambium). These energy sources are combined with vehicle data to include emissions from vehicle operation and extend the system boundary from cradle to wheels.

As such, GHG emissions from vehicle driving in this study incorporate a diverse set of input parameters including vehicle efficiency, temperature/HVAC effect (for PEVs, which see the largest impact), driving distance, fuel type and amount consumed, electricity source, upstream GHG intensity for fuels, and charging patterns. As noted, the vehicle-level evaluation employs a stochastic analysis method to account for uncertainty and variations in input parameters and scenarios.

The estimated GHG emissions for vehicle driving are then combined with the GHG emissions estimates for vehicle and parts manufacturing, assembly, replacements, and end-of-life, to yield total life cycle GHG emissions per vehicle, as illustrated in Figure 2. For the per-vehicle analyses, GHG emissions are characterized for each North American Electric Reliability Corporation (NERC) region (EPA 2015), instead of national fleet average. This region-by-region estimation helps reveal spatial and temporal heterogeneity in GHG emissions for PEVs that depend on regional electricity characteristics.

2.3 Vehicle Attributes by Technology and Model Year

Energy consumption rate is one of the most significant contributing factors for life cycle GHG emissions; this varies with vehicle type, class, technology, and model year. Table 1 summarizes energy consumption rate values adopted in this study, based on NREL's TDA project (NREL 2023a; Brooker, Yang, and Gonder 2024). The values are all in kWh/mile, in which fuel economy, often characterized as miles per gasoline gallon equivalent (MPGGE), is converted to kWh/mile for consistency, using the conversion factor of 0.03 gasoline gallon for 1 kWh (AFDC 2023). This MPGGE to kWh/mile conversion applies to ICEVs, HEVs, and PHEVs in charge sustaining (CS) operation. The standard utility factor curve with a once daily charging assumption is used to combine PHEV electricity and gasoline consumption during the respective charge depleting (CD) and CS modes of operation (SAE International 2010)—though it is acknowledged that charging PHEVs less frequently cause them to use relatively more gasoline whereas more frequent charging can further reduce gasoline consumption. Per Table 1, energy consumption rate (or inverse of vehicle efficiency) generally decreases over time, while showing considerable variations between vehicle technologies, types, and classes.

Table 1. Energy consumption rate, in kWh/mile (1 kWh is equivalent to 0.03 gasoline gallon) (AFDC 2023), for driving, by vehicle technology, type, class, and model year.

		Standard					Premium				
		2020	**2025**	**2030**	**2035**	**2040**	**2020**	**2025**	**2030**	**2035**	**2040**
ICEV	Car	1.15	1.10	1.04	0.98	0.96	1.44	1.36	1.28	1.20	1.18
	SUV	1.43	1.35	1.28	1.20	1.17	1.73	1.65	1.54	1.45	1.42
	PUT	1.72	1.64	1.55	1.47	1.45	1.93	1.83	1.76	1.67	1.63
HEV	Car	0.72	0.60	0.60	0.57	0.57	0.83	0.69	0.70	0.66	0.66
	SUV	0.86	0.72	0.72	0.69	0.69	0.76	0.94	0.78	0.78	0.79
	PUT	0.79	0.66	0.65	0.62	0.61					
PHEV (Charge Sustaining)	Car		0.67	0.68	0.66	0.64	0.83	0.71	0.80	0.84	0.84
	SUV	0.94	0.81	0.84	0.80	0.79	1.10	0.94	0.87	0.89	0.88
	PUT		0.91	0.90	0.85	0.84	1.10				
PHEV (Charge Depleting)	Car	0.29	0.31	0.32	0.32		0.33	0.34	0.36	0.36	0.35
	SUV	0.39	0.39	0.37	0.37	0.36	0.50	0.51	0.42	0.45	0.45
	PUT		0.47	0.46	0.46	0.46	0.48				
BEV	Car	0.30	0.29	0.24	0.24	0.24	0.31	0.28	0.30	0.27	0.27
	SUV		0.32	0.33	0.32	0.31	0.39	0.37	0.34	0.34	0.35
	PUT			0.51	0.47	0.47			0.51	0.51	0.52

2.4 GHG Emissions for Vehicle and Parts

As noted earlier, and as depicted in Figure 2, this study divides GHG emissions for vehicle and parts manufacturing, assembly, replacements, and end-of-life into two parts: HV battery, and everything else. The following section details data collected from a broad literature review to inform assumptions used for the HV battery. This study employed GHG emissions factors based on GREET for everything else. Figure 5 shows total GHG emissions for HV batteries in electrified vehicles along with the other contributions from vehicle/parts manufacturing, assembly, replacement, and end-of-life. For illustration purposes, the figure uses average GHG emissions factors for the HV batteries (specifically, NMC111, as an example), overlaid with GREET-based factors for the remaining parts.

Figure 5 indicates that BEVs create less GHG emissions for body, chassis, transmission, powertrain, and fluids, compared to ICEVs, which results in lower total GHG emissions when excluding the HV battery. GHG contributions from vehicle assembly/disposal (also excluding the HV battery), tires, and the low-voltage battery appear similar across different vehicle technologies. The HV battery notably increases total GHG emissions from manufacturing, assembly, replacements, and end-of-life for PHEVs and BEVs relative to ICEVs or HEVs.

Note that the study assumes the HV battery lasts the life of the vehicle and is not replaced during the vehicle lifetime. The study applies the same assumptions used in GREET for components

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that are replaced during vehicle life. These include assuming that tires are replaced three to four times over vehicle lifetime on average, engine oil 40 times, brake fluid three or four times, transmission fluid once, powertrain coolant three or four times, and windshield fluids about 20 times.

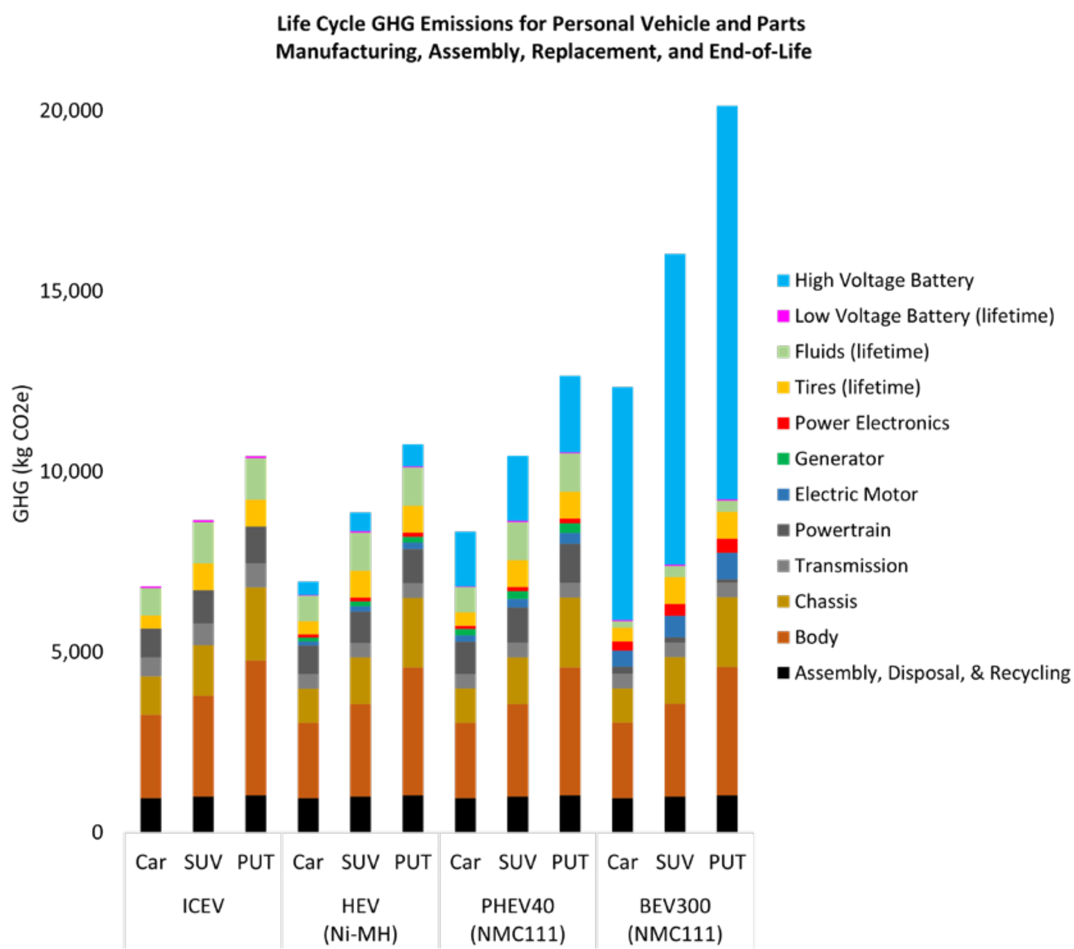

Figure 5. Per-vehicle life cycle GHG emissions for vehicle/parts manufacturing, assembly, replacements, and end-of-life for current model year car/sedan, SUV, and pickup truck – adapted from GREET model.

2.5 Carbon Intensity of HV Battery Production

As previously mentioned, carbon intensity of HV battery (in kg CO_2e per kWh of battery) is estimated based on literature review. The assembled data from literature inform the possible range that HV battery production may contribute to GHG emissions for electrified vehicle manufacturing. The data are primarily based on publications from 2017 to 2022 to maximize data relevance, although some older data are also found as references in these publications. The system boundaries of the studies are limited to cradle-to-gate, covering raw material extraction, material production, cell and component manufacturing, and battery pack assembly.

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The GHG emissions associated with battery production can vary based on geographical location to produce the battery, cathode chemistry, cell design, specific energy, energy consumption, electricity mix, and system boundaries (Bouter and Guichet 2022). Among those parameters, this study focuses on the impact of variation in geographical location, cathode chemistry, electricity mix, and potential future growth of materials sourced from battery recycling. Considered locations include the United States, Europe, China, Japan, and South Korea. The representative cathode chemistries are NMC (Lithium Nickel-Manganese-Cobalt Oxide), NCA (Lithium Nickel-Cobalt-Aluminum Oxide), and LFP (Lithium Iron Phosphate). Table 2 summarizes GHG intensity of HV battery production for different geographical locations and cathode chemistries.

Table 2. Summary of carbon intensity values (kg CO_2e per kWh) based on literature review.

Manufacturing Location	Battery Cathode Chemistry	Carbon Intensity (kg CO_2e per kWh)			
		Average	Median	Data Points	Literature Reviewed
United States	NMC	70	60	11	(Romare and Dahllof 2017) (Qiao, et al. 2017) (Hao, et al. 2017) (Kelly, Dai and Wang 2020) (Bieker 2021) (Shu, et al. 2021) (Accardo, et al. 2021)
	LFP	45	41	8	
	NCA	67	67	2	
Europe	NMC	56	55	6	
	LFP	37	37	5	
	NCA	57	57	1	
China	NMC	105	108	12	
	LFP	56	54	8	
	NCA	96	90	3	
South Korea	NMC	65	64	6	
	LFP	48	48	5	
	NCA	67	67	1	
Japan	NMC	69	68	6	
	LFP	53	53	6	
	NCA	70	70	1	

The data reveal notable variation of HV battery carbon intensity across various geographical locations and cathode chemistries. Batteries produced in China appear to have the greatest carbon intensity among the locations considered, whereas Europe seems to have the lowest compared to the other regions for the same cathode chemistries. This is partly attributable to the electricity mix in each region used for battery production. China's electricity production still heavily relies on fossil fuels, whereas large shares of Europe's electricity generation come from renewable sources and nuclear power. In terms of cathode chemistries, the data suggest that production of LFP is generally less carbon intensive than NMC or NCA, as GHG emissions from the production of ternary precursor in LFP cathodes are considerably lower than from NMC cathodes (Lai, et al. 2022).

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Regarding the impact of electricity mix on battery production carbon intensity, note that electricity mix varies not only across different regions/countries, but also over time. For that reason, this study considers potential changes in future battery production carbon intensity as estimated electricity production shares change over time. Figure 6 illustrates how changing electricity production shares from low-carbon sources (i.e., renewables and nuclear) subsequently flow into changing longitudinal GHG intensity estimates for battery manufacturing that leverages the assumed electricity generation mix. Depending on the electric grid evolution scenario, U.S. HV battery production carbon intensity may decrease by 15% in 2040 compared to current year. Five referenced Cambium scenarios include Mid Case, Low and High Renewable Energy (RE) Cost, and Low and High Natural Gas (NG) Price.

Year	CI (kgCO2e per kWh) for NMC	Renewables Generation Share (%)	Nuclear Generation Share (%)	Renewables + Nuclear Generation Share (%)
2022	77	20%	20%	40%
2040	71	40%	15%	55%

(Adapted from GREET)

0.6% decrease in carbon intensity for every 1% increase in electricity generation share of renewable + nuclear

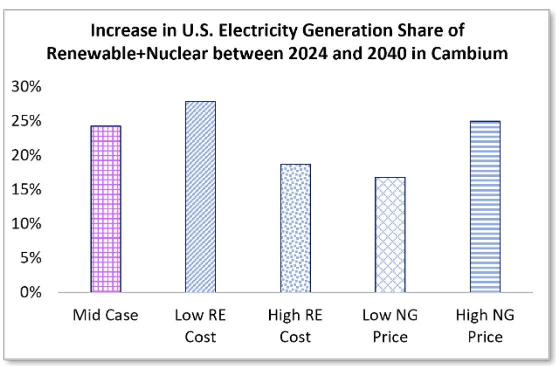

Figure 6. Carbon intensity of U.S. HV battery production for electric vehicles, depending on the future share of low-carbon electricity fuels such as renewables and nuclear.

In addition to longitudinal changes in the share of low-carbon electricity generation sources, other factors that may change battery manufacturing GHG intensity over time include changes in the relative shares of different cathode chemistries and of origin locations (i.e., shares of batteries imported from different locations to the U.S. and the grid mix in those locations). In addition, utilizing recycled materials as a source has the potential to decrease the GHG emission associated with battery production (Chen, et al. 2022). This study explores multiple scenarios to understand how GHG intensity changes when these various factors undergo fluctuations.

This is done by first taking the median literature review values as the initial reference point for the year 2022. These numbers are calculated as a weighted average, considering both battery chemistry and the source of supply. This study follows Bloomberg NEF (BNEF) cathode

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chemistry projections in 2022: 44% NMC, 37% NCA, and 19% LFP (BloombergNEF 2022). With respect to battery supply sources, the corresponding literature-informed starting point assumptions (reflecting current Chinese supply chain dominance) are 70% of available batteries originating from China, 10% from Europe, 5% from Japan, 5% from South Korea, and the remaining 10% produced domestically within the U.S. (International Energy Agency 2022) (S&P Global 2023). Note that while certain chemistries have greater production dominance in specific regions, this analysis makes a simplifying assumption of maintaining the same chemistry mix assumption in each region. These assumptions result in a starting point battery manufacturing GHG intensity of 81 kg CO_2e per kWh for all scenarios. Originating from this starting point, Table 3 summarizes the four future battery manufacturing GHG intensity scenarios established from different combinations of evolving assumptions about the mix of cathode chemistries, supply locations, electricity generation, and battery recycling.

Table 3. Set of scenario combinations of battery manufacturing emissions.

Factor	High Emission Scenario	Moderate Emission Scenario	Base Scenario	Low Emission Scenario
Cathode Chemistry Mix	100% NMC by 2030	30% NMC - 50% LFP - 20% NCA by 2030		100% LFP by 2030
Supply Regionality	China Dominant: 70% China;10% Europe; 5% Japan; 5% South Korea; 10% US by 2030		IRA Case: China: 20%; US: 40%; EU: 20%; Japan: 10%; South Korea: 10% by 2030	100% US by 2030
US Electricity Mix	No impact captured		Cambium Mid Case	Cambium Low Renewable Price
The Impact of Recycling	No impact captured		Impact ramps up to an 18% reduction in battery manufacturing GHG emissions by 2040	

Figure 7 illustrates the four HV battery production GHG intensity trajectories over time. The high-emissions scenario derives from assumed cathode chemistry shifts to predominantly NMC by 2030, with a substantial portion of the battery supply coming from China. The moderate emission scenario derives from assumed transition towards a more balanced composition of cathode chemistries, but with China continuing to be the dominant source of battery supply. The base scenario derives from the same assumed transition toward a more balanced cathode chemistry mix, along with an assumed transition toward more diversified supply locations. The shifted battery sourcing assumptions parallel Inflation Reduction Act (IRA) tax credit requirements, which mandate that by 2027, at least 80% of the battery critical minerals are extracted or processed domestically or in a U.S. Free Trade Agreement (FTA) country (Treasury 2023). Furthermore, the base scenario considers the impact of moderate future decarbonization of the U.S. grid in reducing overall HV battery production GHG emissions. According to the Cambium Mid-case projection, the share of nuclear and renewable energy is set to grow by 24% by 2040 (Gagnon, Cowiestoll and Schwarz 2023).

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While the chemistry mix, supply regionality, and electricity mix assumptions are the dominant factors in determining the range of battery manufacturing emissions scenarios, potential incremental impacts from battery recycling are additionally included in the base and the low-emission scenarios (and are excluded from the high- and moderate-emissions scenarios). Under idealized conditions, materials from retired batteries have been estimated as able to supply 60% of U.S. LDV battery demand by 2040 (Dunn, et al. 2021), though other sources provide more modest estimates for the potential of recycling to reduce battery mineral primary supply requirements—ranging from 10% to 20% in the 2035-2040 timeframe (IEA 2022) (Barlock, et al. 2024). Additionally, the carbon emission of battery remanufacturing through recycled materials is 4.8% - 51.8% less than that of battery production with raw material (Chen, et al. 2022). Taking a relatively aggressive combination from these broad ranges of estimated recycling plus GHG impacts from battery production with recycled materials, the scenarios incorporating recycling considerations for this analysis assume that the net impact ramps up to an incremental 18% reduction in battery manufacturing GHG emissions by 2040.

Lastly, beyond the incremental recycling assumption, the low-emission scenario includes more aggressive GHG reduction assumptions for each of the primary factors—including complete shifts by 2030 to LFP cathode chemistries and to fully domestic production. The electricity mix projection is based on the Cambium Low Renewable Energy Price Case, which foresees a 30% increase in the share of nuclear and renewable energy by 2040.

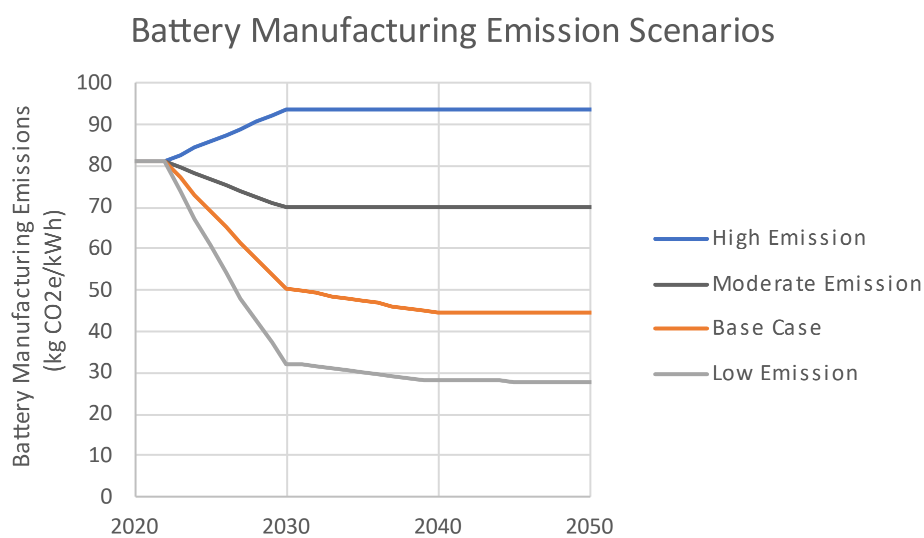

Figure 7. Potential trajectories of GHG intensity from HV battery production over time for the U.S., corresponding to the input assumption factors summarized in Table 3.

2.6 Vehicle Operation – Driving and Refueling

By and large, GHG emissions associated with vehicle operation consist of driving and refueling/charging, whether it is on-road or upstream emissions. Note that while vehicle operation may be considered to include maintenance-related components such as replacing tires,

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engine oil, etc., those components are already accounted for in Section 2.4. Generally, GHG emissions for vehicle driving and charging/refueling can be characterized as:

$$GHG_{VO}[kg\ CO2e] = \sum_{y=1}^{Lifetime}\left(ECR\left[\frac{MJ}{mile}\right] \times D_y[mile] \times CI_{FUEL_y}\left[\frac{kg\ CO2e}{MJ}\right]\right) \quad (1)$$

, where GHG_{VO} represents life cycle GHG emissions for vehicle operation in kg CO_2e, y the y-th year of vehicle lifetime (not model year), ECR the energy consumption rate in MJ/mile, D the driving distance in miles in the y-th year, and CI_{FUEL} the life cycle carbon intensity of fuel (gasoline or electricity) consumed in the y-th year. In other words, life cycle GHG emissions for vehicle operation depend on energy consumption rate, distance traveled, and carbon intensity of fuel used. For electric vehicles, CI_{FUEL} depends on where and when charging occurs, as carbon intensity of electricity varies tremendously between locations as well as different times of day. Gasoline might also have some meaningful geographical variation, but temporal heterogeneity would not be that significant compared to electricity.

Vehicle energy consumption rate (ECR) is summarized in Table 1 above, on which a scaling factor is applied to adjust the baseline values for electric vehicles depending on the location and corresponding HVAC load due to the local climate conditions (Figure 4). For ambient temperature, this study utilizes NOAA's county-by-county 12-month average temperature data, as shown in Figure 8 (NOAA 2023b).

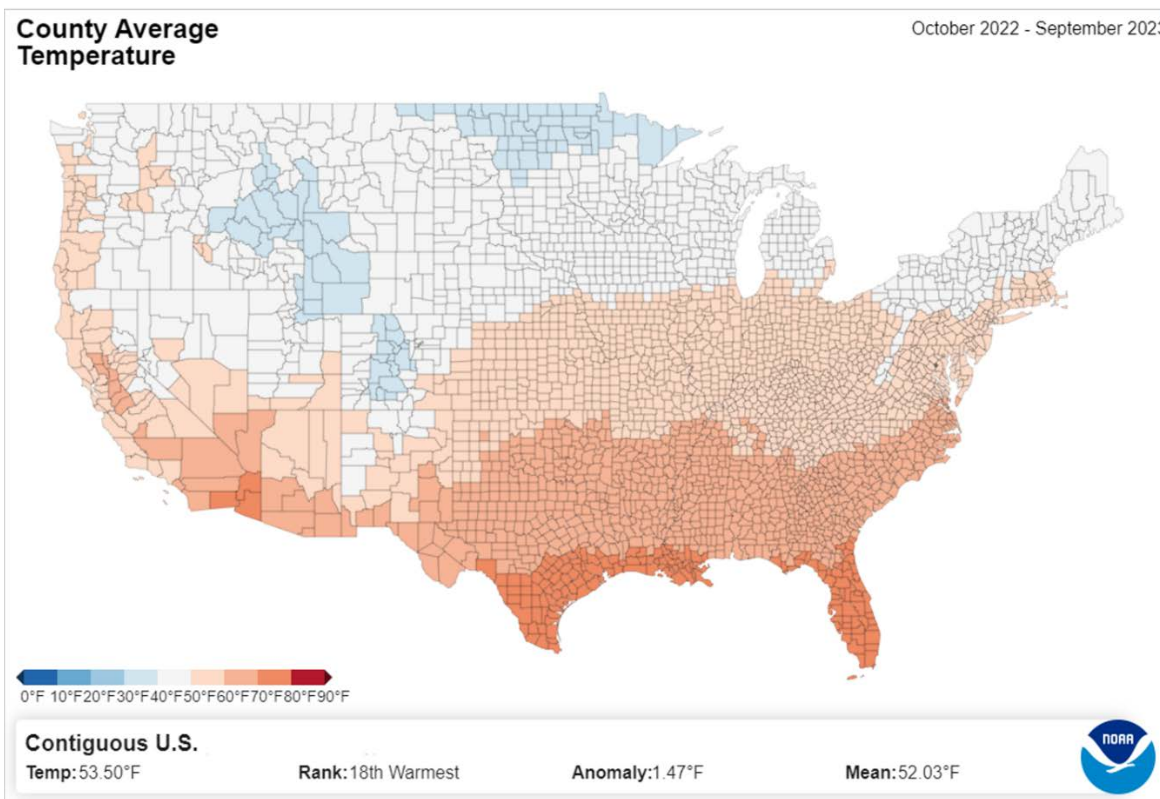

Figure 8. County-by-county annual average ambient temperature (NOAA 2023b).

Different PEVs may experience significant variation in the impact of ambient temperature on their energy consumption rate. In this analysis, the temperature based impacts are informed by test results from two electric vehicles in different ambient temperature conditions (NREL 2023d), which are consistent with independent real-world data on electric vehicle powertrain and HVAC load impact (AAA 2019) (Lee, Elgowainy and Vijayagopal 2019). When overlaid with the 12-month average temperatures in the contiguous U.S. (Figure 8), the electric vehicle energy consumption rate penalty factors generally fall between 1 to 1.3, but for the coldest locations could be as high as 1.7. Disproportionately greater energy consumption is associated with colder climates, mainly due to the lack of internal combustion engine waste heat to warm the cabin in electric vehicles. Note that while ICEVs also experience location- and temperature-varying energy consumption impacts (albeit of generally smaller magnitude than for electric vehicles), this effort takes the conservative approach of only incorporating energy consumption temperature penalties for PEVs into the analysis.

The second contributing factor in Eq. (1) is driving distance in miles, for which this analysis relies on the EPA's latest emissions regulatory data shown in Figure 9 (EPA 2023c). Compared to the older NHTSA data also shown in Figure 9 (NHTSA 2006), EPA's data indicate slightly longer driving distances. Nonetheless, both data sets reveal a few similar patterns. First, driving distance tends to decrease as vehicles age, regardless of vehicle type (sedan, SUV, or pickup truck). Second, cumulative distance traveled after 15 years is around 200,000 miles. Third, pick-up trucks appear to be driven more in comparison with cars/sedans—particularly in the earlier years of ownership.

It is possible that some technologies (e.g., ICEV) are utilized more than others (e.g., BEV), but such technology-dependent variation in annual driving distance or its evolution over time is not considered in this analysis due to the lack of robust data to support such technology-dependent driving or utilization pattern over vehicle lifetime. Simply put, in this study, the same driving distance evolution over vehicle lifetime, shown in Figure 9, is used for all compared powertrain technologies.

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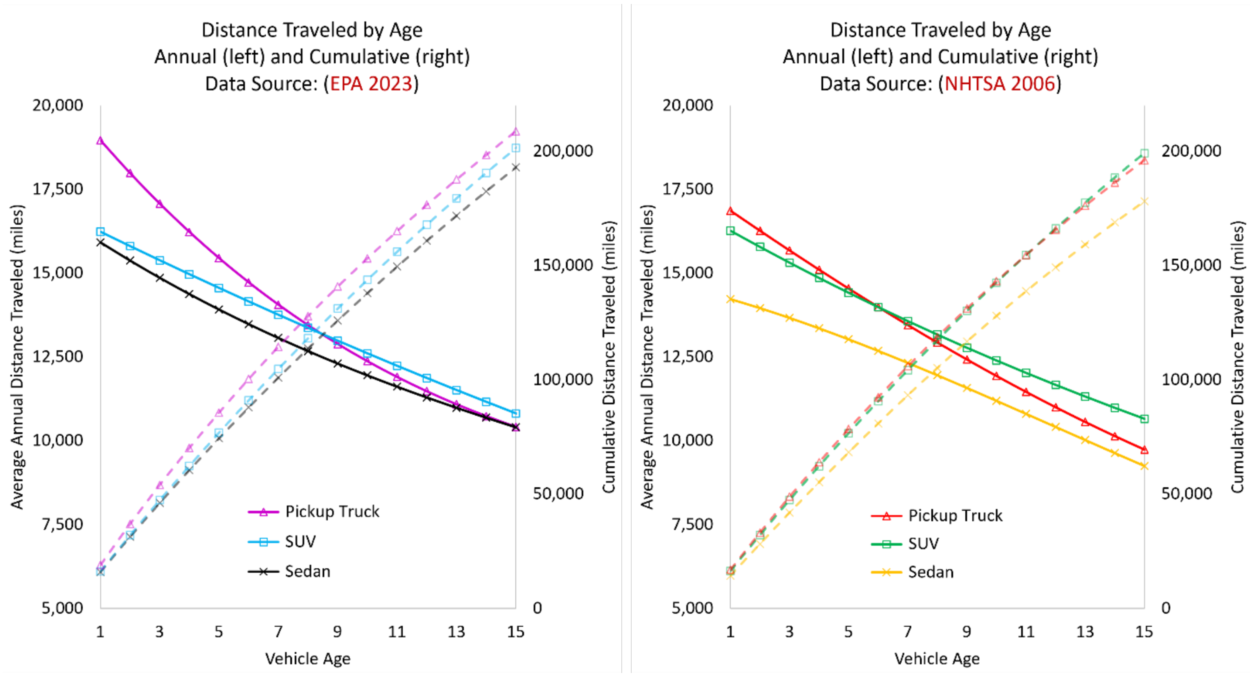

Figure 9. Vehicle miles traveled over vehicle lifetime for different vehicle types from two different data sources – (EPA 2023c) (left) and (NHTSA 2006) (right).

The third contributing factor in Equation (1) is carbon intensity of fuel (CI_{FUEL}). As noted earlier, this study utilizes LiAISON (Ghosh, et al. 2021) (Lamers, et al. 2023) for life cycle carbon intensity of gasoline, as well as of coal, natural gas, nuclear, solar, wind, and other fuels consumed in electricity generating units. Carbon intensity of electricity as a fuel for vehicles can be characterized as:

$$CI_{FUEL_{Electricity}}\left[\frac{kg\ CO2e}{MJ}\right] = \frac{1}{\eta_{T\&D}\times\eta_{Charging}} \times \sum_h \left(P_{Charged_h} \times CI_{Electricity_h}\left[\frac{kg\ CO2e}{MJ}\right]\right) \tag{2}$$

$$CI_{Electricity_h}\left[\frac{kg\ CO2e}{MJ}\right] = \sum_i \left(CI_{EGF_i}\left[\frac{kg\ CO2e}{MJ}\right] \times S_{EGF_i}[\%]\right)\Big|_h \tag{3}$$

, where $CI_{FUEL_{Electricity}}$ represents the life cycle carbon intensity of electricity as fuel for vehicles, $\eta_{T\&D}$ the efficiency of electricity transmission and distribution between the power plants and electric vehicle charger, $\eta_{Charging}$ the charger efficiency, h the h-th hour of day or year, $P_{Charged}$ the probability mass function for electricity drawn from the grid to charge electric vehicles, $CI_{Electricity}$ the life cycle carbon intensity of electricity generated, CI_{EGF} the life cycle carbon intensity of fuels consumed to generate electricity, S_{EGF} the share of fuels consumed to generate electricity, and i the i-th fuel consumed to generate electricity. It must be noted that this study is based on consumption (not generation), as electricity consumed in one area may not necessarily originate from or be generated in that area. The consumption-based approach accounts for the original source or location from which consumed electricity originated, which allows more accurate estimation of electricity mix and thus GHG emissions associated with electricity consumed in different parts of the country.

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In this analysis, $\eta_{T\&D}$ is assumed to be 95% (EIA 2023d), meaning that 5% of generated electrical energy is lost in the process of transmission and distribution between the gate of power plants and the input to an electric vehicle charging station. Charger efficiency, $\eta_{Charging}$, is assumed to be 90%, meaning that 10% of energy is lost on average between the input into the electric vehicle charging station and the output of the charger to the vehicle, for which variation in charger type—such as Level 2 (L2) or direct-current fast charging (DCFC)—or climate/temperature impacts are not explicitly considered/modeled.

The probability mass function for electricity drawn from the grid for electric vehicle charging, $P_{Charged}$, is derived from scenarios modeled with EVI-Pro (NREL 2023c), as illustrated in Figure 10 and Figure 11. As with other modeling parameters, varying inputs from across these different scenarios are included in the stochastic vehicle-level life cycle GHG analyses to explore the range of potential results and the relative importance of different factors on the results. Life cycle carbon intensity for fuels consumed to generate electricity, CI_{EGF_i}, are based on LiAISON. Electricity mix or the share of electricity generation fuels, S_{EGF_i}, comes from Cambium, as discussed in the following section.

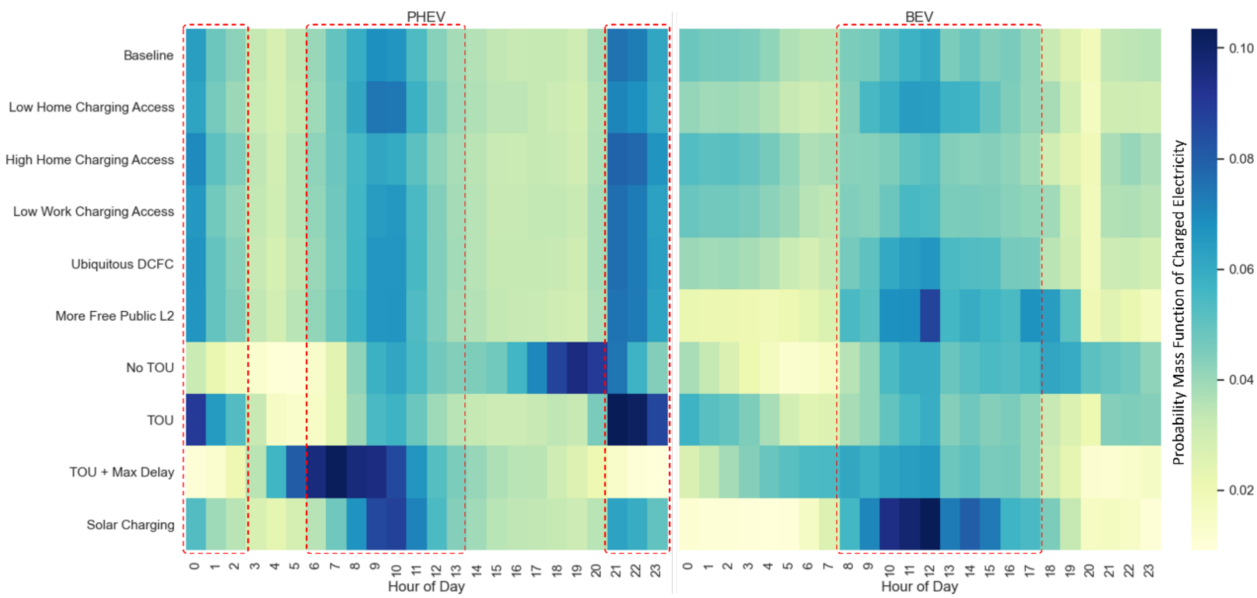

Figure 10. Probability mass function of weekday electric vehicle charging for PHEVs (left) and BEVs (right)—adapted from EVI-Pro (NREL 2023c).

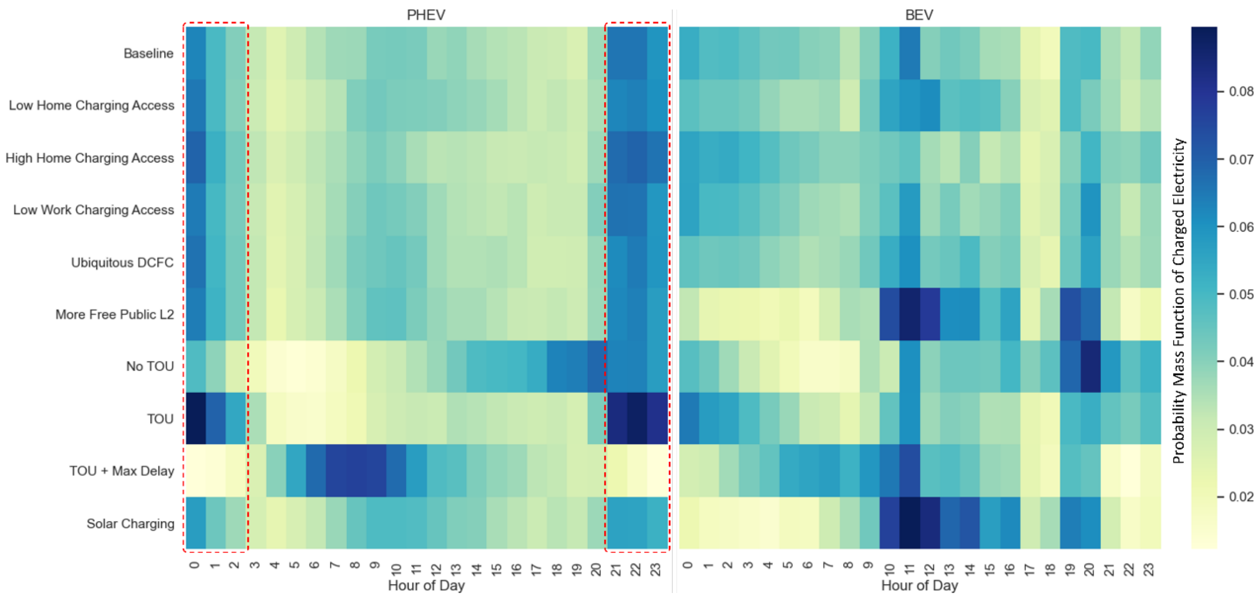

Figure 11. Probability mass function of weekend electric vehicle charging for PHEVs (left) and BEVs (right)—adapted from EVI-Pro (NREL 2023c).

The probability mass functions shown in Figure 10 (for weekdays) reveal that for most scenarios, charged electrical energy for PHEVs are often concentrated in a few hours before and after midnight, as well as in the morning. In the case of BEVs, charged electrical energy for most scenarios is often concentrated during the daytime. Compared to the typical weekday patterns in Figure 10, the typical weekend patterns are distinctively different in Figure 11. For PHEVs under most scenarios, daytime charging on the weekend is markedly less significant relative to weekdays where vehicles could be using workplace charging. For BEVs, weekends (in contrast to weekdays) show less pronounced clusters of charging density across most scenarios.

The assumed charging infrastructure and behavioral factors defining each of the charging scenarios are as follows (CEC 2023):

- Baseline: Baseline assumptions associated with charging infrastructure availability and behavior – see (CEC 2023) for more details.
- Low Home Charging Access: Identical to baseline assumptions, except 10% lower level of home charging access relative to the baseline 67%.
- High Home Charging Access: Identical to baseline assumptions, except 10% higher level of home charging access relative to baseline 67%.
- Low Work Charging Access: Identical to baseline assumptions, except that a 10% lower percentage of commuters are assumed to have access to workplace charging.
- Ubiquitous DCFC: Identical to baseline assumptions, except that electric vehicle drivers without home charging access are assumed to be able to charge their vehicles in an expanded network of DCFC stations (like ubiquitous gas stations).
- More Free Public L2: Identical to baseline assumptions, except that a greater percentage (40% vs. baseline 20%) of electric vehicle drivers are assumed to have access to free public Level 2 chargers in retail locations and so on.

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- No TOU: Identical to baseline assumptions, except that electric vehicle drivers are assumed to start charging their vehicles as soon as they get home, as opposed to potentially delaying to avoid peak hour charges under time-of-use electricity pricing.
- TOU: Identical to baseline assumptions, except that all electric vehicle drivers participate in a time-of-use rates program that encourages participants to charge their vehicles outside the peak hour.
- TOU + Max Delay: Identical to TOU scenario, except that further delay will be implemented for vehicle charging.
- Solar Charging: Identical to baseline assumptions, except that electric vehicle charging during daytime is encouraged to coincide with solar power generation.

2.7 Electric Grid Characterization

The national or regional electric grid in the U.S. is not an isolated system, as electricity can be exchanged between regions and even countries. In contrast to clear demarcation of state or county boundaries, this makes rigid definition of electric grid geographical boundaries challenging to say the least. There are various ways to define or approximate geographical boundaries of electric grid regions. One of the commonly-used boundaries is EPA's eGRID region (EPA 2023b) shown in Figure 12, which is mostly based on utility service territories. However, as can be seen in Figure 12, there are many overlaps between regions, as some customers in the same area might use electricity from utility company A, while other customers might get their electricity from utility company B. To avoid ambiguity as such, this study employs Cambium's Generation and Emission Assessment (GEA) regions as in Figure 13, which is built upon balancing areas, rather than utility service territories. Cambium's GEA regions (Figure 13) are largely similar to EPA's eGRID regions (Figure 12), but GEA regions have clear boundaries for each region – see (Gagnon, Cowiestoll and Schwarz 2023) for more details.

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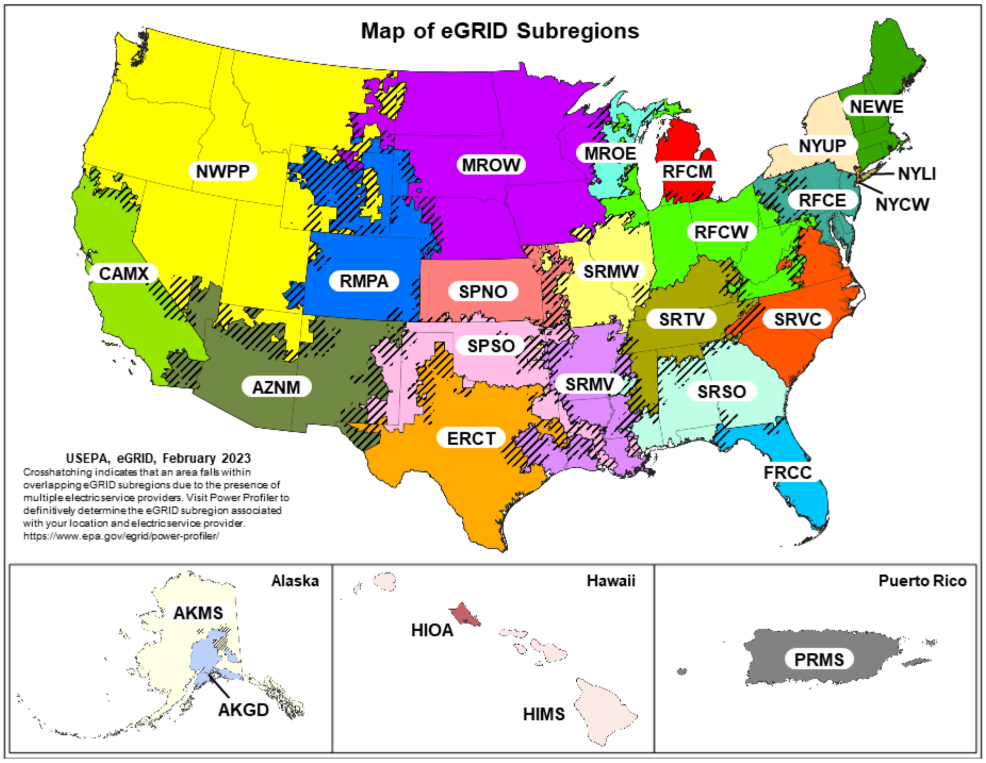

Figure 12. EPA eGRID subregions (EPA 2023b).

In addition to the clearly defined geographical boundaries for each electric grid region across the country, Cambium provides spatially and temporally resolved data for electricity generation and consumption in each region and through 2050 (which was extrapolated in this analysis beyond 2050 to capture the full assumed 15-year life for MY2040 vehicles). This not only allows detailed hourly analysis of electricity generation and consumption, but also enables accounting for longitudinal evolution of the electric grid over the coming decades. Regional, hourly or sub-hourly, and longitudinal representation of the electric grid are crucial for more accurate and rigorous examination of life cycle GHG emissions for PEVs.

However, the fairly large number of Cambium's electric grid regions creates challenges for clear communication and interpretation of life cycle analysis results at that level of geographic disaggregation. This study therefore aggregates electricity consumption mix, S_{EGF_i} in Equation (3), from Cambium's GEA regions to NERC regions, as illustrated in Figure 13, based on total electricity generation for each region as well as geospatial matching. Ideally, incorporating electricity imports and exports between Cambium's GEA regions would help develop more accurate aggregation from GEA regions to NERC regions, but such data were not available during this study.

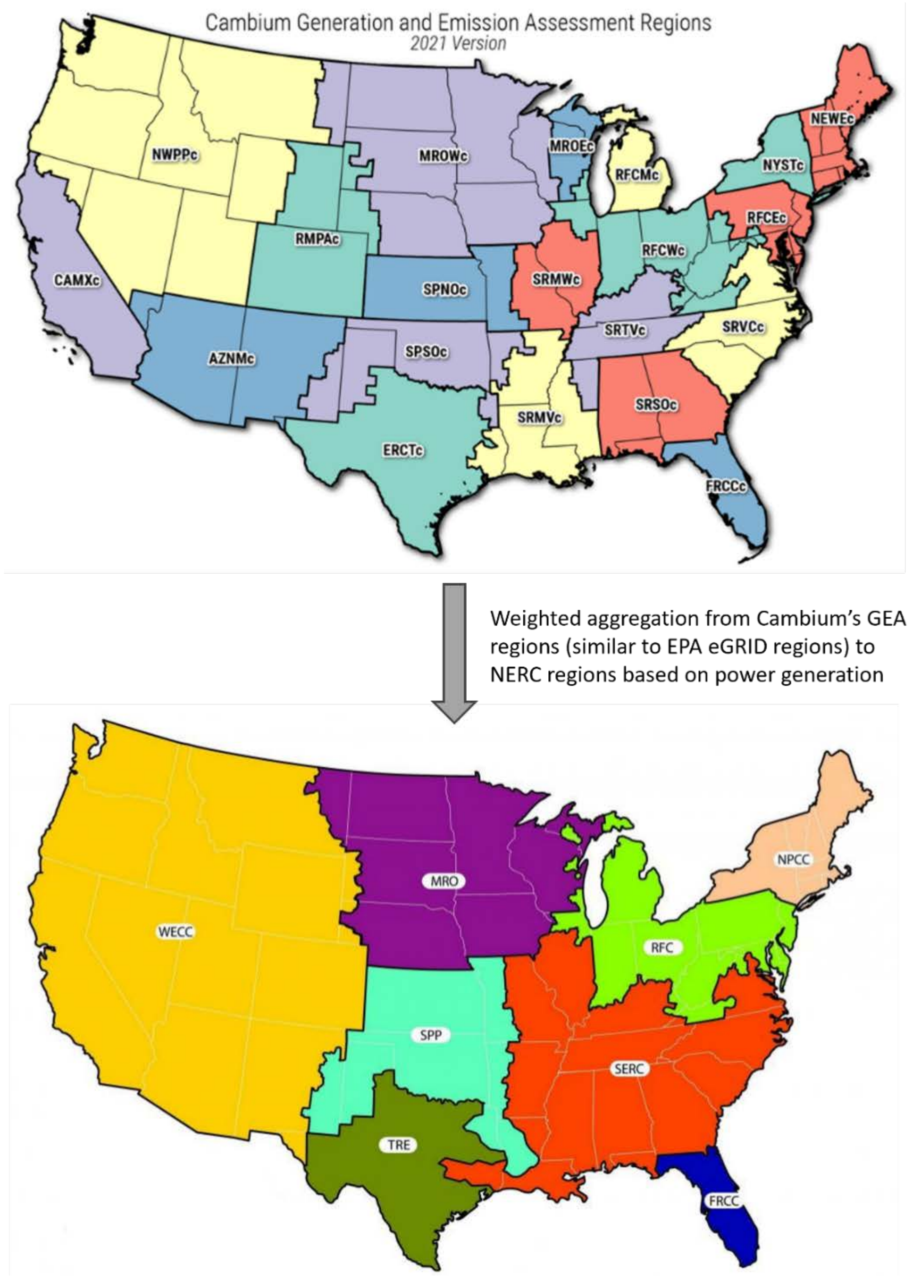

Figure 13. Electric grid regions – Cambium (Gagnon, Cowiestoll and Schwarz 2023) translated to match NERC (EPA 2015).

Figure 14 provides example estimated hourly electricity mix outputs for the baseline scenario derived from Cambium's Mid-case (Gagnon, Cowiestoll and Schwarz 2023)—shown for one week in July of 2024 and 2050 in the U.S. This scenario assumes that nuclear remains a meaningful baseload source between those years, and that natural gas additionally makes up a substantial share owing to its flexibility to ramp up/down relatively fast when needed. The most notable change between 2024 and 2050 is the significant increase in renewable energy sources (e.g., solar and wind) as well as energy storage.

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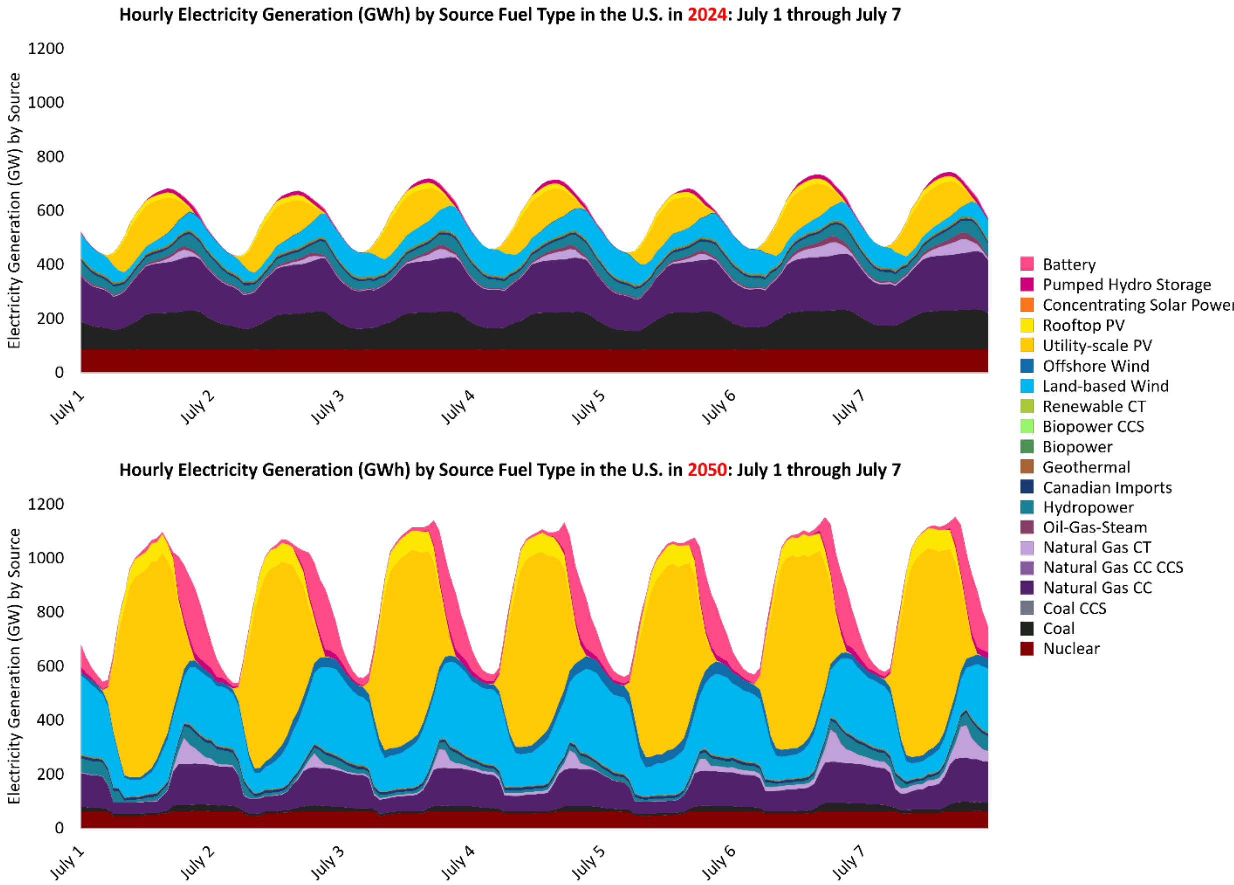

Figure 14. Hourly July U.S. electricity mix by source type in 2024 (top) and 2050 (bottom) for the baseline scenario—adapted from Cambium's Mid-case. Acronyms in the legend include combustion turbine (CT), carbon capture and sequestration (CCS), and combined cycle (CC).

The evolution of electricity generation mixes over the course of the day and over the next few decades (Figure 14) involves transforming the electric grid, including considerable capacity addition of certain fuels and retirement of others. Figure 15 illustrates the changes anticipated by Cambium and reflected in the baseline scenario. As a nation, the U.S. currently generates around 500 GW on average throughout the year, while generating capacity is a little more than 1,200 GW. By 2050, average power generated is estimated to be about 750 GW, whereas the capacity would be a little less than 3,000 GW. The gap between generated electricity vs. capacity lies in the wide range of capacity factors of different fuels. For example, current approximate capacity factors include nuclear at 80%–100%, coal 40%–60%, natural gas 10%–70%, hydro-electric 30%–50%, solar photovoltaic 15%–30%, and wind 25%–40% (EIA 2023b, 2023c).

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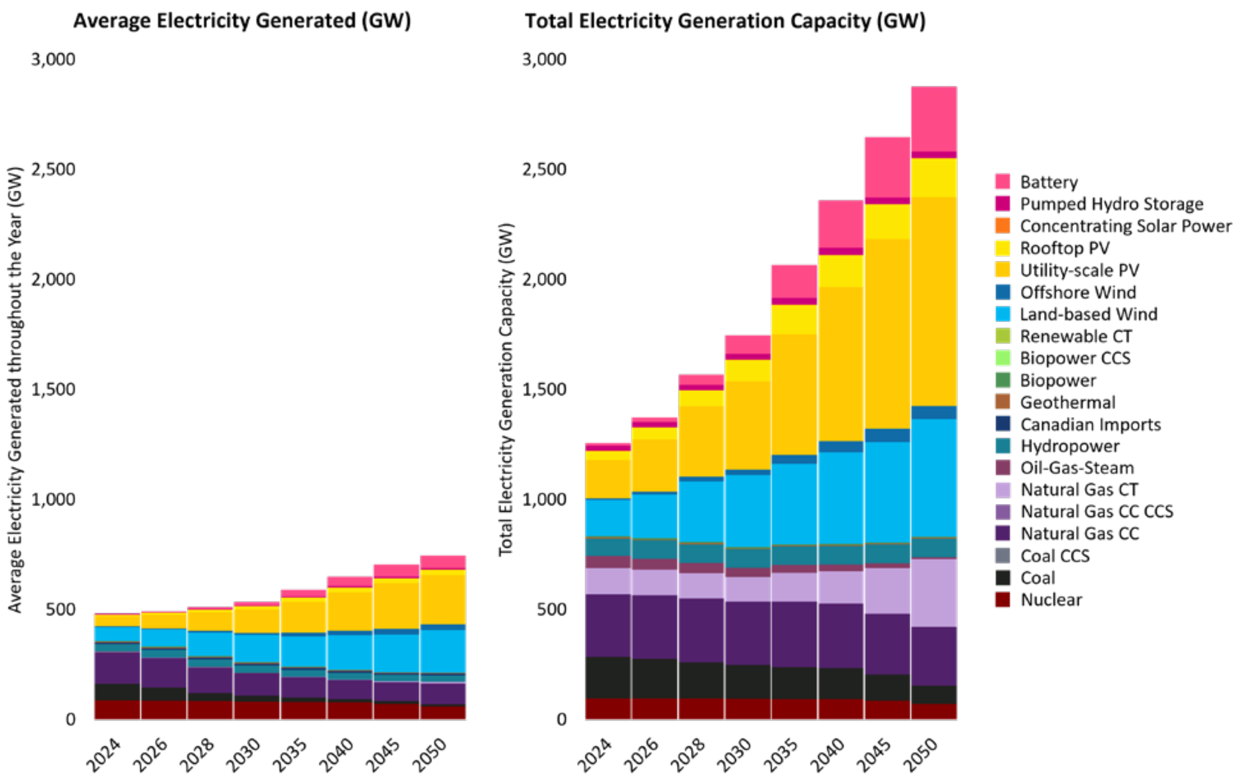

Figure 15. Longitudinal evolution of annual average electrical power generated (left) and generation capacity (right) by source type in the U.S. from 2024 to 2050 for the baseline scenario—adapted from Cambium.

Both hour-to-hour change in electricity mix (Figure 14) and longitudinal structural change in electricity generation fuel or capacity (Figure 15) influence life cycle carbon intensity of electricity for PEVs. Figure 16 demonstrates hourly change in life cycle carbon intensity of electricity across Cambium's GEA regions throughout the year. Figure 16 reveals significant variations in life cycle carbon intensity of electricity throughout the year (8760 hours) within and across the GEA regions. Based on such hour-by-hour carbon intensity data, this study conducts weighted average aggregation to develop a representative 24-hour profile of life cycle carbon intensity for each GEA region.

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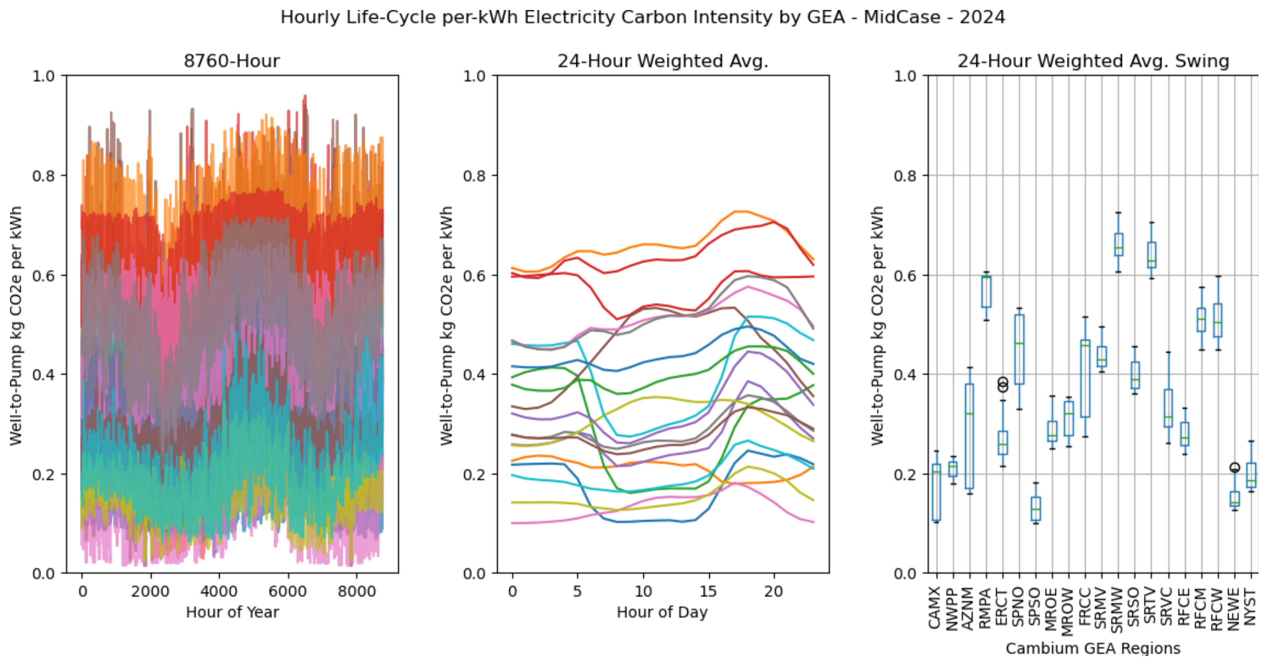

Figure 16. Hourly carbon intensity of electricity in 2024 for each Cambium GEA region in the baseline (Cambium Mid-case) scenario - 8760 hours (left), 24-hour weighted average (middle), and aggregated variation (right).

In addition to the Cambium Mid-case (selected as the baseline scenario for this study), Cambium considers various other future electric grid evolution scenarios—largely based on varying assumptions for natural gas prices and renewable energy costs in the future. Building on the hourly life cycle carbon intensity for the current electric grid shown in Figure 16, Figure 17 depicts the longitudinal change for the Cambium Mid-case along with for the Low Natural Gas Price and the Low Renewable Cost scenarios. The representation of the current electric grid indicates that western and northeastern regions, for example, California (CAMX) and New England (NEWE), have the lowest carbon intensity per electricity consumed, whereas the Midwest such as Illinois and Missouri (SRMW) as well as Tennessee Valley (SRTV) regions have the greatest carbon intensity. By 2050, however, the overall regional patterns change considerably, depending on the scenario, as depicted in Figure 17 and emphasized by the hourly visualizations for each year in Figure 18 and Figure 19. Overall, the low natural gas price scenario leads to greater carbon intensity across the board, while the low renewable energy cost scenario results in lower carbon intensity than in the baseline scenario. Also, it appears that carbon intensity would be generally the lowest during the daytime, regardless of regions or future electric grid scenarios.

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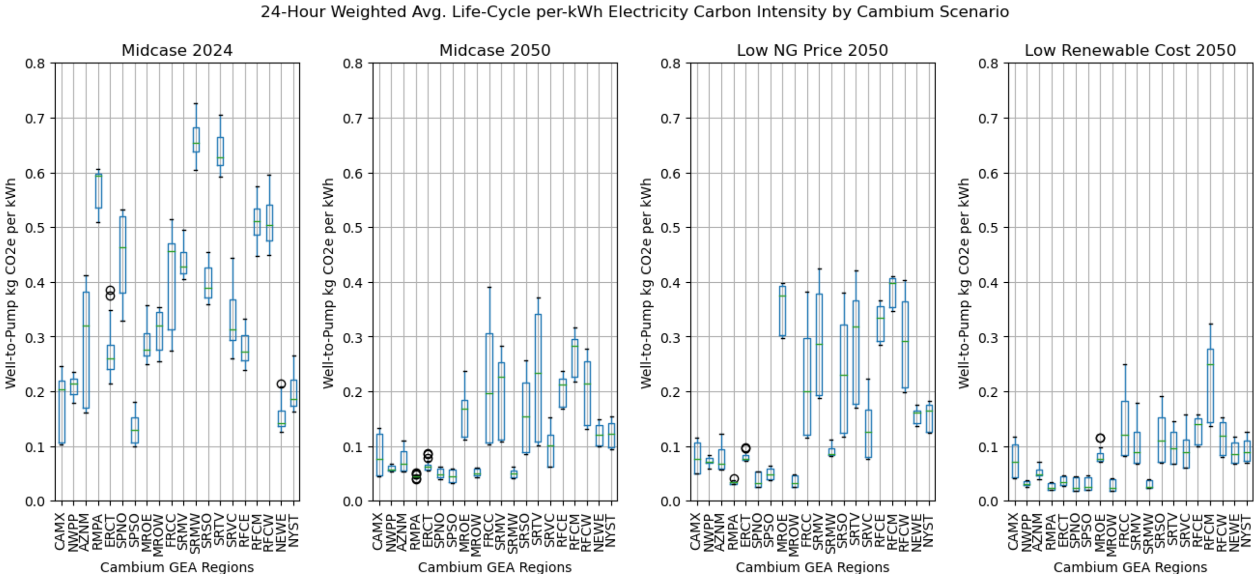

Figure 17. Life cycle carbon intensity of electricity, and its variation, for different GEA regions and different future electric grid scenarios – Cambium Mid-case, Low Natural Gas Price, and Low Renewable Cost.

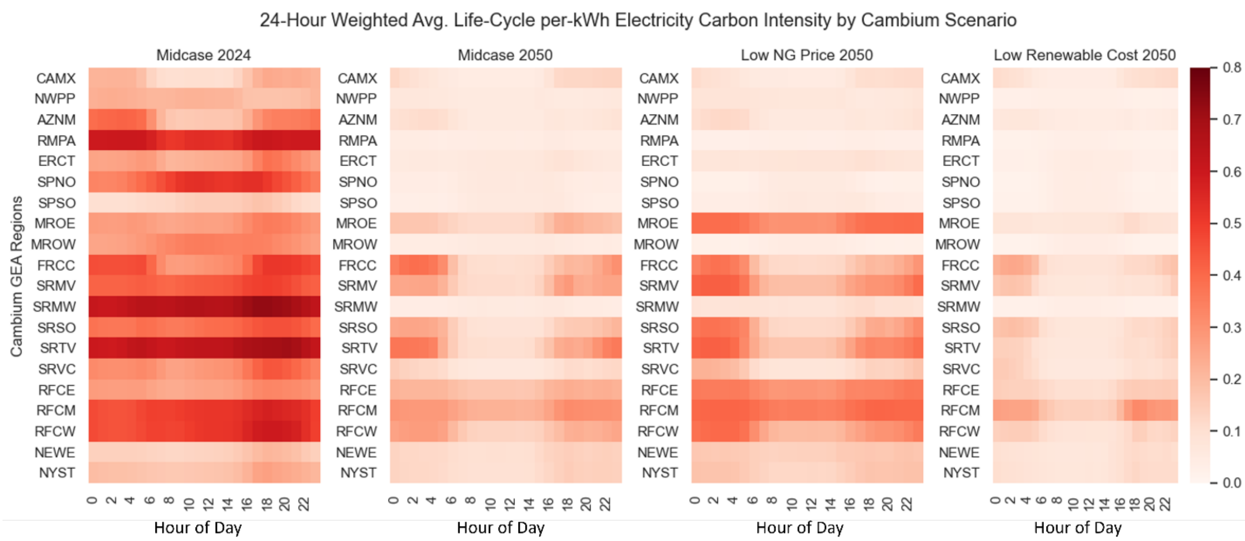

Figure 18. Hourly life cycle carbon intensity of electricity for different GEA regions and different future electric grid scenarios – Cambium Mid-case, Low Natural Gas Price, and Low Renewable Cost.

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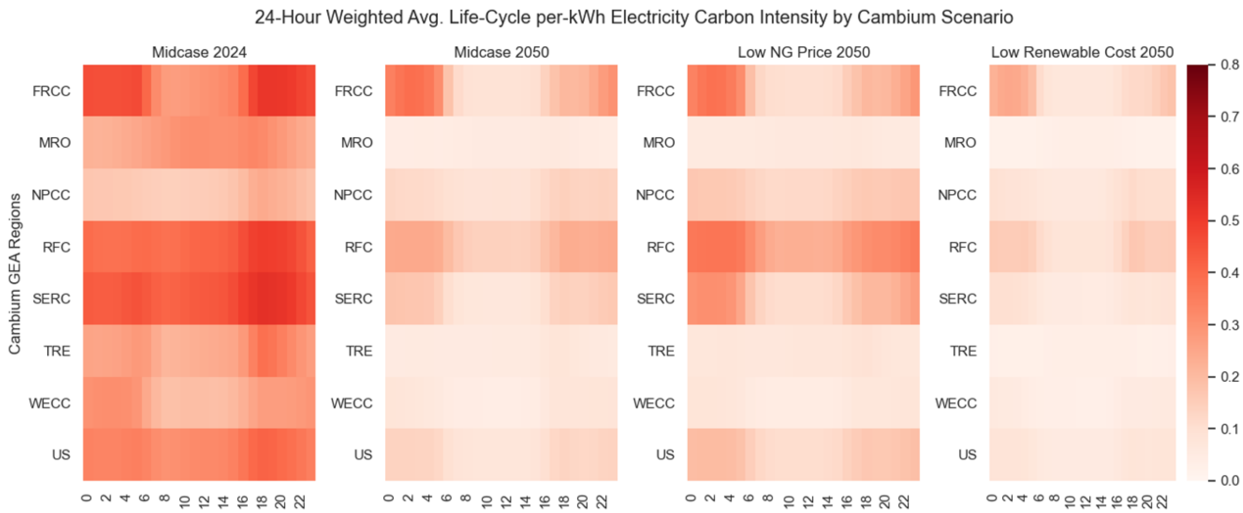

Figure 19. Hourly life cycle carbon intensity of electricity for different NERC regions and different future electric grid scenarios – Cambium Mid-case, Low Natural Gas Price, and Low Renewable Cost.

Cambium includes the capability to consider marginal electricity mix, and while it would have been ideal to leverage long-run marginal estimates from Cambium, the corresponding data were not available at the time of this study completion. Short-run marginal data were available, but the data on average consumption mix were used instead due to providing a heuristically better alternative for long-run marginal, and working better when there are greater penetrations of renewables (Gagnon and Cole 2022) (Gagnon, et al. 2022).

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3 Per-Vehicle GHG Emissions Analysis

Based on the data and methodology discussed in Chapter 2, life cycle GHG emissions (metric ton CO_2e) and GHG emissions (kg CO_2e per mile) are estimated for ICEVs, HEVs, PHEVs, and BEVs. As discussed previously, the primary focus of this analysis is GHG emissions of PEVs (i.e., PHEVs and BEVs) relative to ICEV or HEV. The cross-technology comparisons are presented across a range of scenarios and input parameters, including different vehicle types (car/sedan, SUV, and pickup truck) and categories (standard versus premium), model years (current to 2040), battery chemistries (NMC, LFP, and NCA), future electric grid evolution scenarios, and charging behavior scenarios.

3.1 Baseline GHG Emissions Results

Life cycle GHG emissions results for the model year (MY) 2025 SUV in Figure 20 indicate that the standard ICEV is estimated to emit about 96 metric tons of GHGs over the 15-year expected vehicle lifetime, whereas the premium ICEV is estimated to emit 116 metric tons—with the difference mainly owing to the premium's lower fuel efficiency relative to the standard counterpart (per Table 1). The estimated GHG emissions for the comparable HEVs are much lower—55 metric tons for standard and 60 for premium. Recall for the PHEVs and BEVs that in addition to the base level energy consumption information in Table 1, the vehicle battery size details are summarized in Figure 3. Note that the results here are for the baseline scenario assuming NMC battery chemistry, U.S. average grid mix, the baseline "Mid-case" for grid evolution from Cambium, and the "Baseline" charging behavior estimated via EVI-Pro.

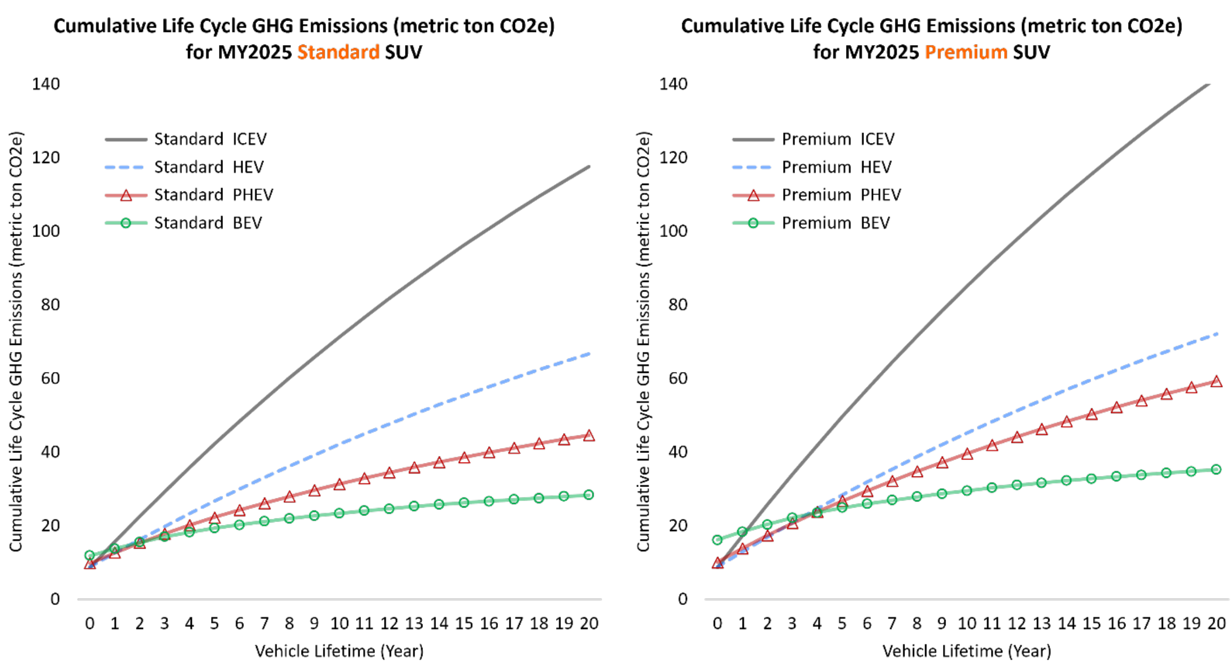

Figure 20. Cumulative life cycle GHG emissions (metric ton CO_2e) over vehicle lifetime for MY2025 SUV and baseline scenario (battery chemistry: NMC, grid region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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In Figure 20, new ICEVs and HEVs start at approximately the same level in year 0, but the gap between them rapidly grows on account of the HEV's 40-45% lower energy consumption rate than the ICEV. PHEVs show a similar pattern to that of the HEVs but achieve even lower life cycle GHG emissions due to their partial substitution of gasoline consumption for electricity consumption from an increasingly lower carbon electric grid. The BEVs go even farther than the PHEVs by completely replacing gasoline with electricity consumption, which helps them achieve in Figure 20 the lowest cumulative GHG emissions over the vehicle's lifetime.

Note that the life cycle GHG emissions at vehicle age 0 (brand new) are above 0 due to GHG emissions associated with the vehicle and parts (Figure 5). At this beginning-of-life stage, the BEVs have somewhat greater embedded GHG emissions relative to the other powertrain types. However, their lower operation phase GHG emissions result in their cumulative GHG emissions crossing below those of the ICEV within one year and below those for both the HEV and the PHEV within about four years. Even considering the decreasing driving distance assumptions as vehicles age (Figure 9), the relative GHG emissions savings for the BEVs widens into the future—and continues growing if vehicles exceed the 15-year lifetime assumed in the analysis.

Life cycle carbon intensity can be estimated by normalizing the life cycle GHG emissions in Figure 20 by the driving distance assumptions in Figure 9. This results in the per-mile GHG emissions for each vehicle displayed in Figure 21.

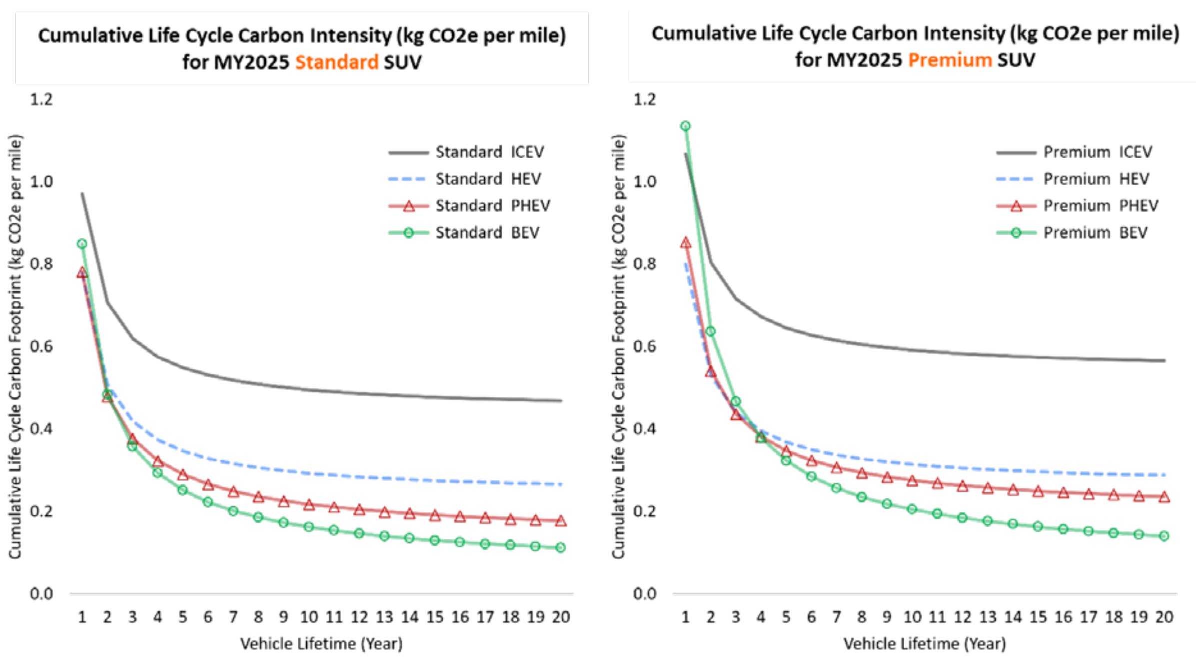

Figure 21. Cumulative life cycle carbon intensity (kg CO_2e per mile) over vehicle lifetime for MY2025 SUV and baseline scenario (battery chemistry: NMC, NERC region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

The overall cross-technology comparison is similar to that in Figure 20, but these results provide a somewhat different lens through which to view the comparison. The relatively larger impact of sunken emissions from vehicle production during the early years of operation are evident from the high initial carbon intensity values in Figure 21 (when those emissions have yet to be amortized over many driving miles). Those values steeply drop through those early years (and

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the relative powertrain orders cross over as in Figure 20), until reaching a stage where the comparison between powertrains holds steady over the later portions of the vehicle lifetime when the contributions from operating emissions dominate.

It is worth noting that this analysis contains somewhat different assumptions and corresponding results in comparison to other studies, including a relatively recent cradle-to-grave (C2G) report published by Argonne National Laboratory (ANL 2022). For example, the ANL C2G report assumes 1.2 kWh/mile for MY2020 gasoline-powered small SUVs used in the summary comparisons (which is close to the consumption rate for car-based SUVs that year in the EPA Automotive Trends Report), whereas per Table 1, this study adopts 1.43 to 1.73 (which is more consistent with MY2020 truck-based SUVs) (EPA 2023a). This explains the slightly greater life cycle (cradle-to-grave) reference carbon intensity in this study. For PEV carbon intensity calculations, both the baseline vehicle energy consumption rate (kWh/mile) and the electricity mix assumptions differ between this study and the ANL C2G report—particularly due to the differing electricity mix assumptions, this results in somewhat lower PEV carbon intensity calculations in this study. The electricity mix assumptions in the ANL C2G report are based on the 2021 Annual Energy Outlook (AEO) (EIA 2022). Relative to 2021 AEO, the overall share of renewables and nuclear is significantly higher both in the Cambium Mid-case used for this study, and in the more recent 2023 AEO (EIA 2023a). For example, the 2021 AEO Reference Case projects 42% penetration of renewables by 2050, whereas that projection increases by over 10% in the 2023 AEO Reference Case.

Despite these modest differences in absolute carbon intensity calculations, the relative difference assessments (of HEVs achieving significant life cycle GHG reductions relative to ICEVs, with PHEVs and then BEVs achieving incrementally greater reductions) are consistent with other studies. As summarized in Figure 22, the baseline percentage reductions from this study in PHEV and BEV life cycle carbon intensity compared to ICEV are respectively 60% and 73% for standard class, and 56% and 72% for premium class. If the default 15-year vehicle lifetime assumption is extended to 20-years, the respective reductions for PHEV and BEV increase by 2% and 3%, regardless of standard versus premium designation.

The assumption around product lifetime is one of the persisting temporal system boundary issues in life cycle assessment and broader policy discussions—e.g., see (Rode, Fischbeck and Paez 2017) (Fofrich, et al. 2020) for the case of power plants. However, for the cross-technology vehicle comparisons in this analysis, the percentage differences appear to stabilize after the first 10 years or so. Relative to the MY2025 comparisons in Figure 22, Figure 23 shows that estimated life cycle carbon intensity reductions over ICEV in MY2040 increase by 6%–8% for PHEV and 3%–5% for BEV.

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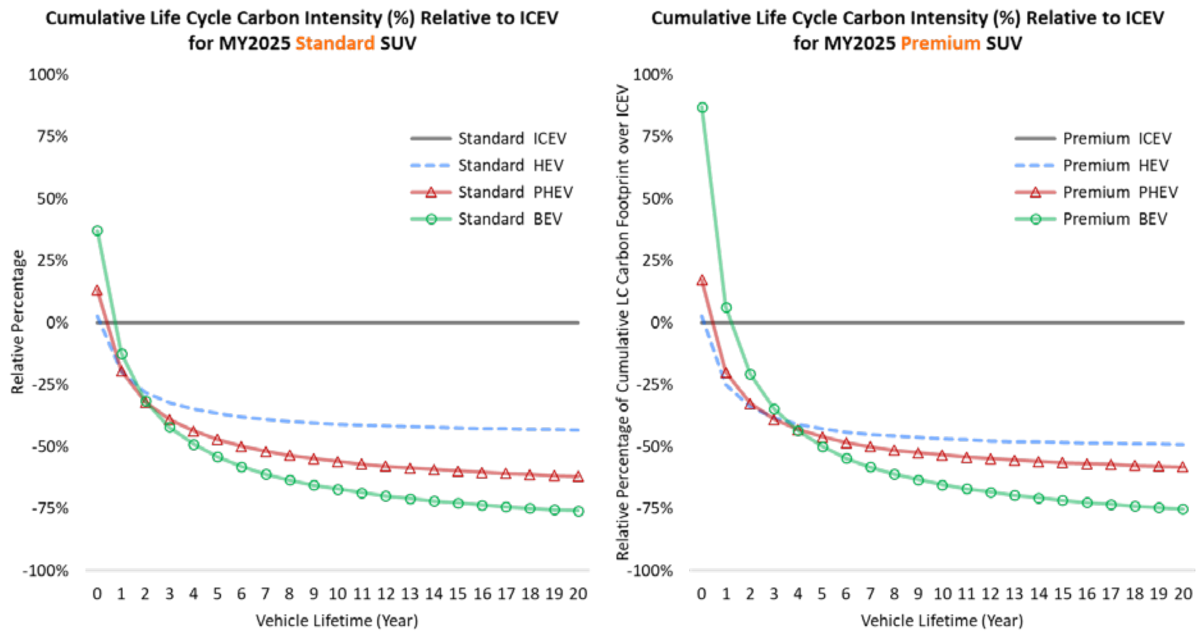

Figure 22. Cumulative life cycle carbon intensity relative to ICEV for MY2025 SUV and baseline scenario (battery chemistry: NMC, NERC region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

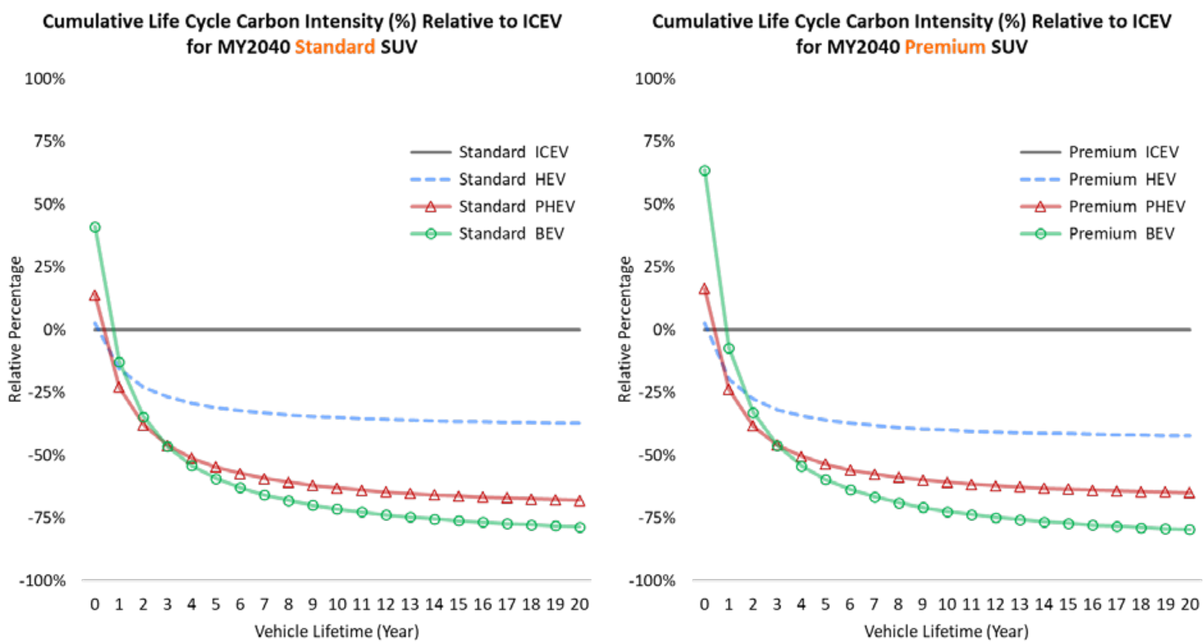

Figure 23. Cumulative life cycle carbon intensity relative to ICEV for MY2040 SUV and baseline scenario (battery chemistry: NMC, NERC region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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Beyond SUVs for which the results are presented thus far (Figure 20 through Figure 23), Table 4 summarizes life cycle carbon intensity, as well as its percentage reduction relative to ICEV, for cars and pickup trucks (PUTs), accounting for different vehicle technologies, types, classes, and model years. Analogous figures to those in the body of this report for SUVs may also be found in Appendix sections A.2 and A.3 for cars and PUTs, respectively. Regardless of vehicle type, class, or model year, it is evident that greater electrification leads to smaller life cycle carbon intensity. It can also be noted that premium vehicles, everything else equal, generally have a greater life cycle carbon intensity compared to standard counterparts. Percentage reduction in life cycle carbon intensity of PHEV relative to ICEV ranges from 56% to 67% for all cases considered in Table 4, and 67% to 78% for BEV relative to ICEV.

Table 4. Cumulative life cycle carbon intensity (kg CO_2e per mile) over vehicle lifetime for MY2025 and MY2040 vehicles, and for standard (Std.) and premium (Pre.), with baseline scenario (battery chemistry: NMC, NERC region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

		MY2025				MY2040			
		Carbon Intensity (kg CO_2e per mile)		Reduction over ICEV (%)		Carbon Intensity (kg CO_2e per mile)		Reduction over ICEV (%)	
		Std.	Pre.	Std.	Pre.	Std.	Pre.	Std.	Pre.
ICEV	Car	0.39	0.47			0.34	0.42		
	SUV	0.48	0.57			0.42	0.50		
	PUT	0.58	0.64			0.52	0.57		
HEV	Car	0.23	0.26	41.1%	45.4%	0.22	0.25	36.1%	40.7%
	SUV	0.28	0.30	42.4%	48.4%	0.27	0.29	36.5%	41.4%
	PUT	0.26		54.6%		0.25		51.9%	
PHEV	Car	0.16	0.18	59.8%	62.7%	0.14	0.13	60.1%	68.0%
	SUV	0.19	0.25	59.8%	56.4%	0.14	0.18	66.2%	63.5%
	PUT	0.20		64.8%		0.17		67.4%	
BEV	Car	0.11	0.12	71.2%	73.9%	0.08	0.09	77.1%	78.0%
	SUV	0.13	0.16	72.7%	71.6%	0.10	0.11	76.1%	77.1%
	PUT	0.19	0.20	67.0%	68.5%	0.13	0.14	74.8%	75.1%

3.2 GHG Emissions Results for Alternative Scenarios

The life cycle GHG emissions and carbon intensity results discussed thus far are based on the baseline scenario. This section explores more diverse scenarios associated with battery chemistry type, electric grid region, future electric grid evolution, and charging behavior. Given the study's focus the impacts of parameter variability for PEV life cycle GHG emissions estimation, only baseline results for ICEV and HEV are presented.

For the standard and the premium SUV, shown in Figure 20 for baseline results, life cycle GHG emissions for all possible combinations PHEV and BEV input parameters are demonstrated in Figure 24 (standard MY2025), Figure 25 (standard MY2040), Figure 26 (premium MY2025), and Figure 27 (premium MY2040). Note that the results are shown only for the first 15 years of vehicle lifetime (the default assumption in this study).

The results in Figure 24 through Figure 27 indicate that GHG emissions reduction benefits of PHEVs and BEVs (relative to comparable ICEVs and HEVs) are robust across all scenarios considered in this study. Battery chemistry appears to have the most influential impact on the initial GHG emissions and corresponding variation, especially for BEVs. Additionally, the observations made previously for the baseline scenario still apply. For example, premium tends to create more GHG emissions on a life cycle basis, although Table 4 implies that the percentage emissions reduction benefits are similar between standard versus premium. Also, it is clearly visible that future model years of PHEVs and BEVs are estimated to provide deeper life cycle GHG emissions reductions relative to comparable ICEVs and HEVs.

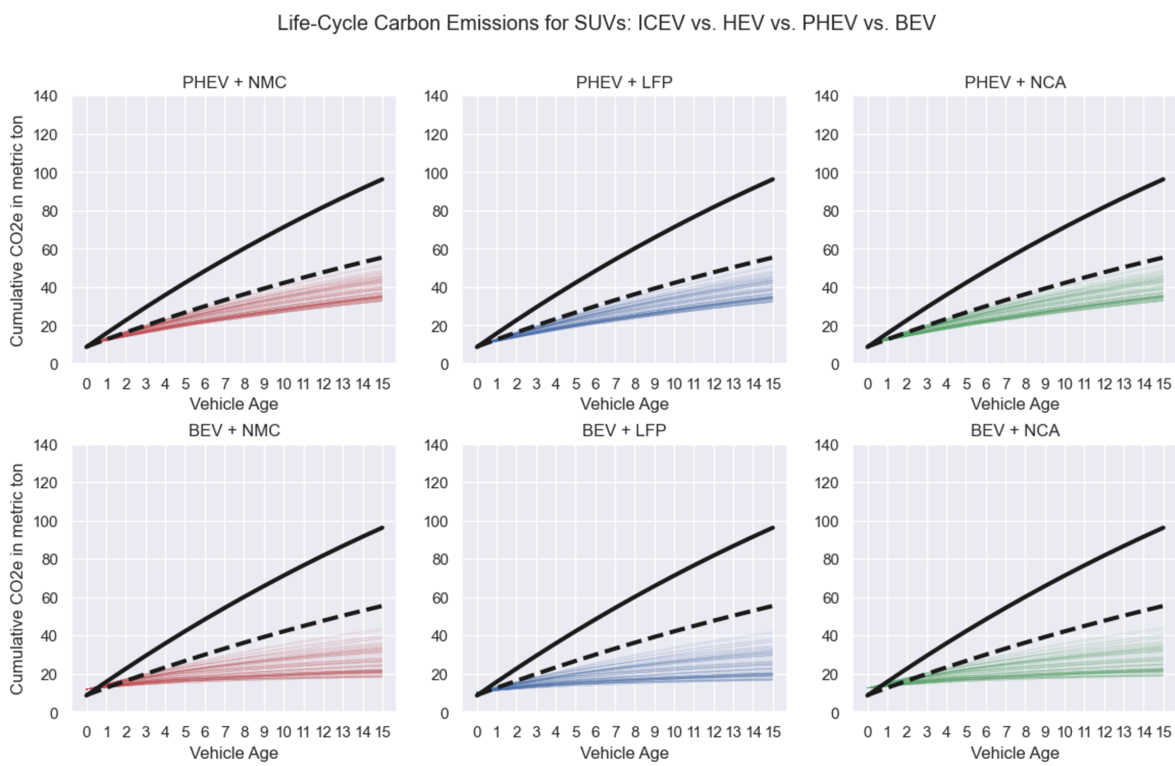

Figure 24. Cumulative life cycle GHG emissions (metric ton CO_2e) over vehicle lifetime for MY2025 standard SUV – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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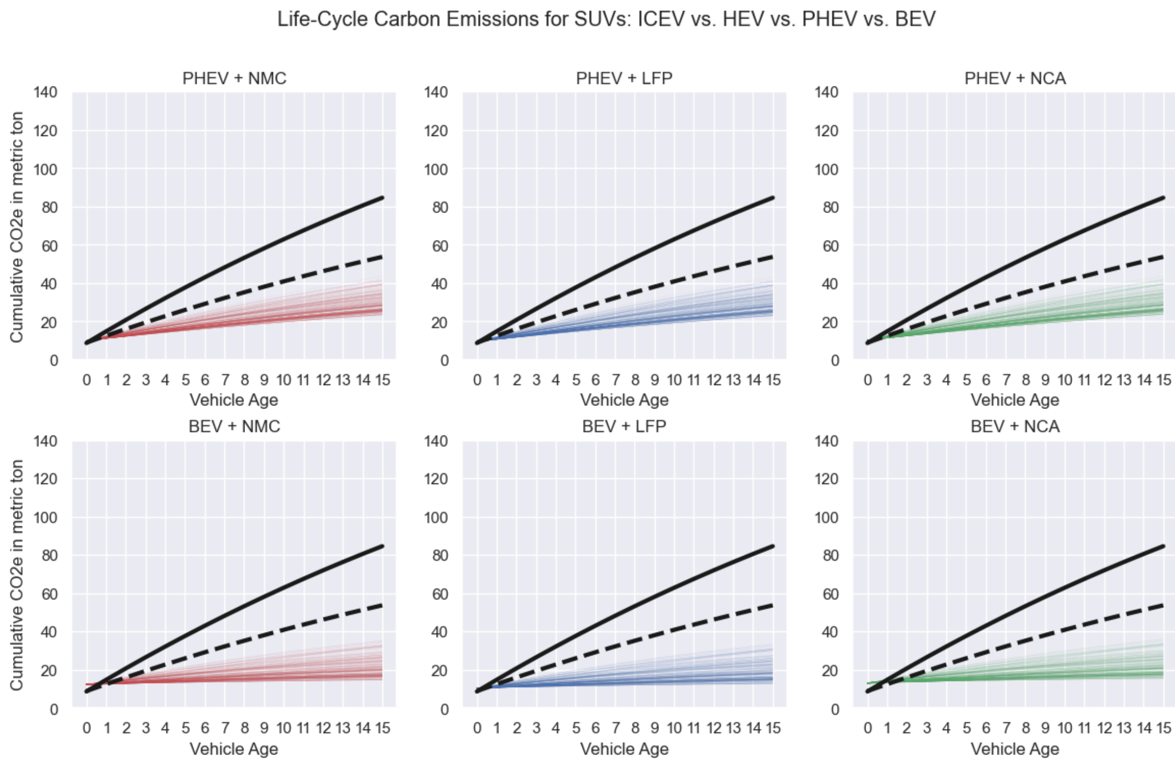

Figure 25. Cumulative life cycle GHG emissions (metric ton CO_2e) over vehicle lifetime for MY2040 standard SUV – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

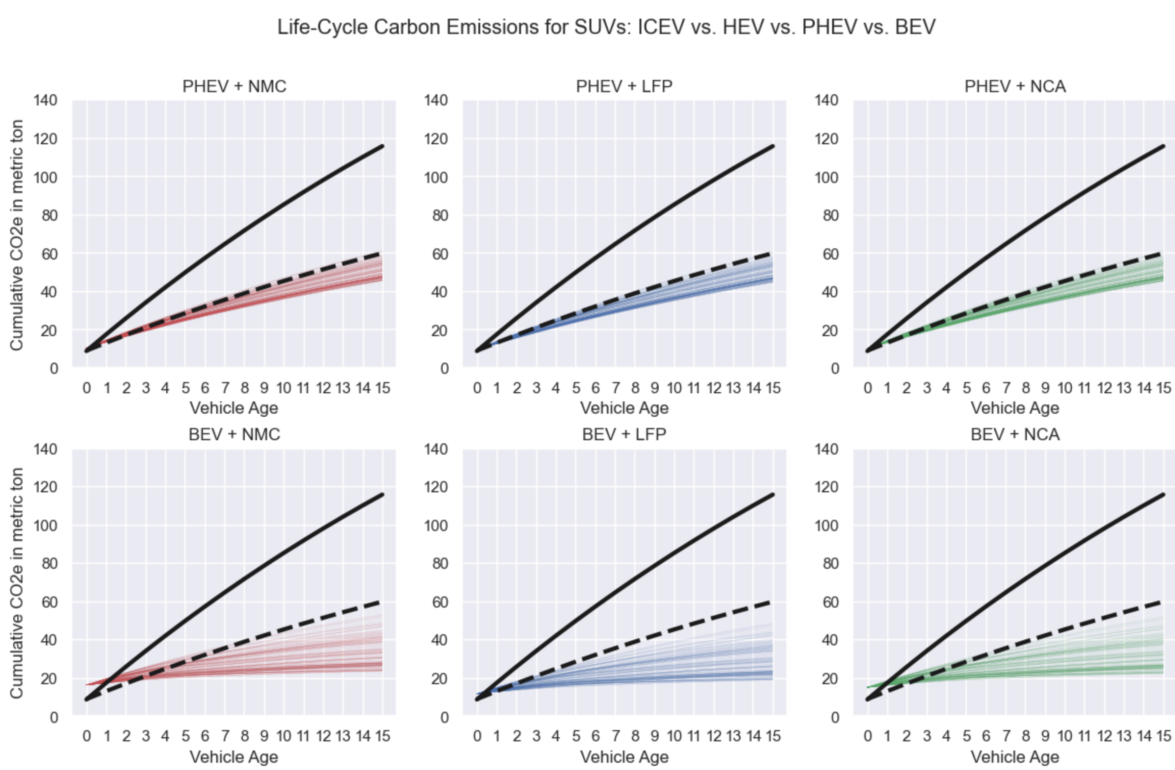

Figure 26. Cumulative life cycle GHG emissions (metric ton CO_2e) over vehicle lifetime for MY2025 premium SUV – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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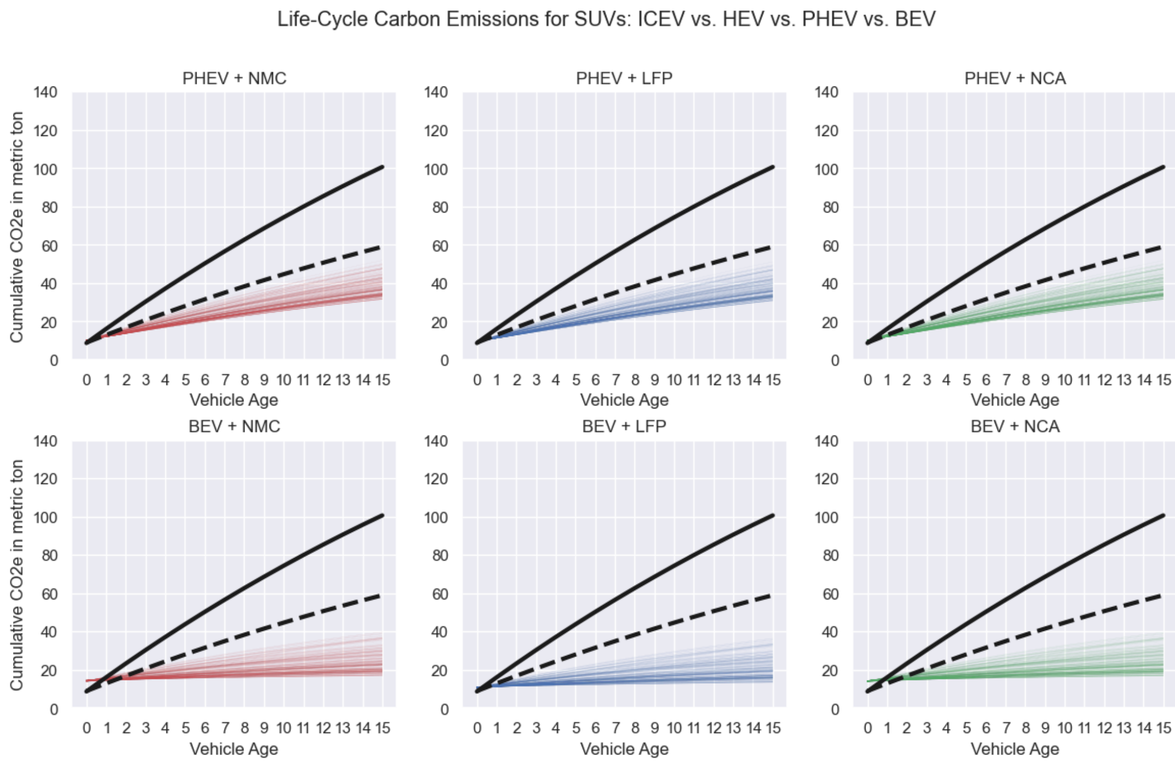

Figure 27. Cumulative life cycle GHG emissions (metric ton CO_2e) over vehicle lifetime for MY2040 premium SUV – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

Table 5 (for PHEVs) and Table 6 (for BEVs) summarize input parameters corresponding to the scenarios from the stochastic analyses in Figure 24 through Figure 27 resulting in the minimum and the maximum estimated life cycle GHG emissions values. In terms of battery chemistry, whether for PHEV or BEV, LFP is estimated to provide the lowest life cycle GHG emissions, and NMC the greatest. As for future electric grid evolution and corresponding generation mix, "Low Renewable Cost" results in the lowest GHG emissions for both PHEV and BEV. With regards to NERC region, MRO achieves the lowest GHG emissions, whereas FRCC results in the greatest GHG emissions for PHEV. The NERC region results are similar for BEVs, except that for MY2040 BEV, RFC becomes the region with the greatest emissions. The difference between PHEV and BEV can be attributed to the fact that PHEV GHG emissions depend on both electricity and gasoline fuel consumption.

In general, the analysis indicates that charging behavior scenario selection causes little variation for life cycle GHG emissions. For instance, only in the 2025 BEV case are different charging behavior scenarios associated with the lowest versus the highest emissions results. The 2025 BEV case and each of the PHEV cases show no difference in charging behavior scenario selection between those scenarios that achieve the lowest versus the highest emissions results.

Table 5. Input parameters and scenarios associated with minimum and maximum life cycle GHG emissions estimated for PHEV SUV for model years 2025 and 2040.

Model Year	Class	Battery Chemistry	Min or Max	Electricity Mix Scenario	NERC Region	Charging Behavior
2025		LFP	Min	Low Renewable Cost	MRO	TOU

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Model Year	Class	Battery Chemistry	Min or Max	Electricity Mix Scenario	NERC Region	Charging Behavior
	Standard or Premium		Max	High Renewable Cost	FRCC	TOU
		NCA	Min	Low Renewable Cost	MRO	TOU
			Max	High Renewable Cost	FRCC	TOU
		NMC	Min	Low Renewable Cost	MRO	TOU
			Max	High Renewable Cost	FRCC	TOU
2040	Standard or Premium	LFP	Min	Low Renewable Cost	MRO	TOU
			Max	High Renewable Cost	FRCC	TOU
		NCA	Min	Low Renewable Cost	MRO	TOU
			Max	High Renewable Cost	FRCC	TOU
		NMC	Min	Low Renewable Cost	MRO	TOU
			Max	High Renewable Cost	FRCC	TOU

Table 6. Input parameters and scenarios associated with minimum and maximum life cycle GHG emissions estimated for BEV SUV for model years 2025 and 2040.

Model Year	Class	Battery Chemistry	Min or Max	Electricity Mix Scenario	NERC Region	Charging Behavior
2025	Standard or Premium	LFP	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	High Renewable Cost	FRCC	TOU
		NCA	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	High Renewable Cost	FRCC	TOU
		NMC	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	High Renewable Cost	FRCC	TOU
2040	Standard or Premium	LFP	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	Low NG Price	RFC	High Home Charging Access
		NCA	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	Low NG Price	RFC	High Home Charging Access
		NMC	Min	Low Renewable Cost	MRO	High Home Charging Access
			Max	Low NG Price	RFC	High Home Charging Access

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3.3 Per-Vehicle Carbon Return on Investment Analysis

The analysis results thus far indicate that BEVs consistently achieve the deepest GHG reduction outcomes, with PHEVs and HEVs also achieving significant though progressively smaller GHG reductions relative to a comparable ICEV. Various automakers have expressed concerns about the potential speed and scale at which their individual companies may secure access to expanded battery resources, and subsequently interest in different ways of quantifying the GHG returns relative to the battery investments for different types of vehicles. This section therefore builds upon the life cycle GHG emissions (metric ton CO_2e) and carbon intensity (kg CO_2e per mile) calculations to explore various ways of assessing per-vehicle carbon return on investment (CROI). The CROI concept is typically used in carbon capture systems to characterize the carbon emissions benefit from an abatement facility/system, accounting for any "invested" carbon emissions that are created to construct and operate the facility/system, as illustrated in Figure 28. This section takes an analogous approach to assess the life cycle carbon emissions savings for a PEV versus an ICEV in proportion to the incremental initial investment for that PEV. Figure 29 depicts this CROI calculation concept for a PEV in comparison to an ICEV.

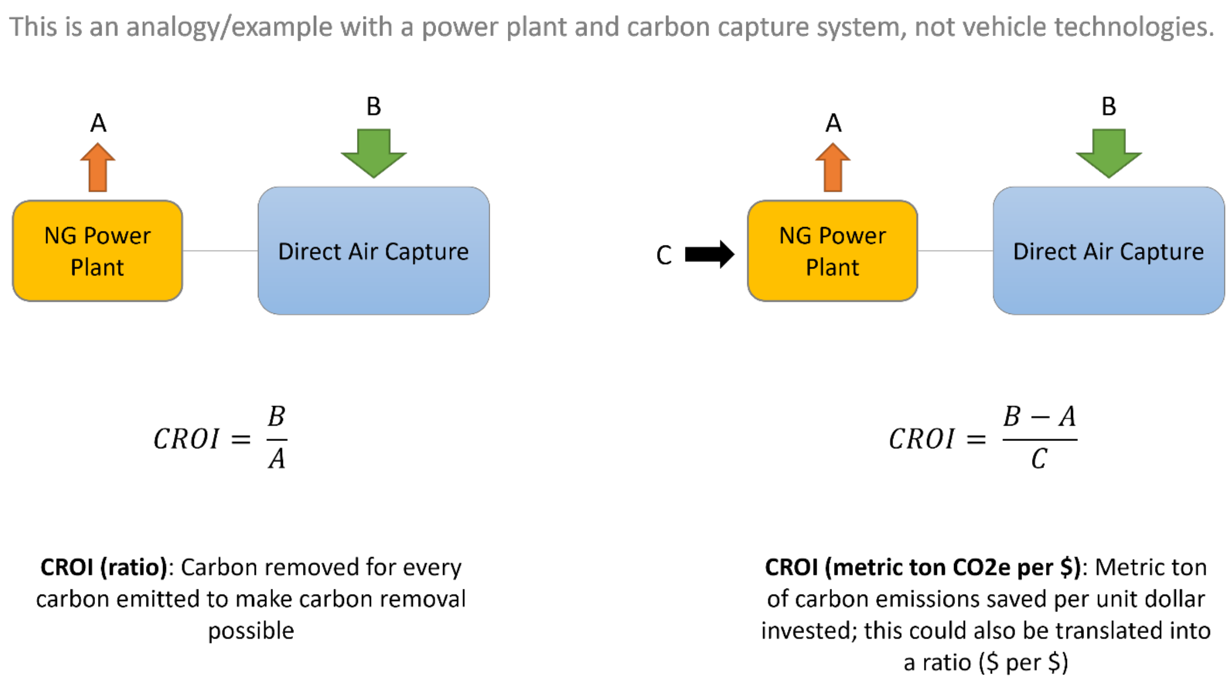
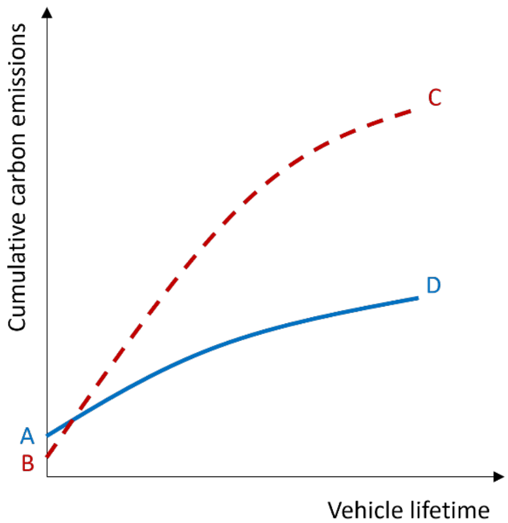


Figure 28. The concept of carbon return on investment (CROI), based on an example of a power plant and carbon capture system, in which CROI characterizes the overall carbon emissions reduction benefit from the carbon capture system.



$$CROI = \frac{Net\ Carbon\ Abatement}{Net\ Investment}$$

$$CROI_{EV} = \frac{C - D}{A - B}$$

Figure 29. CROI for a PEV (solid blue line) relative to an ICEV (dashed red line).

As there are different ways to characterize the relative initial PEV investment ("A-B" in Figure 29), three different PEV CROI formulations are established. Each formulation uses a consistent numerator (the life cycle carbon intensity difference between the ICEV and the considered PEV). The different denominators in each CROI formulation indicate the different focus of each regarding the initial investment for the PEV relative to the ICEV. For $CROI_1$, this is the vehicle production carbon intensity difference between the PEV and the ICEV. The denominators for $CROI_2$ and $CROI_3$ just focus on the PEV battery with different units of measure—battery capacity (i.e., energy) in units of kWh for $CROI_2$, and battery cost (in dollars) for $CROI_3$. The corresponding equations for each of the CROI formulations are:

$$CROI_1 = \left.\frac{LCCI_{ICEV} - LCCI_{xEV}}{LCCI_{xEV,VehProd} - LCCI_{ICEV,VehProd}}\right|_{LCCI_{xEV,VehProd} > LCCI_{ICEV,VehProd}} \tag{4}$$

$$CROI_2 = \left.\frac{(LCCI_{ICEV} - LCCI_{xEV}) \times VMT}{BattCap_{xEV} - BattCap_{ICEV}}\right|_{BattCap_{xEV} > BattCap_{ICEV}} \tag{5}$$

$$CROI_3 = \frac{(LCCI_{ICEV} - LCCI_{xEV}) \times VMT}{BattCost_{xEV}} \tag{6}$$

, where $LCCI$ represents life cycle carbon intensity for either ICEV or the comparable xEV (such as PHEV or BEV), $VehProd$ vehicle production, $BattCap$ battery capacity in kWh, and $BattCost$ battery cost in dollars. Note that life cycle VMT is multiplied to $LCCI$ for $CROI_2$ and $CROI_3$ to improve the readability of the metrics, in which the numerator's unit becomes kg CO2e rather than kg CO2e per mile. Considering all conditions (model year, battery chemistry, etc.), Figure 30 to Figure 32 respectively plot the $CROI_1$ to $CROI_3$ calculation results for all combinations of vehicle class (standard or premium) and vehicle type (car, SUV, or pickup truck)[1]. The comparisons show that while BEVs achieve greater overall per-vehicle GHG

[1] Note that the one combination for which CROI calculations are not included is due to the TDA effort (used as the vehicle attribute source in this analysis) having not created a premium PHEV pick-up truck.

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emissions reductions, PHEVs achieve greater per-vehicle CROI for each of the evaluated CROI formulations. That said, assessing aggregate potential GHG emissions reduction for different PEV powertrains requires moving beyond individual vehicle-level analyses and considering whether sufficient growth in battery availability could support large-scale replacement of ICEVs by each type of PEV. This is the focus for the remainder of the report.

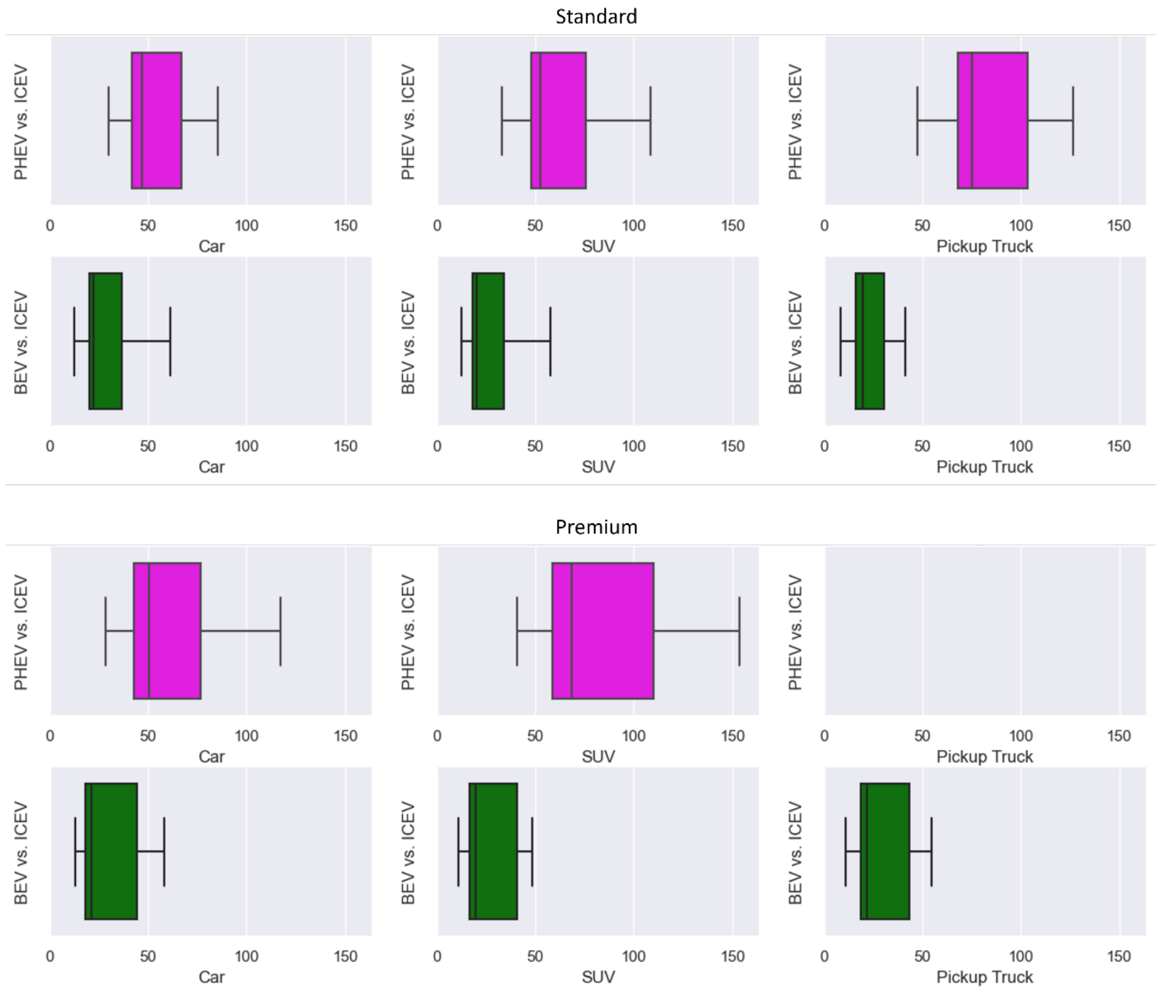

Figure 30. CROI$_1$ results for standard (top) and premium (bottom) vehicles—which are unitless for this formulation. While BEVs achieve greater overall per-vehicle GHG emissions reductions, these results show the analyzed PHEVs achieve a higher ratio of PEV vs. ICEV GHG savings relative to the PEV's incrementally higher vehicle production GHG emissions.

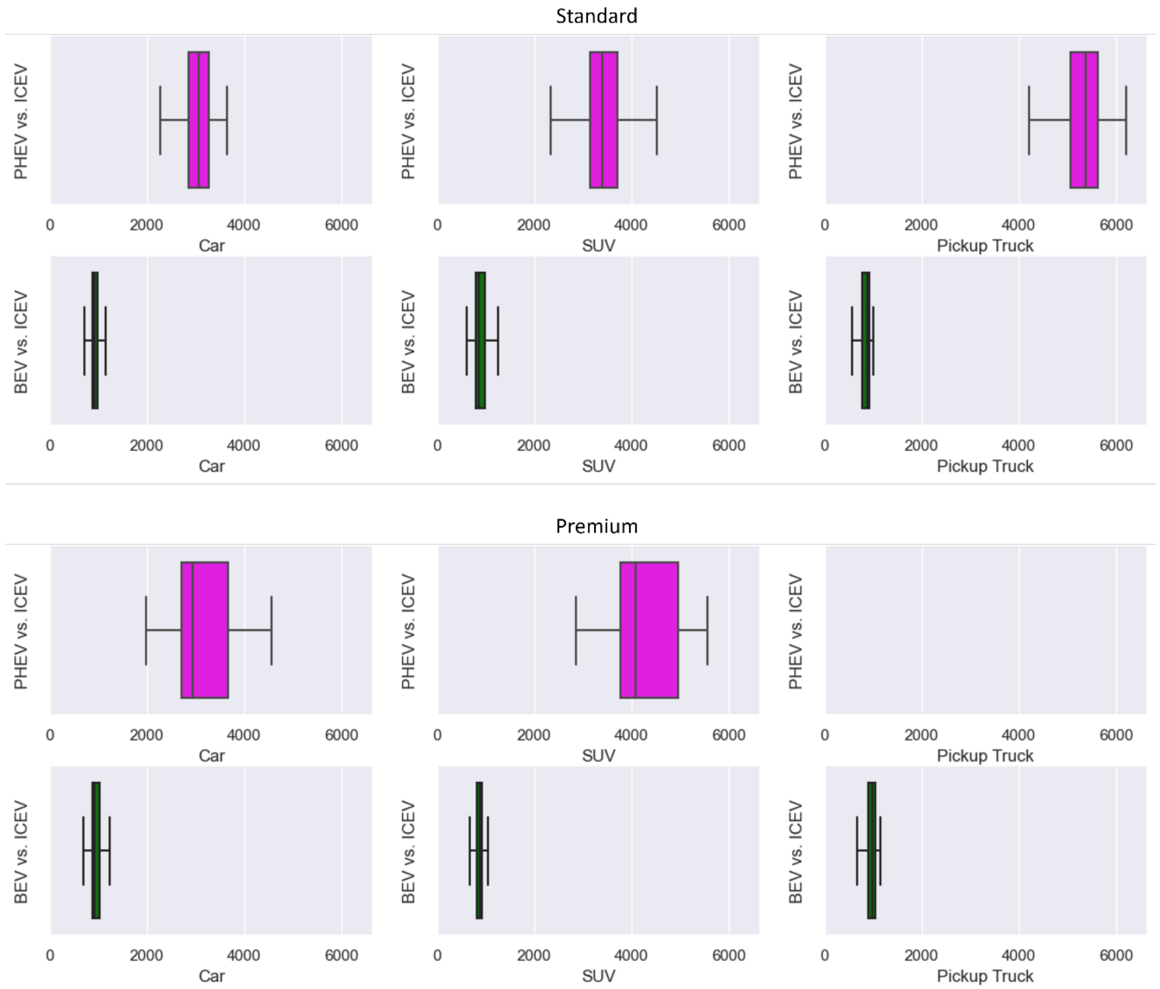

Figure 31. CROI$_2$ results for standard (top) and premium (bottom) vehicles—which have units of kg CO_2e per kWh for this formulation. While BEVs achieve greater overall per-vehicle GHG emissions reductions, these results show the analyzed PHEVs achieving a higher ratio of PEV vs. ICEV GHG savings relative to the energy content of the PEV's battery.

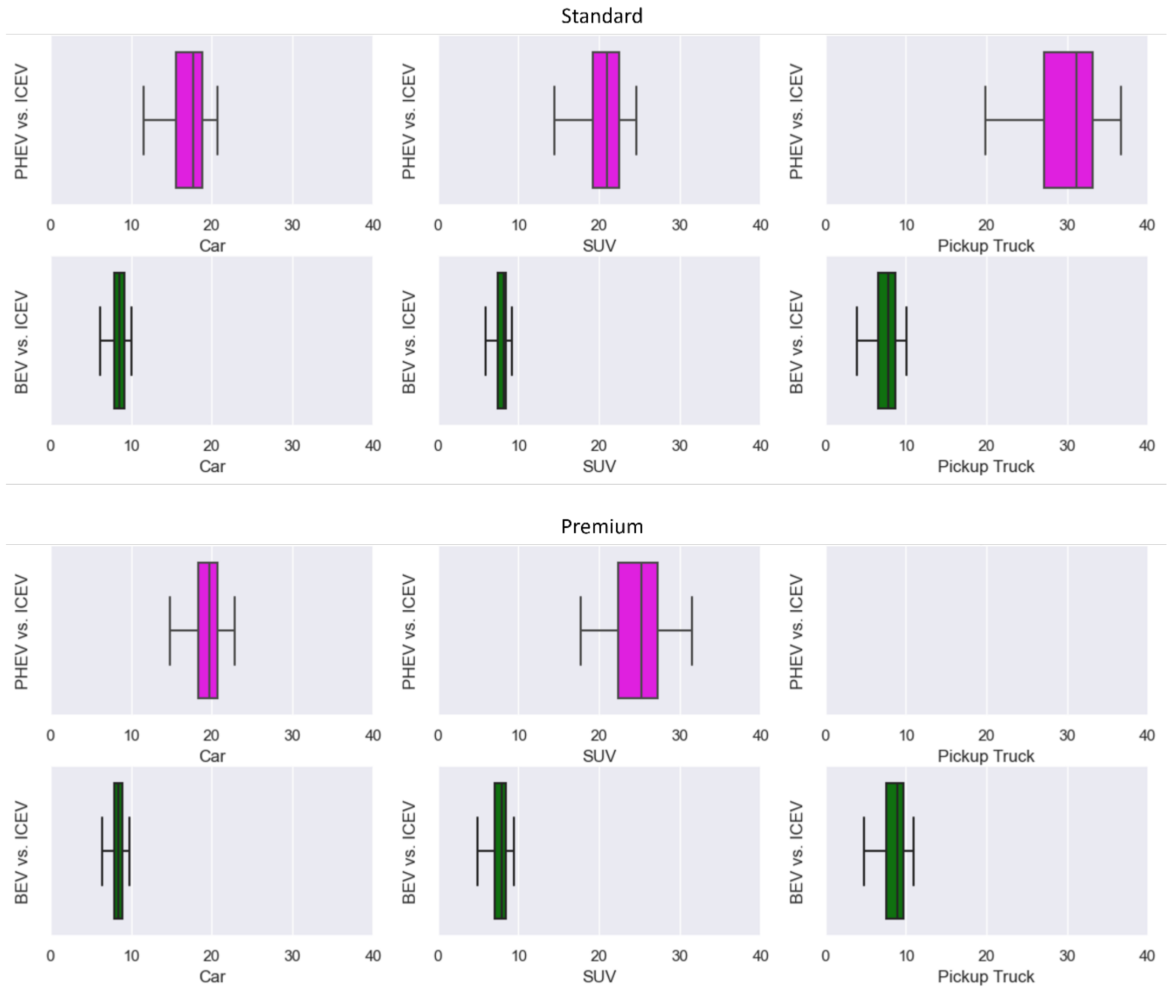

Figure 32. CROI$_3$ results for standard (top) and premium (bottom) vehicles—which have units of kg CO_2e per dollar for this formulation. While BEVs achieve greater overall per-vehicle GHG emissions reductions, these results show the analyzed PHEVs achieving a higher ratio of PEV vs. ICEV GHG savings relative to the cost of the PEV's battery.

4 Battery Growth Scenarios for National-Level Analysis

The remainder of this report builds upon the preceding foundation of life cycle GHG emission calculation inputs and individual vehicle-level assessments—expanding the analyses to the level of the U.S. national LDV fleet. This chapter focuses on the first step for these national-level analyses, which is to establish a range of prospective growth scenarios for the quantity of batteries available to produce new light-duty (LD) PEVs for the U.S. market. The established scenarios are then used in the next chapter to examine the degree to which all U.S. LDV sales could be replaced by varying PEV designs, each with a different battery size. Acknowledged limitations in this analysis approach include the simplified representation of battery availability as having a hard limit and of the LDV market monolithically shifting to a single PEV design (to the extent possible under assumed battery growth constraints). In reality, no market conditions exist that would limit consumers from selecting an LDV from among multiple powertrain types or battery sizes. Real-world complexities that introduce dynamics for battery growth include price responses to supply/demand interactions and different chemistries becoming viable based on those price and supply/demand interactions along with further technology development. Real-world considerations for the LDV market include varying consumer interest in automakers' production of multiple different vehicle designs based on factors such as vehicle capabilities, performance, and price. These limitations should be kept in mind when viewing the outputs of the simplified national-level analysis in this report. Likewise, the way that the battery growth scenarios are applied in the next chapter is kept in mind for establishing the range of those scenarios in this chapter.

4.1 Approach

In addition to the limitations just acknowledged, it should be emphasized that the battery growth scenarios established in this chapter are not intended to be predictive. Activities to scale up battery production and to address questions around material sourcing and supply chains are highly dynamic and the subject of significant public and private investment. Factors that may influence battery production levels include the quantity of raw materials for leading battery chemistries that can be economically extracted from currently known material deposits, the size and location of potential new source discoveries, potential breakthroughs in new battery technologies and corresponding material availability, and the rate at which new battery production facilities can scale up. In the context of establishing prospective battery growth levels to support complete conversion of U.S. LDV sales to a given type of PEV, another consideration is the degree to which the vehicles (and their batteries) would be produced domestically versus continuing to have some portion produced abroad and imported to the U.S. Note that roughly half of model year 2019 passenger cars (the most recent year with posted data) were imported versus produced domestically (NHTSA 2024).

Given all the uncertainties, the simplified approach for this chapter is to first establish a reference battery growth scenario, and to subsequently scale it up and down to establish a range of potential battery growth trajectories over which to conduct the theoretical analyses in the next chapter. 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

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assumed to match the growth rate of total capacity levels for existing and currently announced battery manufacturing facilities in the U.S. and Canada—as detailed in the next sub-section.

4.2 Establishing the Reference Scenario

Just a few years ago, the total lithium-ion battery production capacity in North America was less than 100 GWh/year. However, this has been rapidly changing with dozens of new battery factories either planned, under construction, or newly operational—spurred at least in part by the 2021 Infrastructure Investment and Jobs Act (IIJA, also commonly known as the Bipartisan Infrastructure Law, or BIL) and the 2022 Inflation Reduction Act (U.S. Congress 2021) (U.S. Congress 2022). Recent analysis rolling up the existing plus new facility announcements in the U.S. and Canada indicates that total production capacity is expected to exceed 1,300 GWh/year in 2030 (Bellan 2023) (NREL 2024) (Gohlke, Barlock and Mansour 2024). The established reference battery growth scenario correspondingly derives from a simplified 175 GWh/year annual growth rate assumption to reach a level of roughly 1,300 GWh/year in 2030, with continued growth at the same rate thereafter.

Different combinations of factors could result in this prospective reference scenario for the growth of batteries available for U.S. LDVs. One possible narrative for the scenario is to directly use the indicated North American battery production capacity growth with these (or, equivalently, offsetting deviations from the following) simplifying assumptions: (1) negligible PEV/battery production outside of North America for future U.S. LDVs; (2) that the battery production facilities achieve their announced production capacity targets; (3) negligible diversion of batteries produced from these facilities for other uses; and (4) no additional contribution from further facility investments or from advancements in new technologies such as sodium-ion batteries—meaning that no additional new battery production capacity comes on-line.

However, there exists significant uncertainty for such simplifying assumptions, and potential for different battery growth narratives, which is why this chapter focuses on establishing a range of battery growth scenarios and not simply a single scenario.

4.3 Highlighting Sources of Uncertainty

The simplifying assumptions from the preceding discussion that combine to define one potential narrative for the reference scenario simultaneously highlight key factors that may drive variation in the range of prospective battery growth scenarios. The considerations include the following.

<u>Contribution of imports to the U.S. LD PEV market</u> – The example reference scenario narrative includes the simplifying assumption of negligible PEV/battery production outside of North America for future U.S. LDVs. Such an assumption is supported by the fact that current federal incentives favor PEVs that are assembled in North America and that use battery components mostly produced or assembled in North America and with critical minerals mostly extracted or processed in the U.S. or in a U.S. Free-Trade Agreement partner country. However, given that roughly half of U.S. passenger cars are currently imported (NHTSA 2024), and that PEVs manufactured outside of North America may still qualify for IRA tax incentives if they are leased (Barry 2023), a non-negligible portion of future U.S. LD PEVs may very well be supplied

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by batteries sourced from abroad. Such an outcome could be one contributing factor to a higher battery growth scenario narrative than that of the reference scenario.

Production facilities securing materials and achieving capacity targets – The example reference scenario narrative includes the assumption that existing and announced North American battery production facilities collectively achieve their stated annual output capacity targets on schedule. However, the facilities may encounter obstacles—such as challenges in securing sufficient constituent material supplies—which could cause them to fall short of their announced capacity targets. Such an outcome could be one contributing factor to a lower battery growth scenario narrative than that of the reference scenario.

Battery diversion for other uses – The example reference scenario narrative includes the assumption that there is relatively minimal diversion of batteries produced from the announced manufacturing facilities for uses beyond LD PEVs. This assumption is supported by the fact that LDV electrification is cited as a major reason for the battery production expansion. However, there will certainly be some portion of those produced batteries diverted to other uses—which would serve to reduce their relative availability for new U.S. LDVs. Such an outcome could be another contributing factor to a lower battery growth scenario narrative than that of the reference scenario.

Further investments and/or progress in new technologies – The example reference scenario narrative includes the assumption that there will not be further substantive facility investment announcements beyond those that have been made to date, and that advancements in new technologies (such as sodium-ion as a potential complement to lithium-ion batteries) do not pan out. This assumption provides a conservative position for the reference scenario and potential lower than reference scenario narratives. However, recent history suggests that new investment announcements and/or further technology progress may very well occur. Such an outcome could result in further new production capacity coming on-line and could be another contributing factor to a higher battery growth scenario narrative than that of the reference scenario.

This discussion highlights several important considerations that may contribute to higher or lower battery growth scenarios. While it is not feasible under this study to rigorously quantify the uncertainty range for each of these potential influencing factors, some discussion follows regarding battery materials considerations given the significant attention being directed towards the potential for critical mineral supply chains to constrain battery production (and significant activities seeking to avoid such constraints).

4.4 Examining Potential Material Supply Constraints

Note that many minerals, including lithium, nickel, manganese, and cobalt are important in various types of HV batteries and could potentially become limiting factors for battery production—though also that there are major on-going efforts to strengthen supply chains for such minerals, and that the diversity of chemistries that may be used for HV vehicle batteries may provide some inherent battery supply chain resiliency. Nevertheless, lithium (Li) has received particular attention given its importance as a cathode material for each type of Li-ion battery (Ambrose & Kendall, 2019; Wurzbacher, et al., 2022; Shan, 2023; Defense Transportation Journal, 2023). The following example analysis therefore explores how Li-ion

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battery production could be constrained if supplied only by mined or refined lithium from the U.S. and current U.S. Free Trade Agreement (FTA) countries.

With the caveat that U.S. and FTA countries along with mineral deposit discoveries are continually evolving, this example analysis leverages figures on estimated mined and refined lithium availability per year out to 2032 from the U.S. and FTA countries derived from a 2023 analysis of Benchmark Mineral Intelligence data—which has consistent U.S. plus FTA lithium estimates as a recently published report on battery critical materials (Benchmark Mineral Intelligence 2023) (Barlock, et al. 2024). For completeness, the analysis additionally considers the extent to which material recovery from U.S. battery recycling and manufacturing scrap may increment the lithium supply from U.S. and FTA mining and refining. Analysis to estimate such material quantities leverages LIBRA—the Lithium-Ion Battery Resource Assessment Model (NREL 2023e). LIBRA is a system-dynamics model that evaluates the macro-economic viability of the battery manufacturing, use, and recycling industries across the global supply chain under differing dynamic conditions. LIBRA assesses the dynamic flows of materials, along with growth in manufacturing and recycling.

Focusing on the year 2032 (the farthest out with available estimates from the Benchmark Mineral Intelligence data), the PEV market is estimated to still be ramping up with relatively few PEV batteries having reached end of life. Lithium from U.S. battery recycling and manufacturing scrap at that time (estimated at ~9,000 tonnes/year) will therefore only modestly increment the availability estimates from mining and refining in the U.S. and in FTA countries (e.g., U.S. and FTA mining is estimated to total ~240,000 tonnes/year in 2032). Nevertheless, these modest increments are included for the example analysis.

The next step to make the net estimates more relevant for this analysis entails converting the Li availability estimates in units of mass (e.g., tonnes) to battery estimates in units of energy (e.g., GWh). Table 11 in the Appendix of this report indicates how the conversion of Li mass to battery energy varies for different Li-ion battery chemistries. The example analysis includes varying the value from 0.1 kg Li/kWh cell to 0.125 kg Li/kWh cell. The rationale for this range comes from recognizing the possibility of a future production mix with a high proportion of chemistries such as LFP would push the conversion factor towards the lower end of that range, but that alternate future production mix possibilities (such as with a higher proportion of NMC955) would push the conversion factor towards the higher end of that range.

The approximate midpoints of this 2032 example analysis (based on the future estimates from the 2023 Benchmark data, plus estimated U.S. recycling and manufacturing scrap) indicate sufficient U.S. plus FTA mined lithium to produce roughly 2,200 GWh/year of Li-ion batteries, and sufficient U.S. plus FTA refined lithium to produce roughly 1,500 GWh/year of Li-ion batteries. Based on the more recent critical materials report (Barlock, et al. 2024), the equivalent 2030 mined lithium estimates from domestic sources only translates to roughly 900 GWh/year of batteries.

4.5 Establishing the Range of Battery Growth Scenarios

A potential lower battery growth scenario narrative following from the preceding discussion could include assuming that future U.S. LD PEVs are only supplied by refined lithium from U.S.

plus FTA sources, and that half of the U.S. plus FTA refined lithium is used for applications other than U.S. LD PEVs. An alternate narrative resulting in comparable constraints would be to assume that future U.S. LD PEVs are only supplied by mined lithium from domestic U.S. sources. Either of these narratives are roughly equivalent to scaling the reference battery growth scenario by a factor of 0.5, so this scaling is selected to establish the lower sensitivity scenario.

Given the difficulty in quantifying potential factors contributing to a high sensitivity scenario (such as the extent to which imports may continue contributing to U.S. LDV sales plus the potential for additional production facility investments and/or advancements in technologies such as sodium-ion to expand battery production capacity), a more modest upward scaling factor of 1.2 is selected to define the high sensitivity scenario. As will be discussed later, a more bullish upward scaling factor for the high sensitivity scenario would have little further impact on the ability to convert new U.S. LDVs to PEVs.

The below bullets along with Figure 33 summarize the resulting range of simplified battery growth scenario assumptions to feed into the national-level theoretical lowest carbon vehicle analysis in the next chapter:

- Reference scenario – assumed linear growth rate of batteries available to new U.S. LDVs is established to match the growth rate of total capacity levels for existing and currently announced battery manufacturing facilities in the U.S. and Canada.
- Low sensitivity scenario - reflects a factor of 0.5 scaling applied to the reference scenario.
- High sensitivity scenario - reflects a factor of 1.2 scaling applied to the reference scenario.

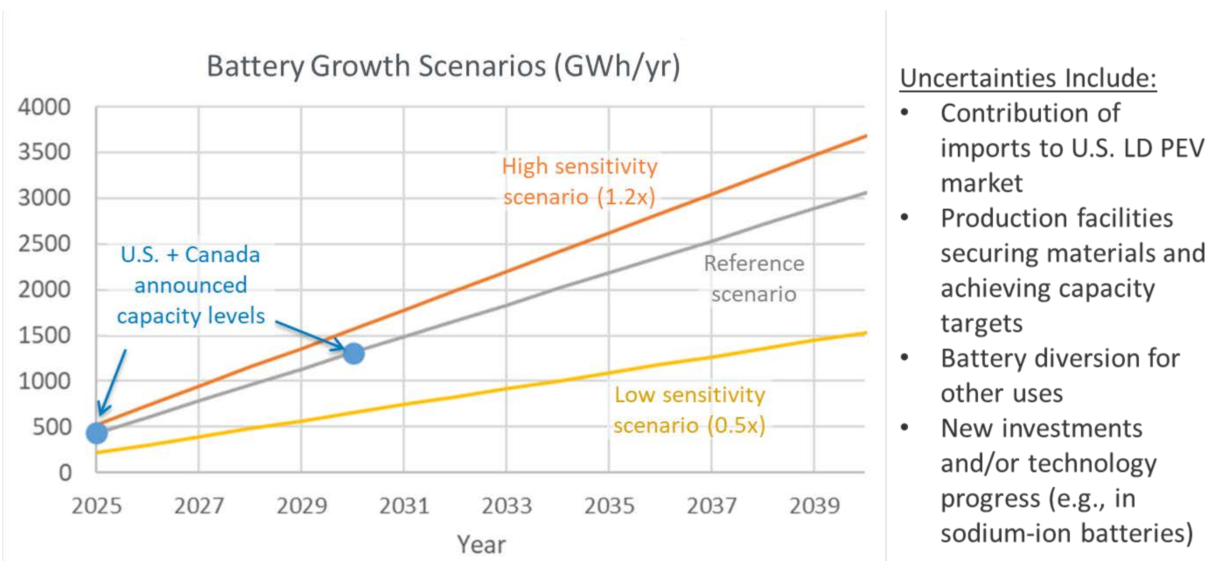

Figure 33. Battery growth scenario trendlines established for the theoretical analysis of fully converting new U.S. LDVs to different types of PEVs. Reference scenario growth rate informed by total capacity levels for existing and announced manufacturing facilities in the U.S. and Canada. Note, though, that emphasis should be placed on the range of sensitivity scenarios given the many uncertainties, such as those summarized on the right side of the figure.

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5 National-Level Theoretical Lowest Carbon Vehicle Analysis

This chapter builds upon the battery growth scenarios established in Chapter 4, along with several inputs from previous chapters, to conduct the theoretical analyses for replacing all new U.S. LDVs with a given type of PEV. The analyses then compare the total carbon emissions for a range of prospective PEV replacement cases to determine which PEV reduces carbon emissions most under the different battery growth scenarios at several analysis years. As with the preceding analyses, the carbon emissions calculations include both manufacturing and in-use emissions. Note that each analysis iteration allocates the entire available battery supply to a single PEV configuration, without regard to real-world production decisions or how marketable that configuration may be to customers. If battery availability is insufficient under a given PEV scenario to fully replace all new U.S. LDVs, the analysis allocates the available batteries as far as possible toward that type of PEV, while reserving the appropriate remainder for allocating across HEVs to fill out the balance of new U.S. LDVs.

5.1 Vehicle Assumptions

To streamline the analysis, a vehicle with representative characteristics is chosen as the basis for all powertrain options. The selected crossover SUV is chosen for having an efficiency close to the sales weighted average and the highest selling class type (Stone 2018). While the chosen vehicle matches several of the evaluated powertrain options, the efficiency, power, and battery size assumptions had to be established for the others. As a simplification, this analysis assumes that the charge-sustaining fuel economy for the HEV and each type of PHEV match, and likewise that the electricity consumption rate holds constant across BEVs of different ranges. All 2025 assumptions are based on existing vehicle data. The improvements through time are based on improvement trends from ADOPT (Brooker, Yang and Gonder 2024) and are similar to projections from EIA (Annual Energy Outlook 2023). The assumptions are shown in Table 7.

Table 7. Vehicle Assumptions

	Fuel Economy 2025/2050 (MPG)	Electric Efficiency 2025/2050 (kWh/mi)	Battery Energy (kWh)	Engine Power (kW)	Motor Power (kW)
Conv.	29/34			151	
HEV	39/42		1.3	131	128
PHEV20	39/42	0.36/0.34	9	131	174
PHEV40	39/42	0.36/0.34	18	131	174
PHEV60	39/42	0.36/0.34	27	131	174
BEV100		0.31/0.29	30		150
BEV150		0.31/0.29	45		150
BEV200		0.31/0.29	60		150
BEV300		0.31/0.29	85		150
BEV400		0.31/0.29	110		150

5.2 Scenario Assumptions

The varying scenario assumptions regarding battery growth, grid, and manufacturing emissions established in the previous chapters are leveraged to capture the range of potential PEV emissions outcomes in this analysis. Figure 34 shows the wide range of grid emission scenarios considered. These include the nationally representative assumptions from the preceding vehicle-level analyses, along with a few others to capture the full range of national projections. The lowest carbon grid scenario comes from the TDA study (Brooker, Yang and Gonder 2024) and assumes a completely zero-carbon grid by 2035. The highest grid emissions scenario comes from EIA's 2020 AEO, where emission rates still drop by 36%. All scenarios assume a 95.1% distribution efficiency (Ou and Cai 2020).

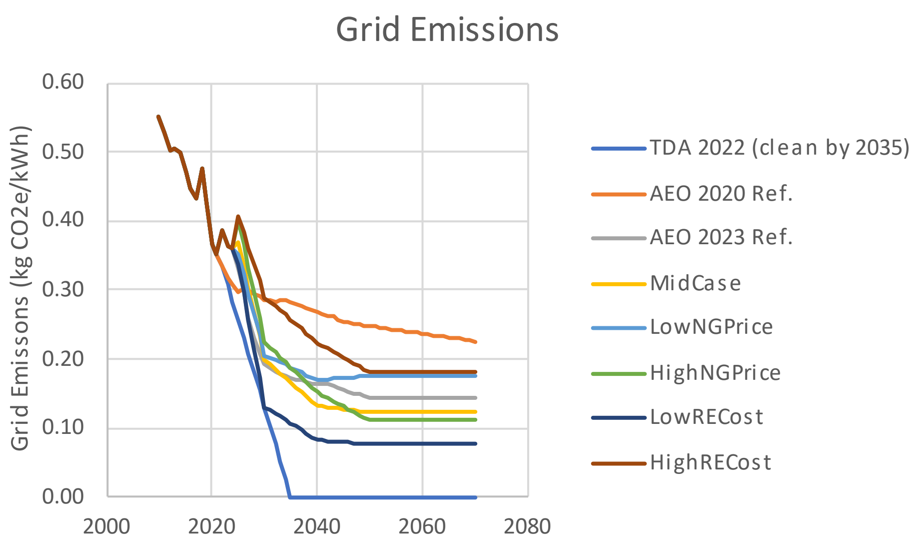

Figure 34. Electricity generation emission scenarios.

For battery manufacturing emissions, the four scenarios previously shown in Figure 7 are used. Table 8 shows other vehicle assumptions.

Table 8. Vehicle emission assumptions.

	Value	Source
Engine Manufacturing Emissions (kg CO_2/kW)	10	Previous tasks.
Motor Manufacturing Emissions (kg CO_2e/kW)	3	Previous tasks.
Glider Manufacturing Emissions (kg CO_2e/kg)	4	5400 kgCO_2e/1360 kg glider mass https://www.iea.org/data-and-statistics/charts/comparative-life-cycle-greenhouse-gas-emissions-of-a-mid-size-bev-and-ice-vehicle
Glider Mass (kg)	1,511	Estimate by subtracting powertrain mass from curb mass for conventional vehicle.

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	Value	Source
Gasoline (kg CO_2e/gallon)	11	8.887 kg/gallon from burning * 1.25 for production https://www.fueleconomy.gov/feg/label/calculations-information.shtml
Annual Travel (miles)	13,476	https://www.fhwa.dot.gov/ohim/onh00/bar8.htm
Annual Sales (million)	15	Approximation based on trends since 1976 https://www.statista.com/statistics/199983/us-vehicle-sales-since-1951/
Vehicle Life (years)	15	

5.3 Baseline Scenario Results

The baseline scenario assumes the following selections:

- Reference battery availability.
- Moderate battery manufacturing emissions.
- Mid-case grid emissions.

The carbon emissions by powertrain can be seen in Figure 35. The chart shows results for three different years going from left to right. For each year, a set of stacked bars shows the emissions by powertrain broken down by category. Note that the percentage next to each PEV label along the x-axis indicates the proportion of new U.S. LDVs that could become that type of PEV given the scenario's assumed battery availability constraints. Each bar stack starts at the bottom with glider manufacturing emissions. It then adds the engine, battery, and motor manufacturing emissions. The next two stack segments are for gasoline and electricity in-use emissions. Finally, the top stack segment indicates fuel use emissions from any alternative vehicles needed when the battery availability assumption prevents fully replacing all new U.S. LDVs with the given PEV. When this occurs, a percentage number is also included just above the alternative HEV gasoline bar segment to indicate the proportion of the new vehicle fleet assumed to be filled in by the alternative HEV. 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 varying grid mix assumptions account for most of the variation.

At a top level, Figure 35 reinforces observations from the earlier per-vehicle analysis—specifically 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 growth 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), and that the official goal is to reach 50% combined PEV and fuel cell vehicle sales by 2030 (White House 2021), there are certainly considerations beyond battery growth rate that make it unrealistic to expect complete changeover of all new U.S. LDVs to PEVs in 2025. On the other hand, the farther out results in 2032 and in 2040 indicate sufficient battery availability under this scenario for full replacement of new U.S. LDV sales with any of the indicated types of PEVs.

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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. The superior theoretical emissions reduction for the BEV100 is even more striking in 2025, as under this scenario there is sufficient battery availability for 97% of new U.S. LDVs to be BEV100s with supplemental gasoline consumption only coming from the remaining 3% of the fleet assumed to become HEVs. The larger battery BEVs require more of the fleet to become HEVs, resulting in substantially more GHG emissions from gasoline consumption. Similarly, PHEV gasoline consumption while in charge-sustaining mode results in comparable total emissions as the larger battery BEV plus alternative HEV results. Note, however, that while the shortest range BEV is shown to be the theoretical lowest carbon option, the analysis does not consider utility limitations regarding how much driving can be covered by that vehicle. Relatedly, the analysis was not structured to identify the lowest carbon option when also considering marketability. Historically, low range BEVs, which also have slower acceleration, have not sold well (Zhou 2023).

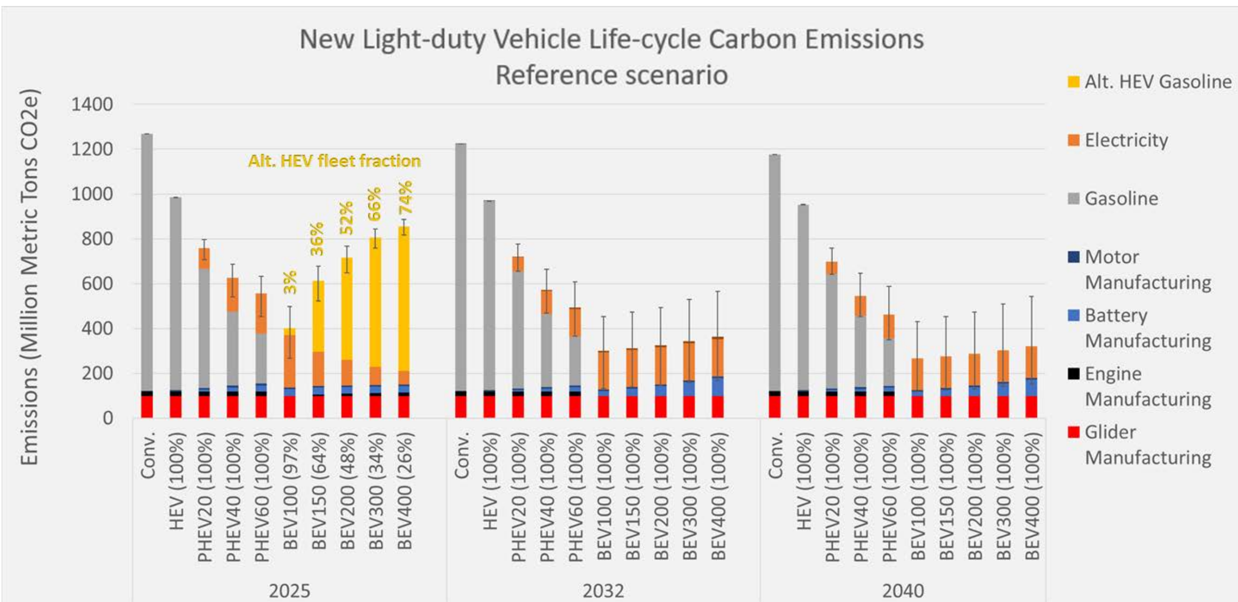

Figure 35. Theoretical national-level carbon emissions by powertrain under the reference battery growth scenario.

5.4 Battery Availability Sensitivities

Recall that in addition to establishing the reference battery growth scenario, the previous section described selection of both high and low sensitivity scenarios. Figure 36 indicates the results from re-running the analysis under the high sensitivity battery growth scenario. As battery availability in the reference scenario was sufficient in 2032 and 2040 for all new U.S. LDVs to become any of the considered PEV options, the results for those years remain unchanged with the higher assumed battery growth. The 2025 results change a small amount under the high sensitivity scenario with fewer alternative HEVs required for each BEV configuration. However, the overall findings remain unchanged for that year as well, with the BEV100 showing the theoretical lowest carbon emissions potential, but having the same caveats regarding known marketability limitations as noted above.

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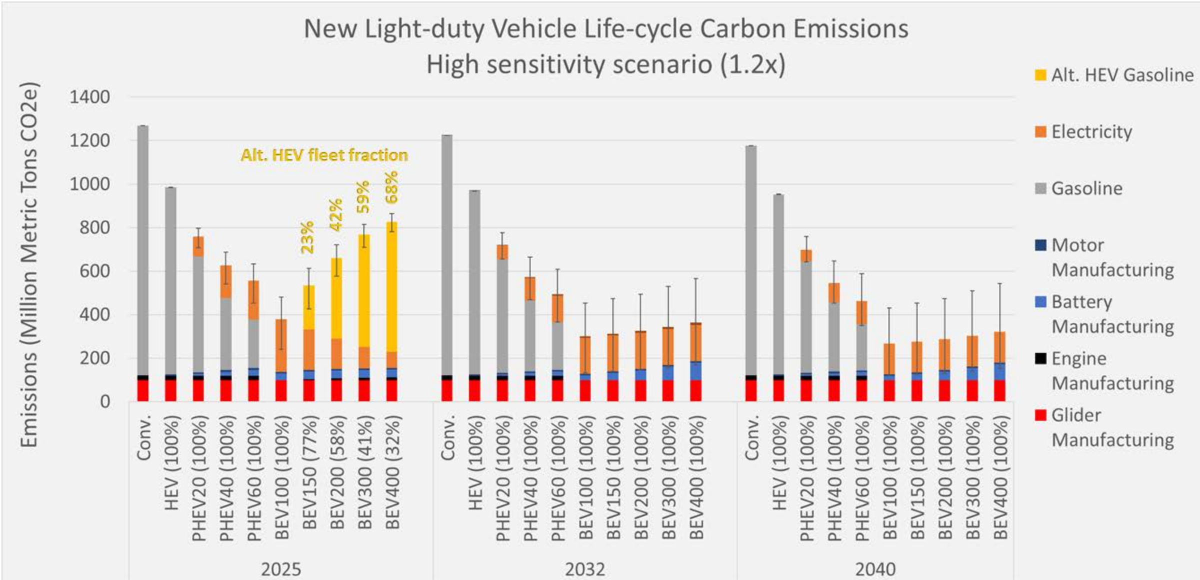

Figure 36. Theoretical national-level carbon emissions by powertrain under the high sensitivity battery growth scenario.

The results for the low sensitivity scenario in Figure 37 show substantially more variation from the results for the reference and for the high sensitivity scenarios in Figure 35 and Figure 36. 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 longer-range BEVs 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 just over a 50% reduction relative to the conventional vehicle case. The comparable theoretical carbon emissions for the 2032 BEV100 in this scenario is roughly 75% lower than those for the conventional vehicle.

The 2025 results for the low sensitivity scenario also show noteworthy differences from the reference and the high sensitivity battery growth scenarios. The restricted battery availability in the low sensitivity scenario results in all PEVs other than the PHEV20 configuration requiring some number of alternative HEVs. The theoretical minimum carbon emissions configuration in this scenario (delivering a 44% reduction relative to the 2025 conventional vehicle case) is essentially a tie between the PHEV40 coupled with 9% of the fleet being alternative HEVs and the BEV100 coupled with 52% of the fleet being alternative HEVs. The configurations for the PHEV20 along with for the PHEV60 and for the BEV150 with varying levels of alternative HEVs are not far behind—achieving emissions reductions between 36%-40% relative to the conventional vehicle case.

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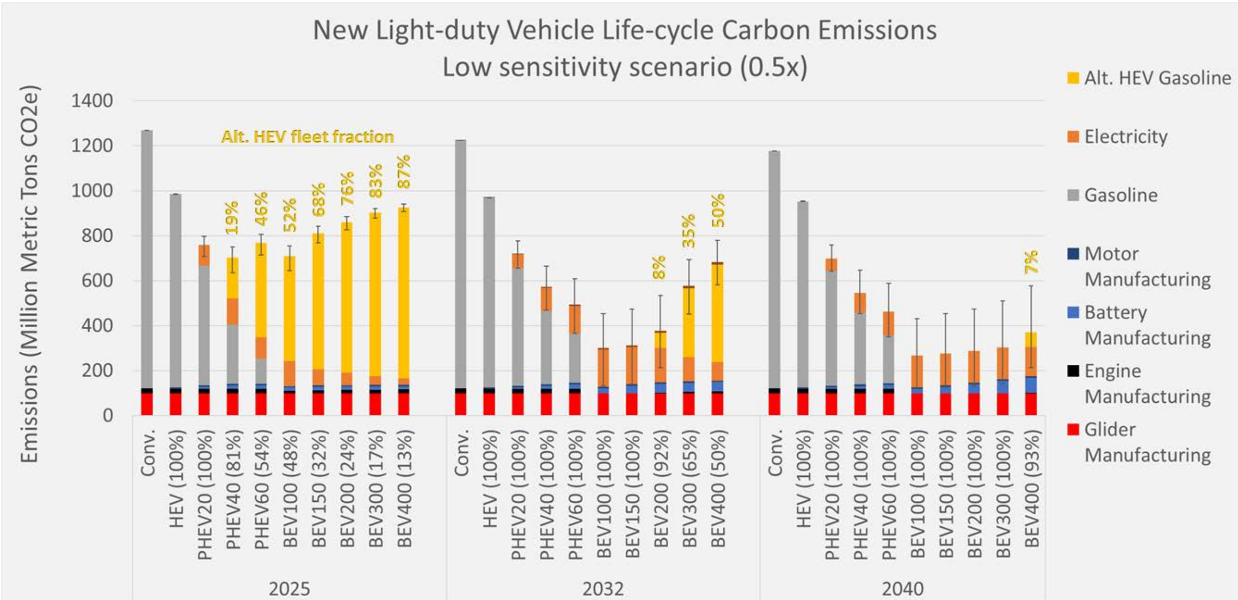

Figure 37. Theoretical national-level carbon emissions by powertrain under the low sensitivity battery growth scenario.

5.5 Summary of the National-Level Analyses

The battery growth assumptions have a significant impact on the theoretical analyses for replacing all new U.S. LDVs with a given type of PEV. To underscore this, Figure 38 re-plots the potential carbon emissions reduction for three example powertrains from both the reference and the low sensitivity battery growth scenarios against the assumed GWh/year constraint at each analyzed year from Figure 35 and Figure 37. Starting at the left side of Figure 38, the assumed ~218 GWh/year constraint in 2025 under the low sensitivity battery growth scenario prevents all three types of PEVs from fully replacing all new U.S. LDVs, resulting in significant numbers of alternative HEVs being used to fill out the new LDV fleet for the theoretical analysis—especially for the BEV300. Under this assumed battery availability constraint, the PHEV40 and the BEV100 (supplemented by HEVs) effectively tie for the theoretically lowest carbon emissions—achieving ~44% lower carbon emissions than a fully ICEV fleet. For the next higher battery availability constraint of ~435 GWh/year, the PHEV40 can fully replace all new U.S. LDVs, and the BEV100 is nearly able to do so. However, the BEV100 under this scenario pulls away to a significantly deeper theoretical decarbonization level of nearly 70% lower than an ICEV fleet versus roughly 50% lower carbon emissions for the PHEV40.

For all higher levels of assumed battery availability constraints, the BEV100 continues to achieve the deepest theoretical decarbonization results—exceeding 75% lower than a conventional vehicle fleet. For the 830 GWh/year assumed battery availability constraint, this is significantly greater decarbonization than achieved by both the PHEV40 and the BEV300, but by the next analyzed case with assumed battery availability exceeding ~1,500 GWh/year, the BEV300 can fully replace all new U.S. LDVs and it achieves nearly the same levels of decarbonization as the BEV100.

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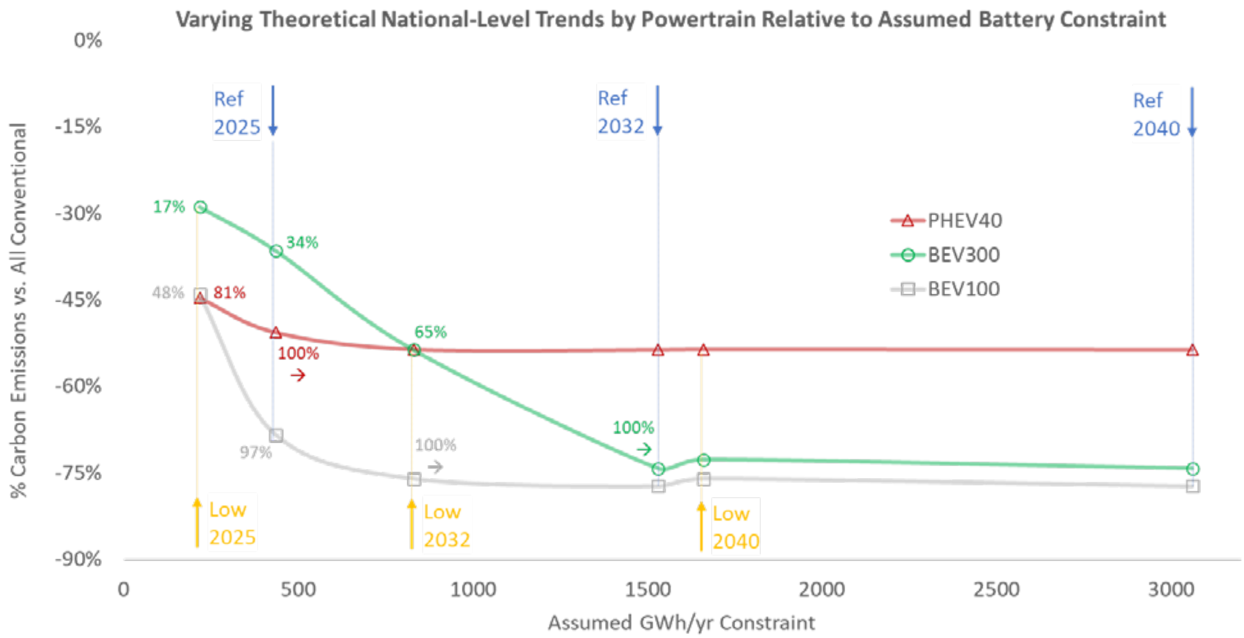

Figure 38. Summarized impact of battery availability on theoretical national-level carbon emissions reduction for three powertrains—drawn from the reference ("Ref") and the low sensitivity ("Low") battery growth scenario analyses. The small font percentages next to each point indicate the fraction of new U.S. LDV sales that could be that powertrain at each assumed GWh/year constraint (while allowing the remainder of the fleet to be HEVs). Once 100% of new U.S. LDV sales could become the given type of powertrain, points at higher assumed GWh/year availability levels are no longer labeled.

Figure 38 most significantly underscores the major role that the battery availability assumptions play in determining the theoretical carbon emissions reduction achievable by each powertrain (at least for constraints under ~1,500 GWh/year). One more subtle impact is illustrated by the slight increase in the theoretical carbon emissions for the two BEVs when moving from the battery availability constraint of just over 1,500 GWh/year from the 2040 low sensitivity scenario to the slightly higher constraint from the 2032 reference scenario. Rather than the lines remaining flat, this increase occurs because 2040 is assumed to have a lower carbon grid mix than in 2032—which is also why the theoretical BEV decarbonization results go down again for the 2040 reference scenario with the largest assumed GWh/year battery availability constraints shown on the far right of the figure.

Reminders of caveats and limitations from the theoretical national-level analyses include that there are a host of considerations beyond battery availability that would make monolithic replacement of all new U.S. LDVs by a single type of PEV unrealistic, particularly for a near-term analysis year such as 2025. These include the array of in-process automaker production plans, and heterogeneity in consumer preferences. Likewise, while the results show short range BEVs as generally having the lowest theoretical carbon emissions (and largely avoiding battery availability constraints over most of the evaluated scenarios), the analysis did not consider impacts from any utility limitations for these vehicles. Given that short range BEVs have been available the longest but have not sold well, more rigorous analysis should capture the extent to which these vehicles may continue to struggle with market acceptance. Such further analysis

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should identify the combination of vehicle-level carbon emissions and large-scale marketability for different PEV designs to minimize overall carbon emissions across different levels of assumed battery availability constraints.

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6 Conclusions

The vehicle-level analyses in this report highlight the significant range of life cycle GHG emissions that may result from varying input scenarios for longitudinal electric grid evolution, spatial heterogeneity of regional electric grid characteristics, PEV charging behavior, and evolution of HV battery chemistry mix and manufacturing processes. Nevertheless, for each given set of input assumptions: HEVs achieve significant life cycle GHG emissions savings relative to ICEVs; PHEVs achieve further savings while requiring additional battery content; and BEVs achieve the deepest savings (plus avoid all tailpipe criteria emissions) though require the most per-vehicle battery content. Reflecting uncertainty in the future growth trajectory of batteries for use in U.S. LDVs, the study establishes a range of future battery growth scenarios as inputs for the national-level analyses.

The national-level analyses show that battery growth assumptions have a significant impact on the theoretical replacement of all new U.S. LDVs with a given type of PEV. When battery availability is sufficient, BEVs achieve the lowest national-level GHG emissions outcomes (as in the per-vehicle analysis), with relatively consistent results across BEVs of different ranges. Under moderately constrained battery availability assumptions, the analyses generally show short-range BEVs as having a pronounced GHG emissions advantage. Under the nearest-term and most constrained battery availability assumptions, only the lowest range PHEV configuration could fully replace all new U.S. LDVs, while all other PEV configurations would need to combine with some proportion of alternative HEVs to fully replace new U.S. LDVs. Under these assumptions, the depths of GHG emissions reductions are more limited than when battery availability is greater, and the theoretical minimum GHG emissions outcomes are comparable between PHEVs and short-range BEVs.

Limitations for the national-level analyses in this report include the acknowledgement that monolithic replacement of all new U.S. LDVs by a single type of PEV may not be realistic—particularly in the near term—and that utility and marketability constraints are not considered. Extension of this work incorporating realistic market dynamics modeling would give further insights on the best combinations of vehicle GHG reductions and large-scale marketability to minimize overall GHG emissions under different battery growth scenarios. Given the criticality of battery availability to enable the deepest theoretical decarbonization outcomes, the analyses underscore the importance of ongoing investments and actions to continue expanding battery availability and to mitigate potential supply chain bottlenecks. While complete replacement of all new U.S. LDVs with PEVs may not be immediately feasible, maximizing penetration across the range of PEV designs will support significant GHG emissions reduction. 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).

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Appendix

A.1 LiAISON Assessment of Passenger Vehicle Environmental Impact Energy Sources in the U.S.

Table 9. Global warming impact (kgCO2eq.) of production of 1 kilowatt hour of electricity (at the plug) and 1 kilogram of gasoline (at the pump) for the U.S.

Fuel sources	2020	2030	2040	2050	2060
electricity coal	1.074	1.048	1.024	1.020	1.013
electricity coal with ccs	0.166	0.155	0.146	0.145	0.142
electricity gas combined cycle	0.426	0.418	0.411	0.410	0.407
electricity gas combined cycle with ccs	0.136	0.132	0.130	0.128	0.125
electricity gas conventional power plant	0.611	0.609	0.609	0.609	0.606
electricity geothermal	0.066	0.061	0.059	0.057	0.048
electricity hydro	0.006	0.006	0.006	0.006	0.006
electricity solar concentrated solar power	0.049	0.048	0.048	0.048	0.047
electricity solar photovoltaics	0.045	0.039	0.036	0.034	0.029
electricity wind	0.012	0.012	0.012	0.011	0.011
gasoline 5% ethanol by volume	0.822	0.930	1.034	1.199	1.202
gasoline with H_2 from coal gasification with CCS	5.163	4.793	4.843	4.682	4.065
gasoline with H_2 from electrolysis and CO_2 (DACS)	15.469	13.396	13.275	12.237	9.321

Table 10. Human toxicity impact (kg 1,4-DCB-eq.) of production of 1 kilowatt hour of electricity (at the plug) and 1 kilogram of gasoline (at the pump) for the U.S. (not used in the present study; simply included here to provide the comprehensive set of LiAISON data in this appendix)

year	2020	2030	2040	2050	2060
electricity coal	0.40	0.39	0.38	0.38	0.38
electricity coal with ccs	0.29	0.27	0.25	0.25	0.25
electricity gas combined cycle	0.01	0.01	0.01	0.01	0.01
electricity gas combined cycle with ccs	0.02	0.02	0.02	0.02	0.02
electricity gas conventional power plant	0.02	0.02	0.02	0.02	0.02
electricity geothermal	0.04	0.04	0.04	0.04	0.03
electricity hydro	0.00	0.00	0.00	0.00	0.00
electricity solar concentrated solar power	0.01	0.01	0.01	0.01	0.01
electricity solar photovoltaics	0.04	0.04	0.04	0.03	0.03
electricity wind	0.01	0.01	0.01	0.01	0.01
gasoline 5% ethanol by volume	0.12	0.12	0.19	0.31	0.30
gasoline with H_2 from coal gasification with CCS	3.91	3.72	3.77	3.75	3.31
gasoline with H_2 from electrolysis and CO_2 from DACS	7.73	6.66	6.70	6.53	4.41

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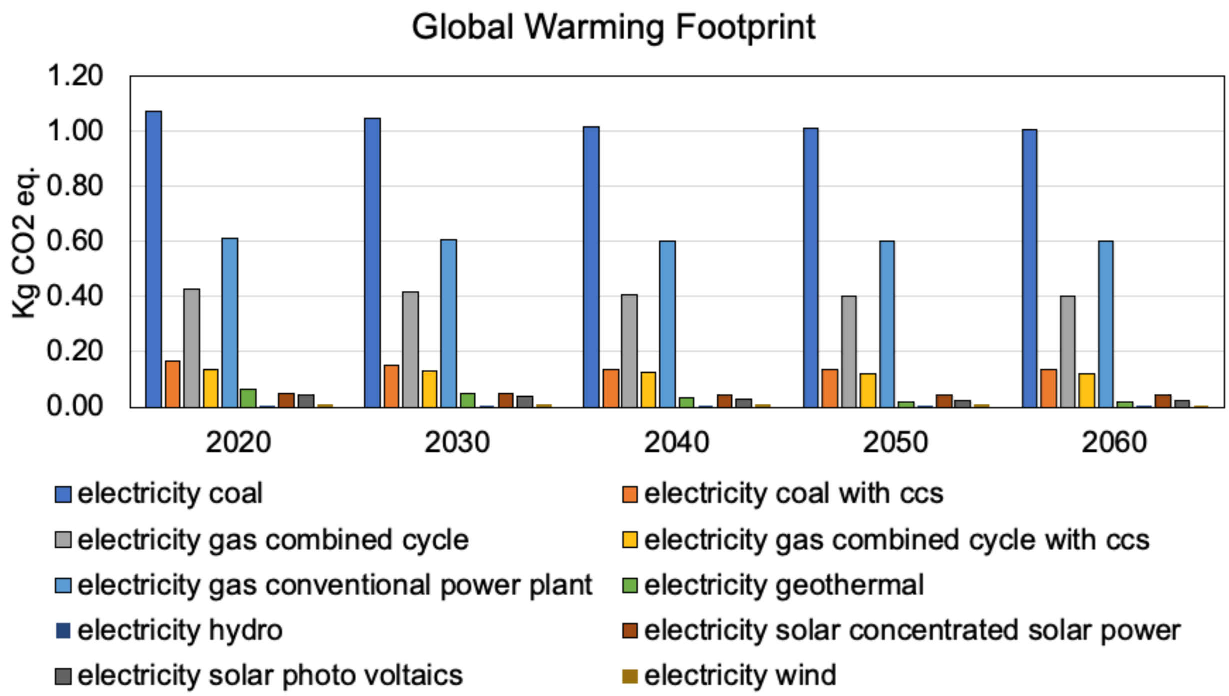

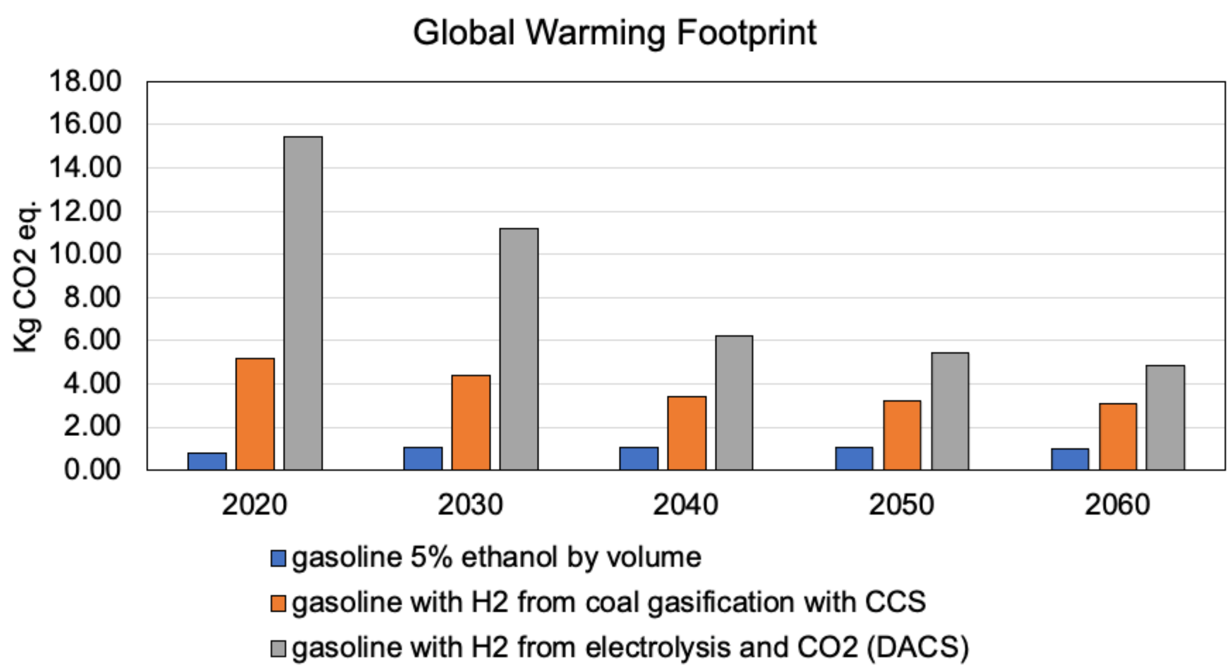

Figure 39. Global warming impact (kgCO2eq.) of production of 1 kilowatt hour of electricity (at the plug) and 1 kilogram of gasoline (at the pump) for the U.S.

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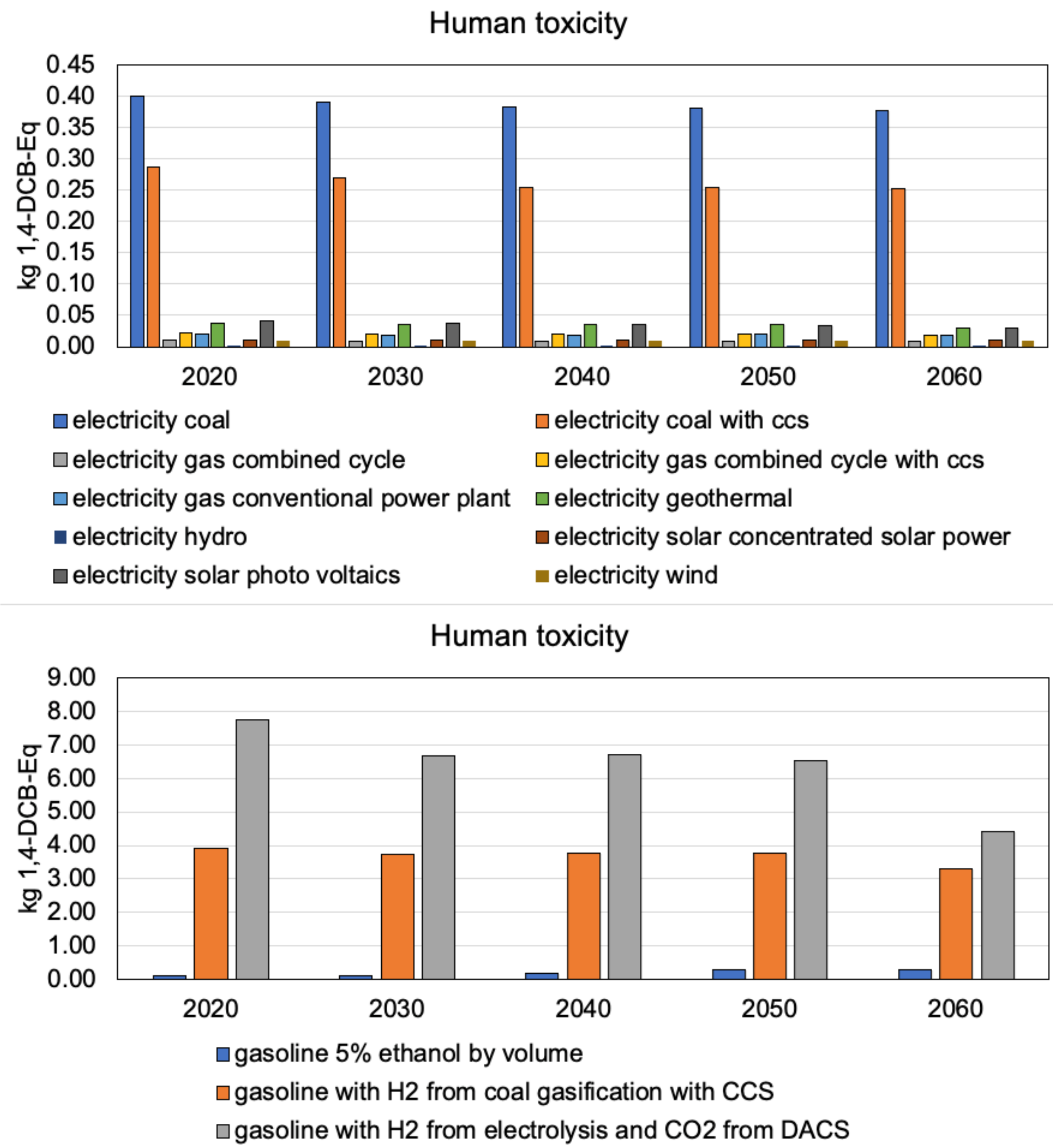

Figure 40. Human toxicity impact (kg 1,4-DCB-eq.) of production of 1 kilowatt hour of electricity (at the plug) and 1 kilogram of gasoline (at the pump) for the U.S. (not used in the present study; simply included here to provide the comprehensive set of LiAISON data in this appendix)

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A.2 Additional Results for Per-Vehicle Life Cycle GHG Emissions Analysis: Car/Sedan

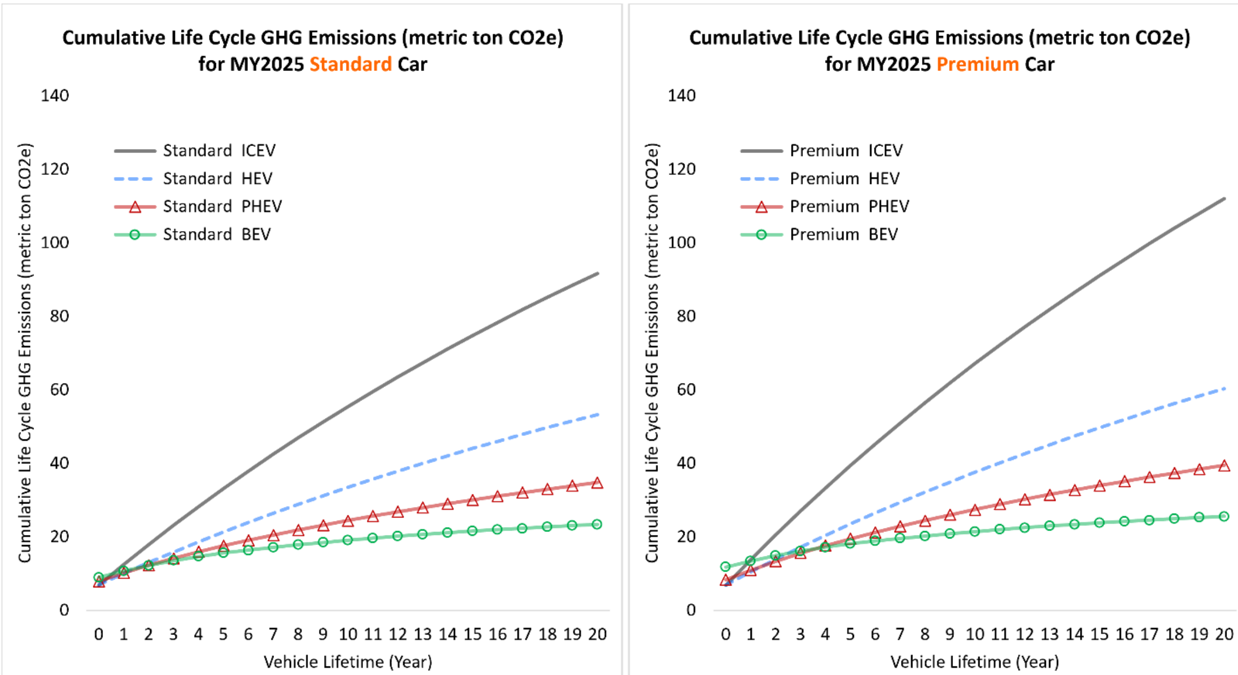

Figure 41. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 car/sedan and baseline scenario (battery chemistry: NMC, grid region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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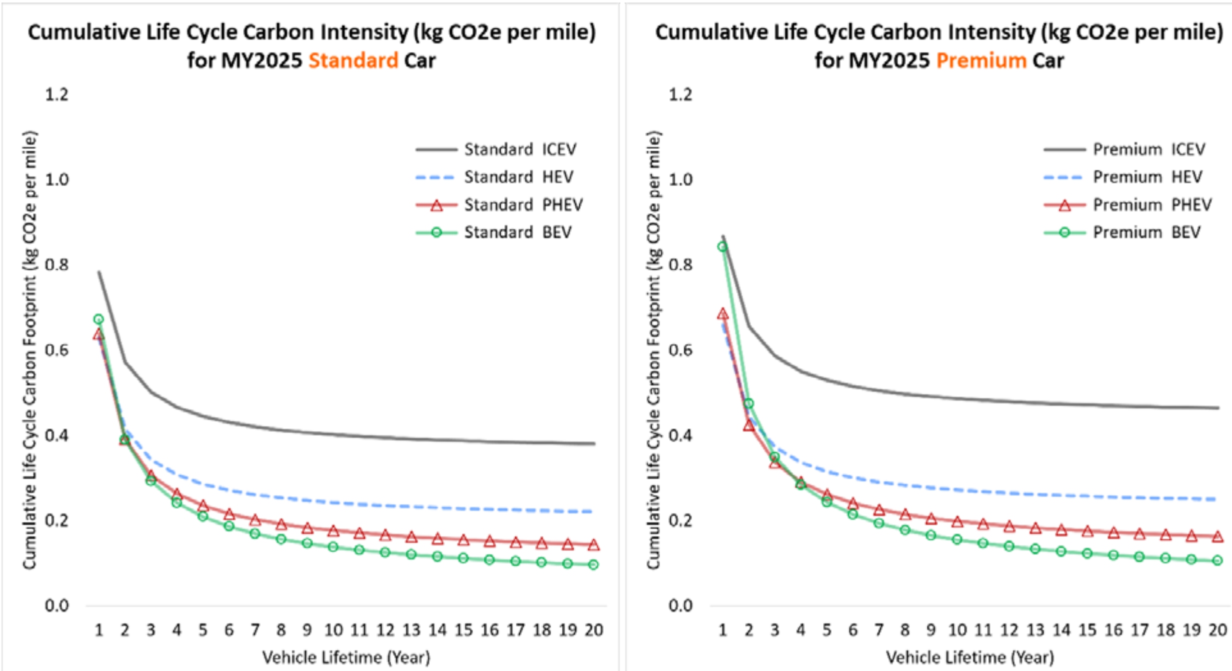

Figure 42. Cumulative life cycle carbon intensity (kg CO2e per mile) over vehicle lifetime for MY2025 car/sedan and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

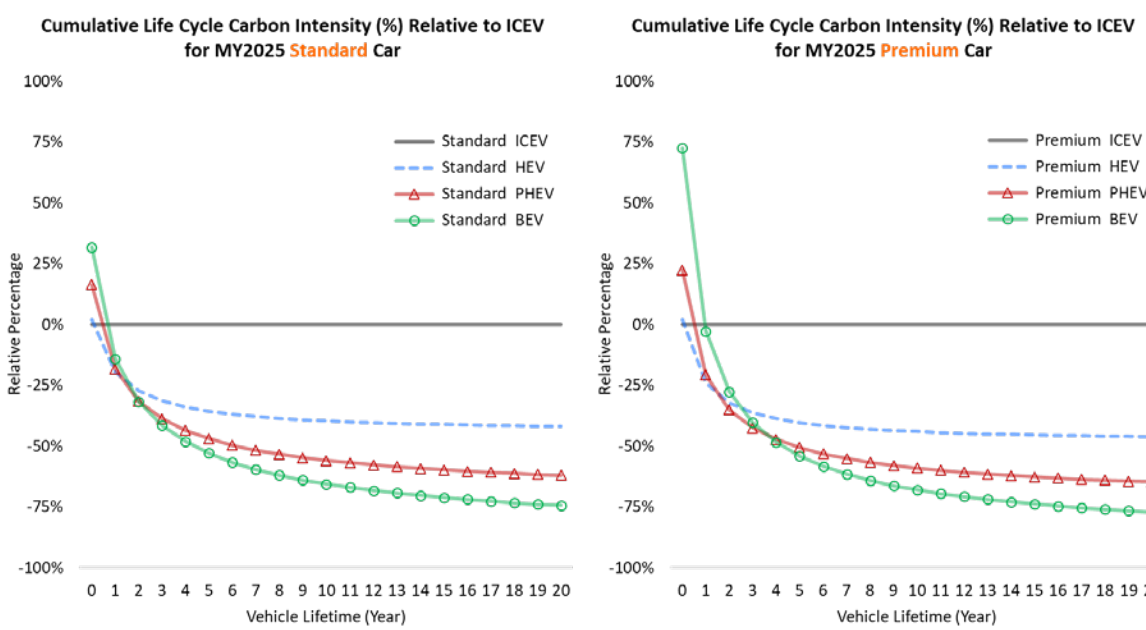

Figure 43. Cumulative life cycle carbon intensity relative to ICEV over vehicle lifetime for MY2025 car/sedan and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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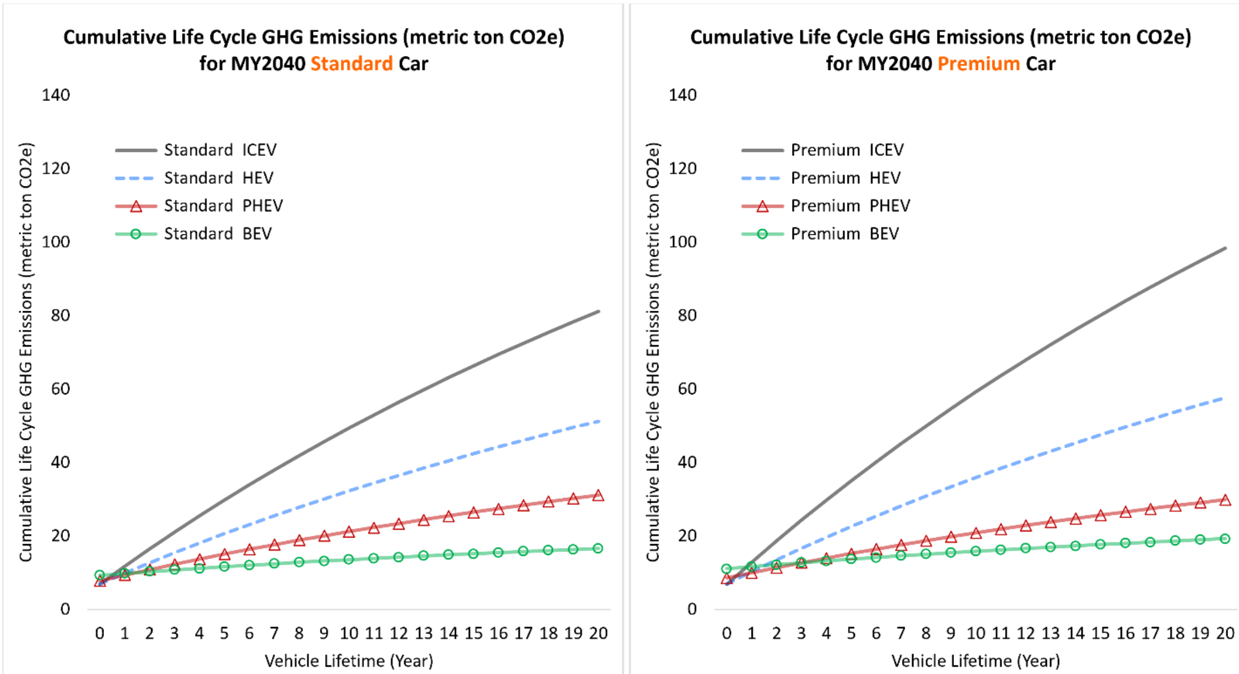

Figure 44. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 car/sedan and baseline scenario (battery chemistry: NMC, grid region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

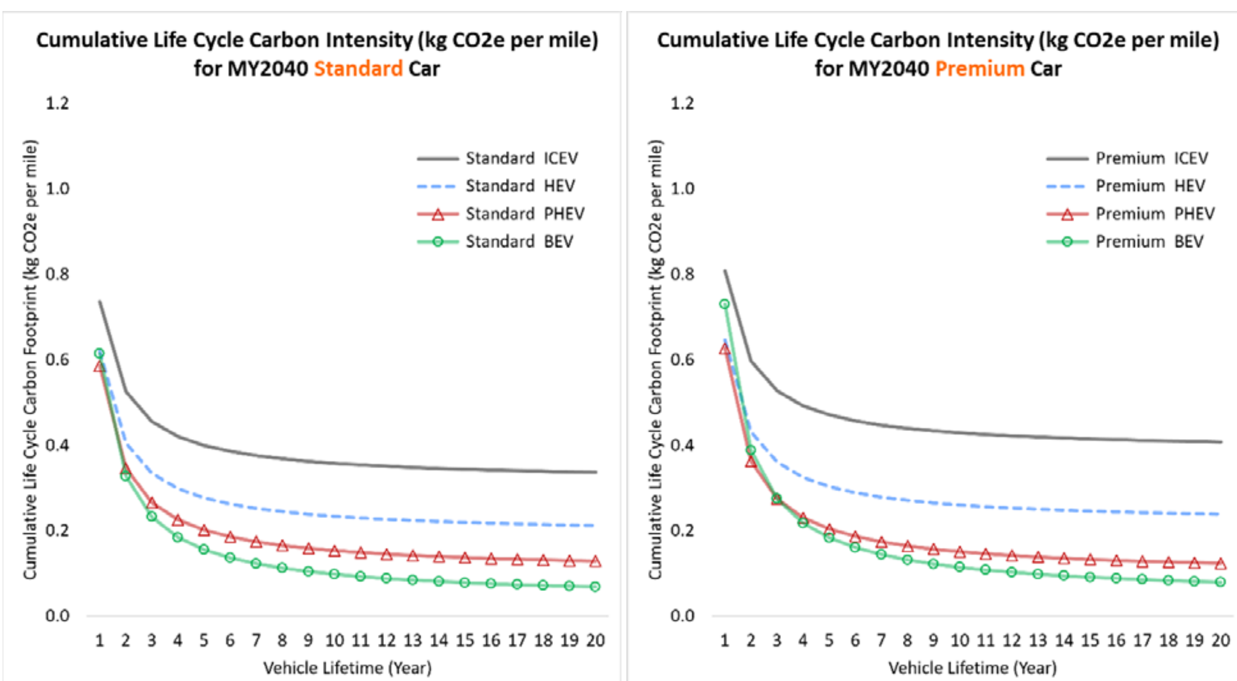

Figure 45. Cumulative life cycle carbon intensity (kg CO2e per mile) over vehicle lifetime for MY2040 car/sedan and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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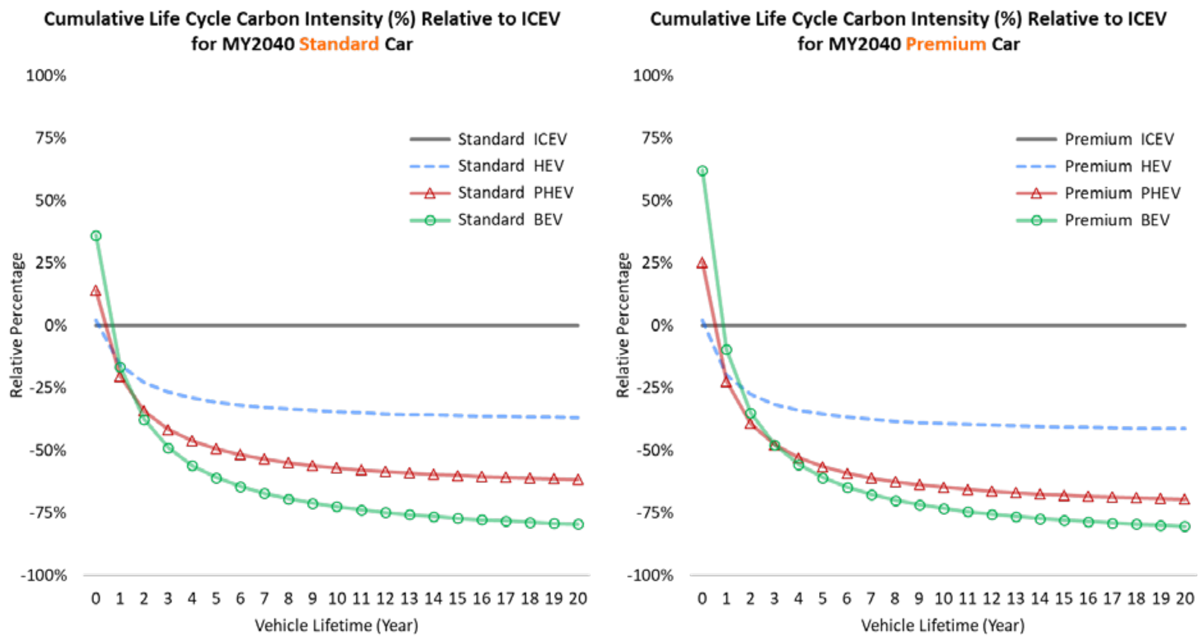

Figure 46. Cumulative life cycle carbon intensity relative to ICEV over vehicle lifetime for MY2040 car/sedan and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

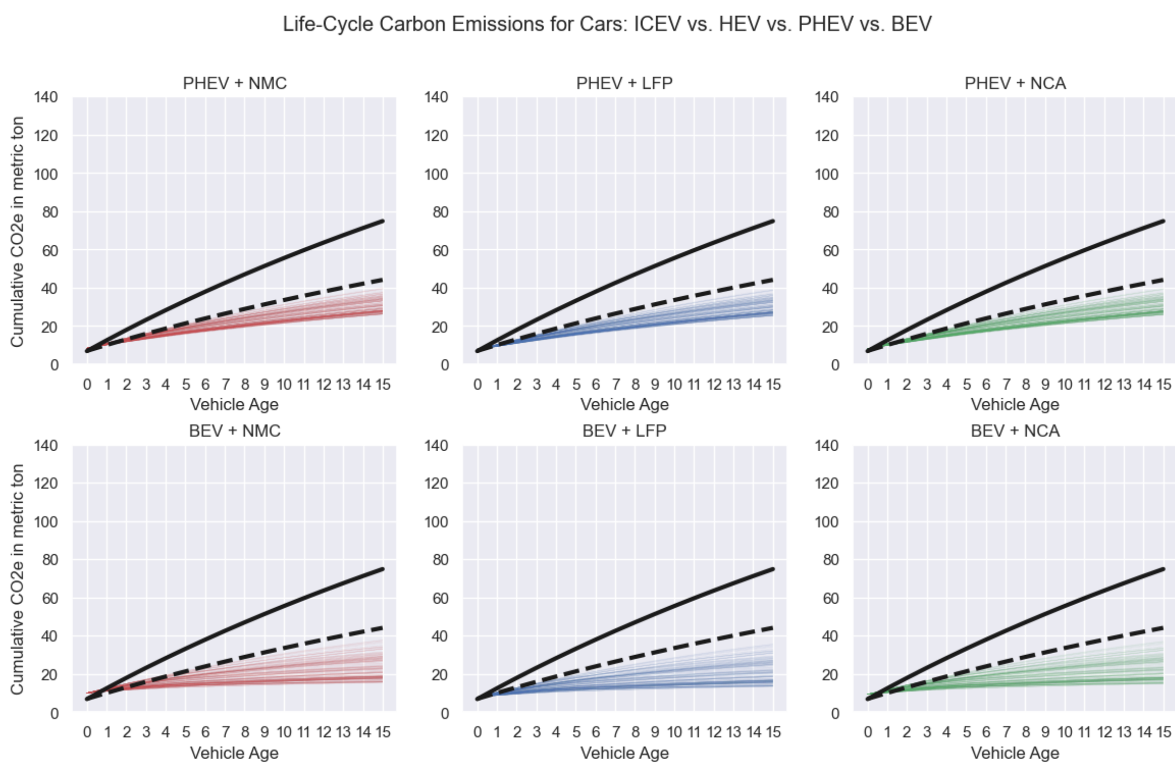

Figure 47. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 standard car/sedan – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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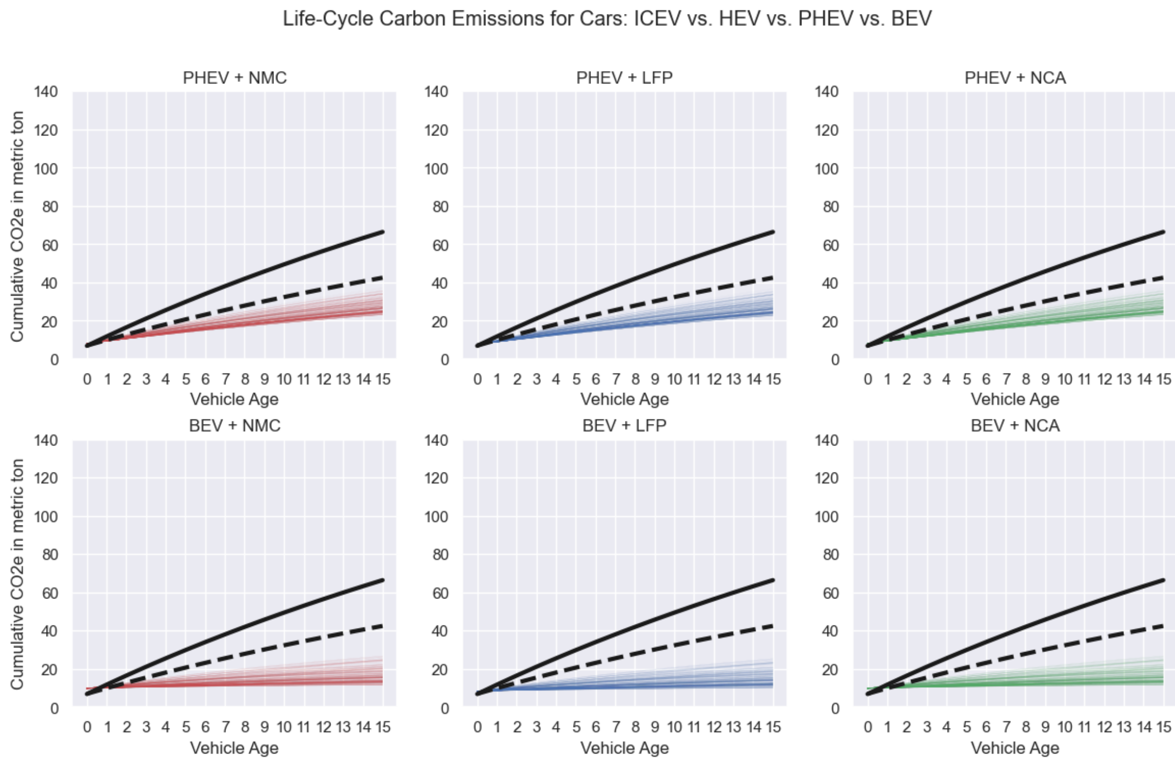

Figure 48. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 standard car/sedan – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

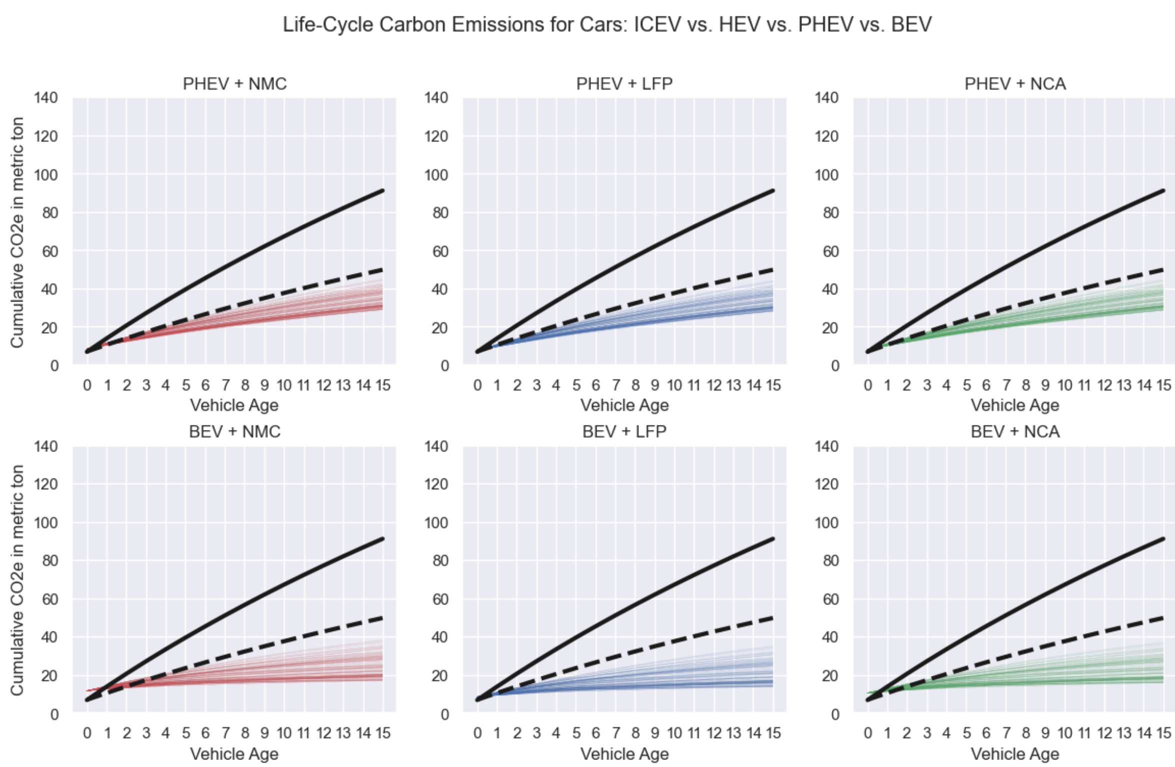

Figure 49. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 premium car/sedan – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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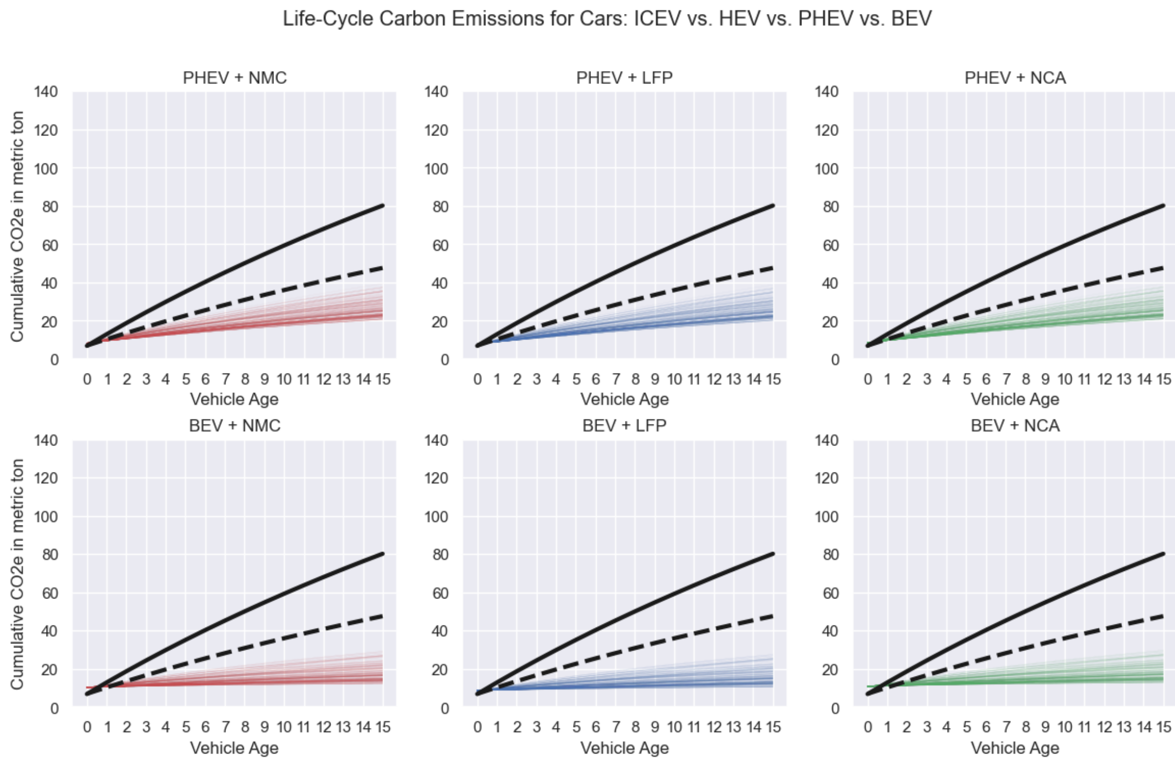

Figure 50. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 premium car/sedan – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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A.3 Additional Results for Per-Vehicle Life Cycle GHG Emissions Analysis: Pickup Truck

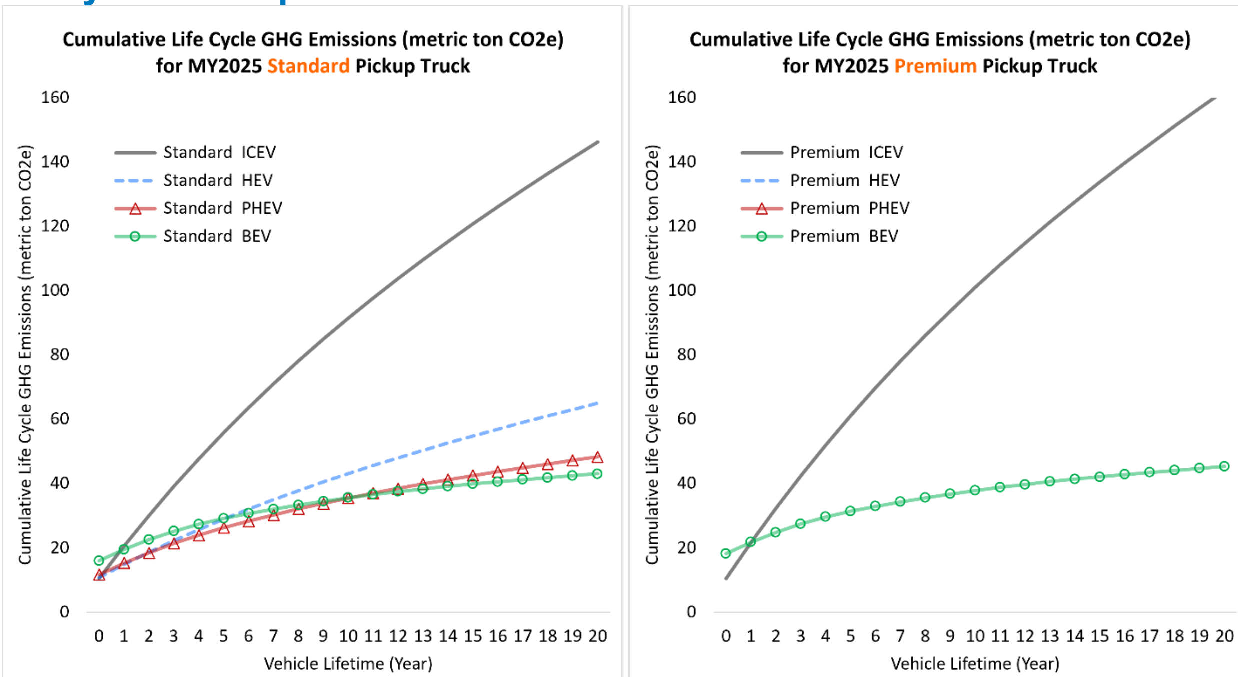

Figure 51. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 pickup truck and baseline scenario (battery chemistry: NMC, grid region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

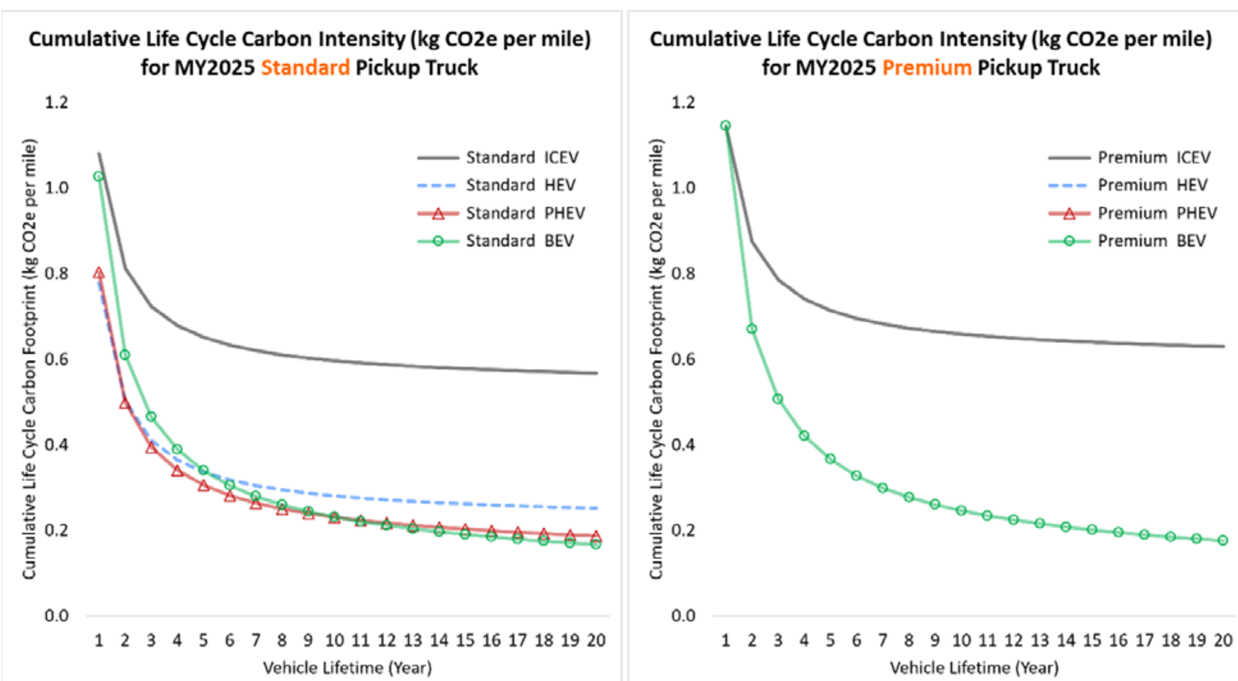

Figure 52. Cumulative life cycle carbon intensity (kg CO2e per mile) over vehicle lifetime for MY2025 pickup truck and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

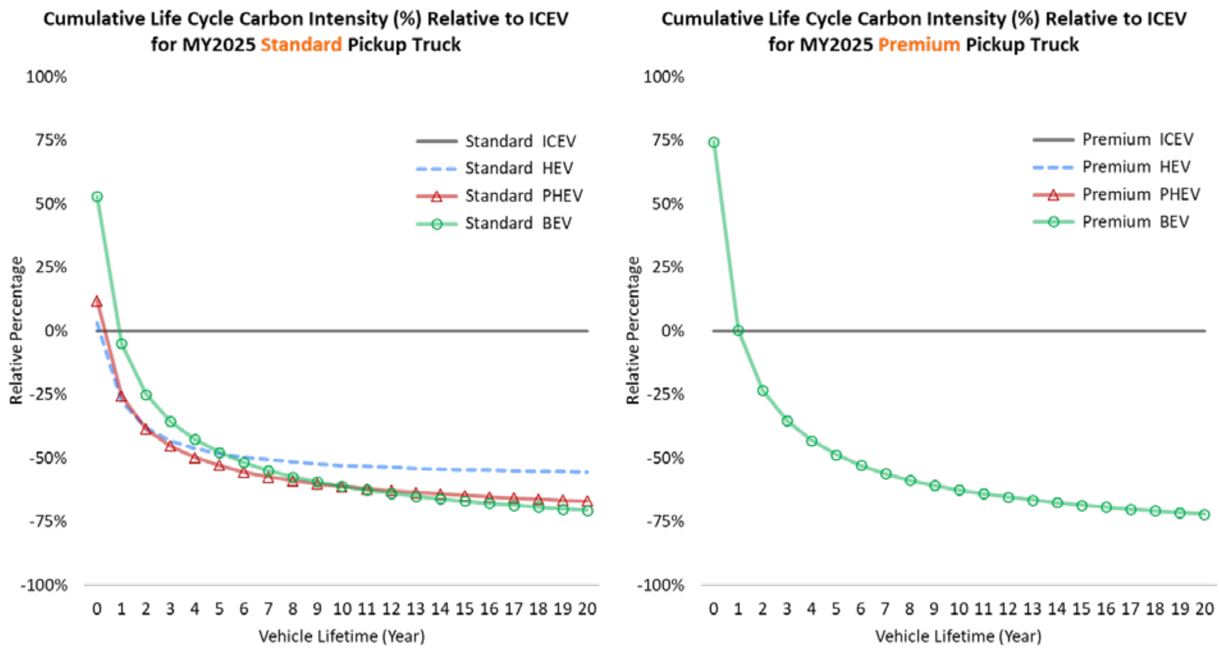

Figure 53. Cumulative life cycle carbon intensity relative to ICEV over vehicle lifetime for MY2025 pickup truck and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

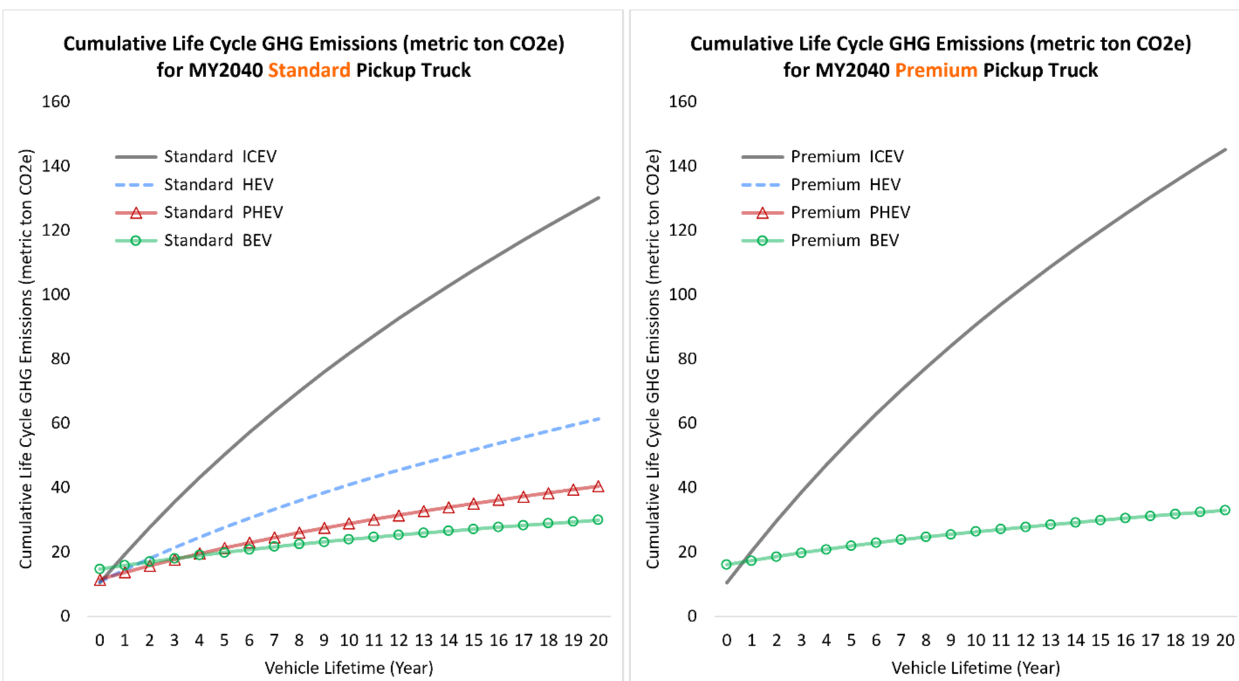

Figure 54. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 pickup truck and baseline scenario (battery chemistry: NMC, grid region: U.S. average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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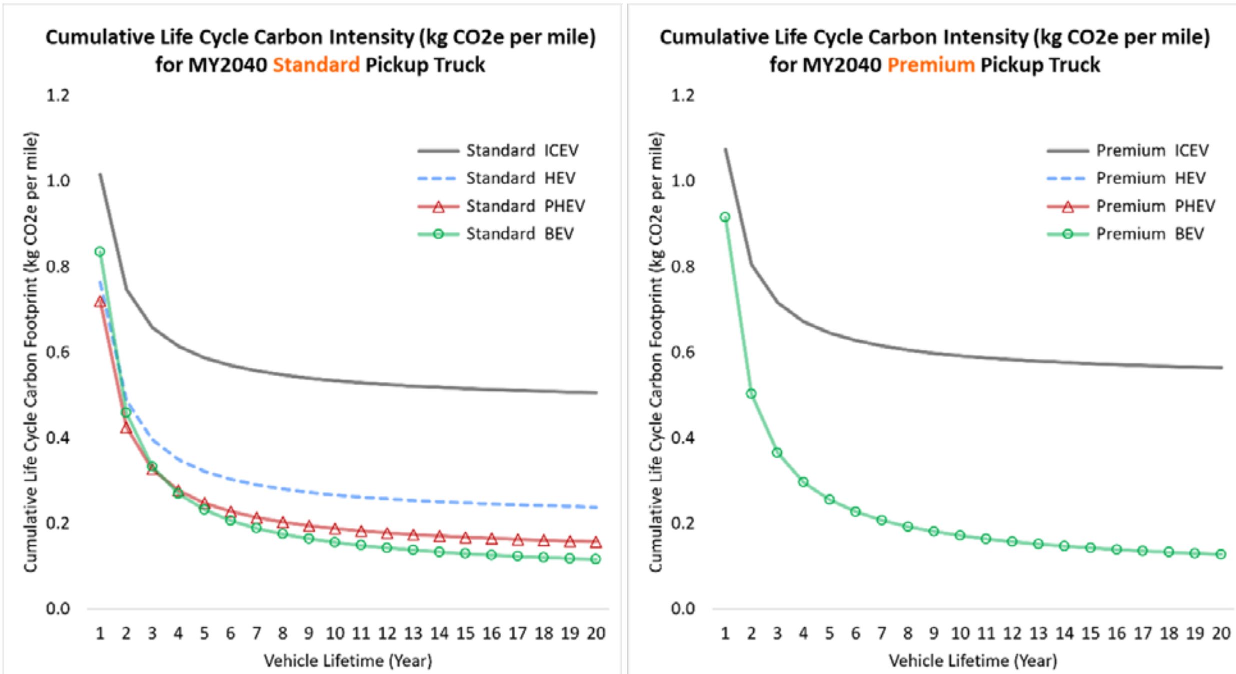

Figure 55. Cumulative life cycle carbon intensity (kg CO2e per mile) over vehicle lifetime for MY2040 pickup truck and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

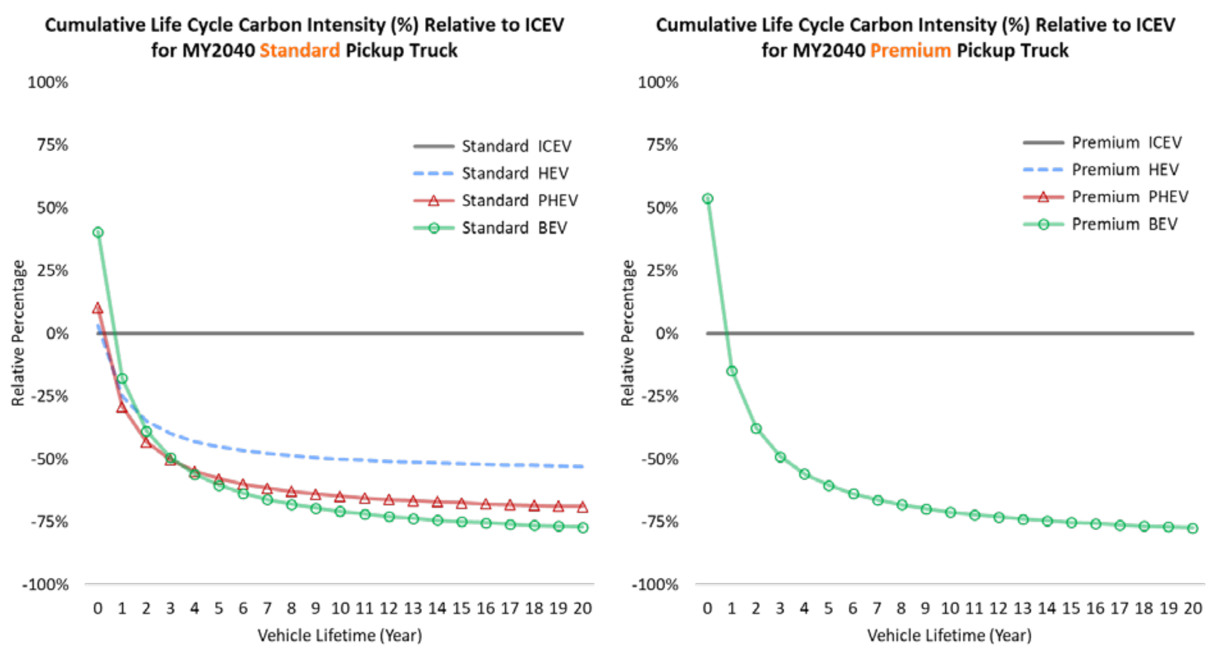

Figure 56. Cumulative life cycle carbon intensity relative to ICEV over vehicle lifetime for MY2040 pickup truck and baseline scenario (battery chemistry: NMC, NERC region: US average, future electric grid in Cambium: Mid-case, and charging behavior in EVI-Pro: Baseline).

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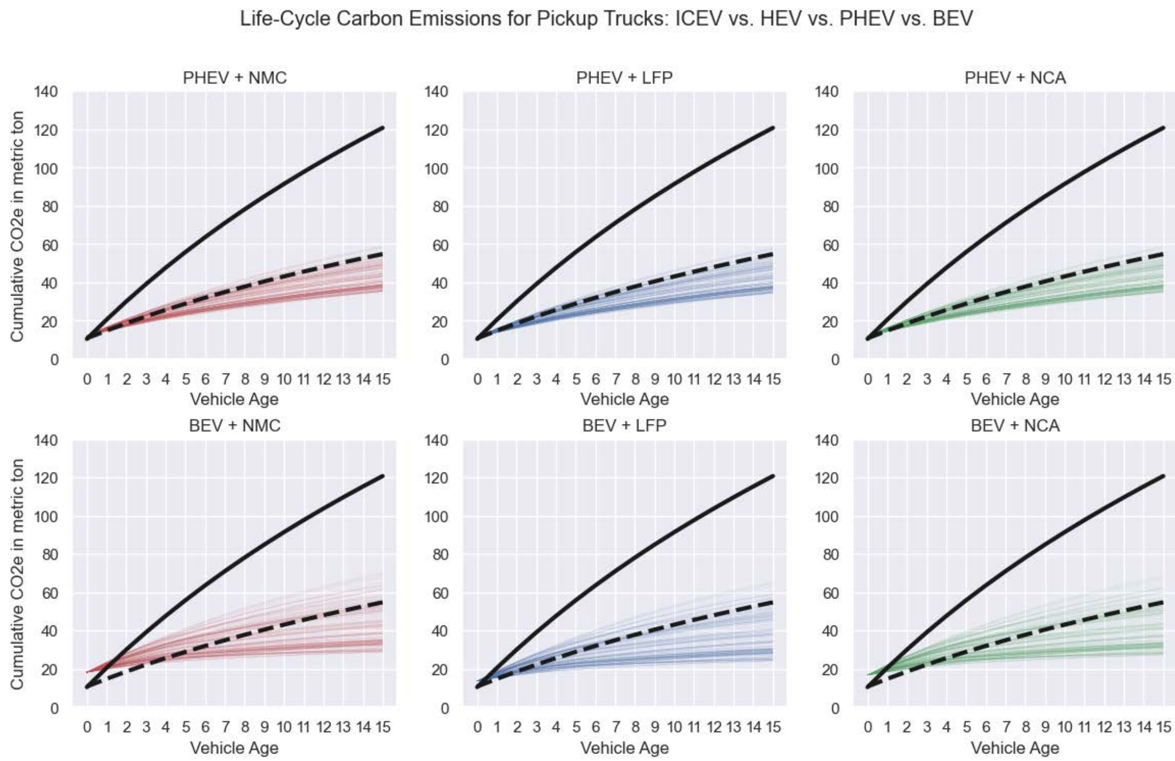

Figure 57. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 standard pickup truck – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

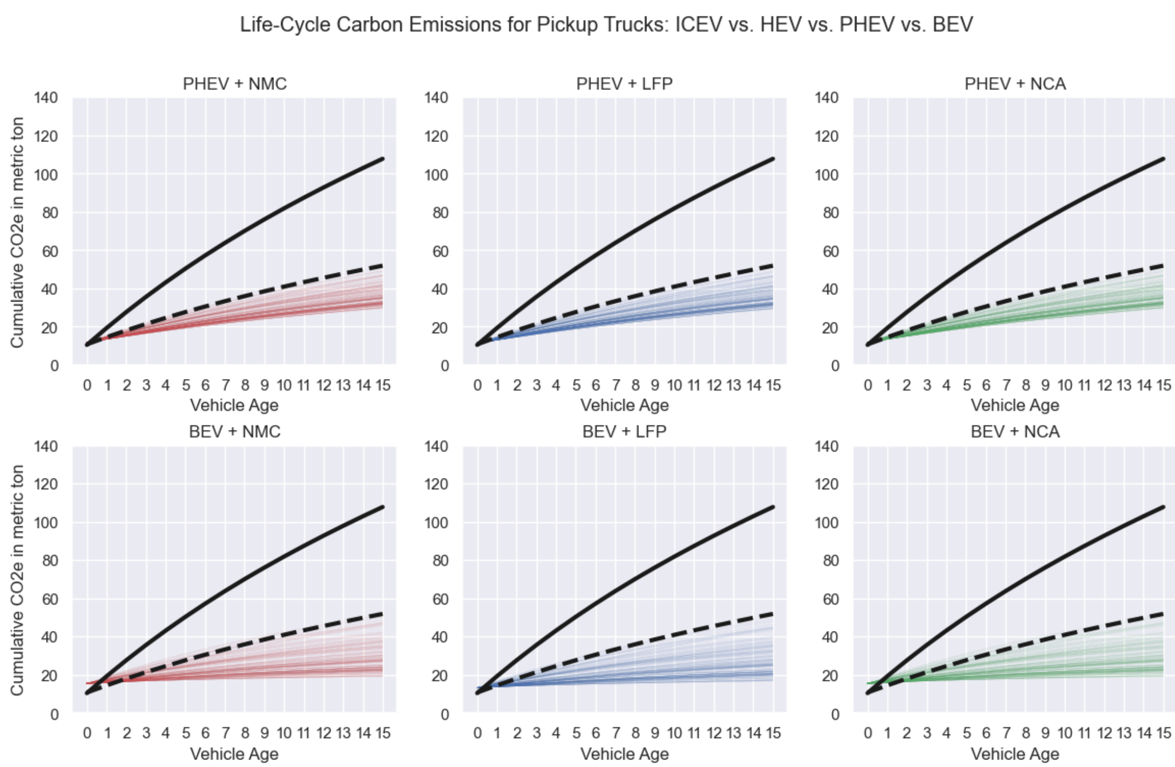

Figure 58. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 standard pickup truck – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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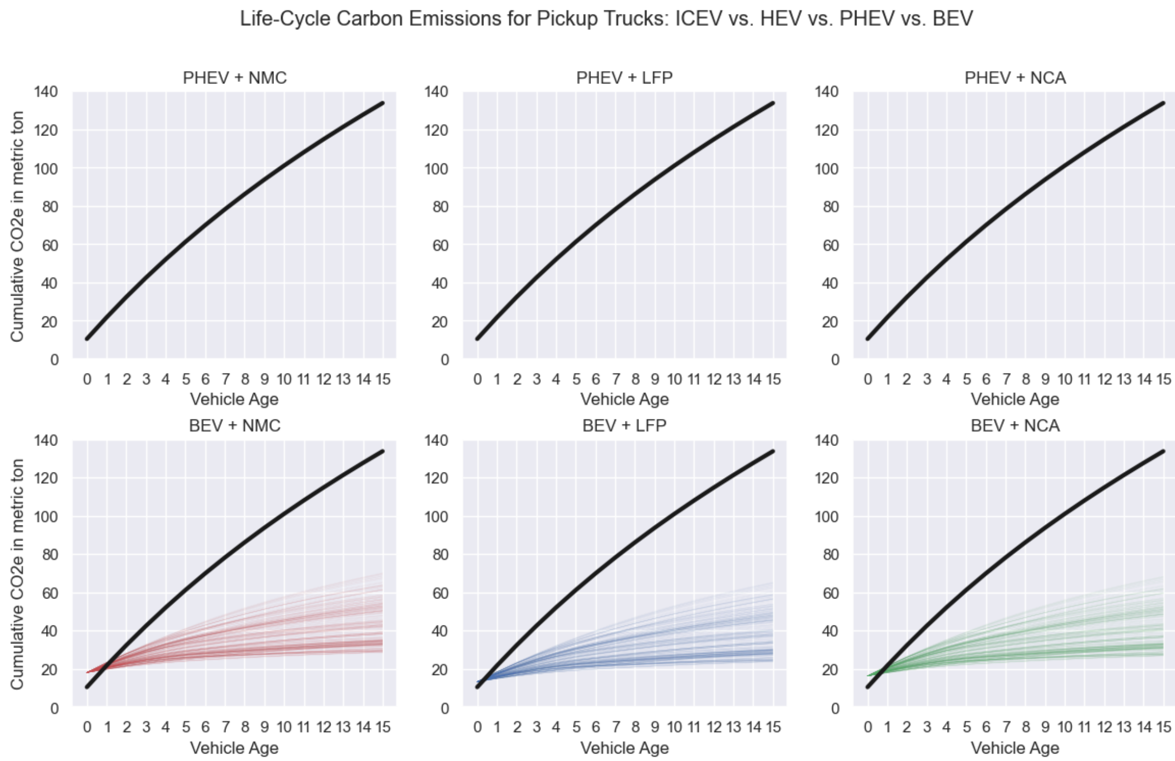

Figure 59. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2025 premium pickup truck – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

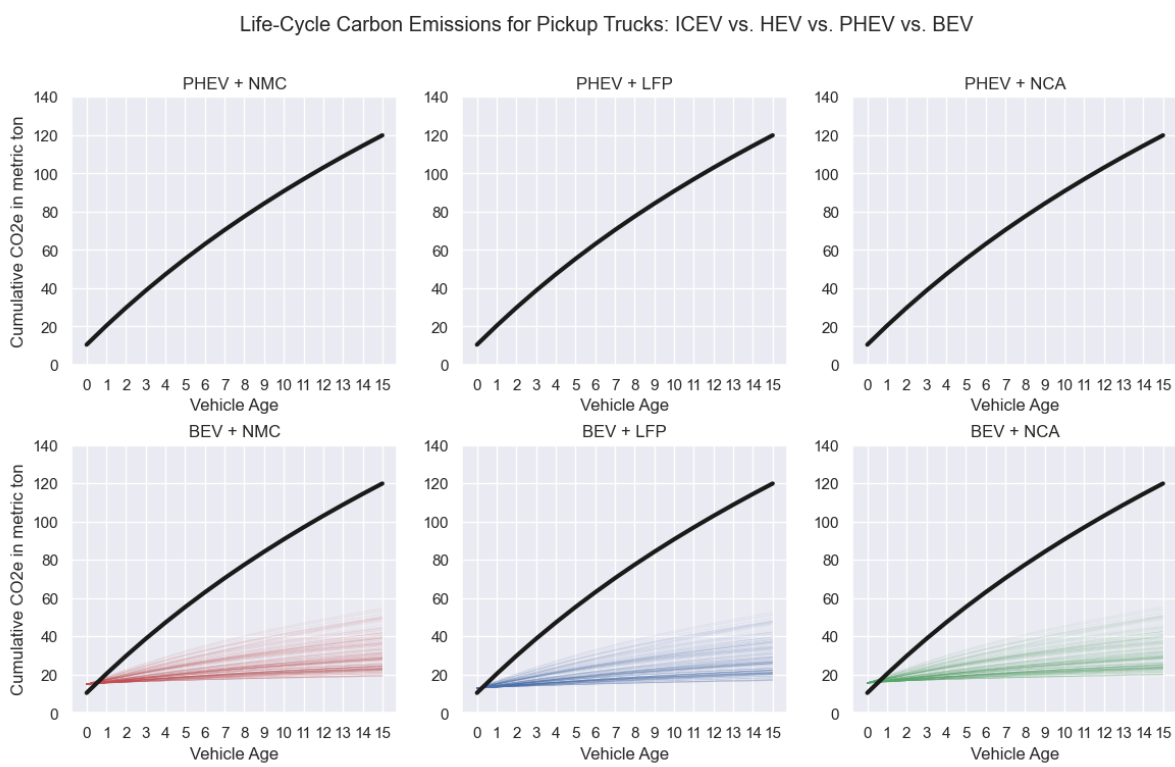

Figure 60. Cumulative life cycle GHG emissions (metric ton CO2e) over vehicle lifetime for MY2040 premium pickup truck – solid black: ICEV, dashed black: HEV, colored thin lines: PHEV/BEV.

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A.4 Battery Chemistry Information

Table 11. Battery type and associated kg of lithium per kWh of cell. Source: Dai, Qiang, Jeffrey Spangenberger, Shabbir Ahmed, Linda Gaines, Jarod C. Kelly, and Michael Wang. 2019. "EverBatt: A Closed-Loop Battery Recycling Cost and Environmental Impacts Model." ANL-19/16, 1530874. https://doi.org/10.2172/1530874.

Battery Type	kg Li/ kWh cell
LCO	0.129
LFP	0.09
LMO	0.0904
NCA	0.1203
NMC111	0.1396
NMC442	0.1225
NMC532	0.1065
NMC622	0.09
NMC811	0.088
NMC955	0.132

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