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ANL-22/71

Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010 – 2021

Energy Systems and Infrastructure Analysis Division

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Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010 – 2021

by
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LIST OF ACRONYMS

AALA	American Automobile Labeling Act
BEV	Battery Electric Vehicle
CPI	Consumer Price Index
CUV	crossover utility vehicle
DOE	Department of Energy
DOT	Department of Transportation
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency
EV	electric vehicle
eVMT	electric vehicle miles traveled
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
FHWA	Federal Highway Administration
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
gVMT	gasoline-fueled vehicle miles traveled
GVWR	gross vehicle weight rating
GWh	gigawatt-hour
HEV	hybrid electric vehicle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
kWh	kilowatt-hour
LDV	light-duty vehicle
LFP	lithium iron phosphate ($LiFePO_4$)
LMO	lithium manganese oxide
MDIUF	Multi-Day Individual Utility Factor
mpg	miles per gallon
MPGe	miles per gallon gasoline equivalent
mph	miles per hour
MSRP	manufacturer's suggested retail price
MY	model year

NCA	nickel cobalt aluminum
NHTS	National Household Travel Survey
NHTSA	National Highway Traffic Safety Administration
NMC	nickel manganese cobalt
OEM	original equipment manufacturer
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
SAE	Society of Automotive Engineers
SUV	sport utility vehicle
VIO	vehicles in operation
VMT	vehicle miles traveled

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ASSESSMENT OF LIGHT-DUTY PLUG-IN ELECTRIC VEHICLES IN THE UNITED STATES, 2010 – 2021

ABSTRACT

The number of plug-in electric vehicles (PEVs) sold in the United States has consistently grown since 2010, reaching 4% of the light-duty vehicle market in 2021. This report examines how the characteristics for these PEVs has changed over this decade, evaluating range, energy efficiency, costs, and performance. Given the vehicle characteristics, this report estimates miles driven, electricity consumption, petroleum reduction, and greenhouse gas emissions attributable to electric vehicles. This report also explores vehicle manufacturing and battery production, considering supply chains from battery cells to assembly. Over 2.1 million PEVs have been sold in the United States through December 2021, with 1.3 million of these all fully-electric battery electric vehicles (BEV), and 800,000 plug-in hybrid electric vehicles (PHEV) which have the capability of using gasoline. The sales-weighted average range for BEVs reached 290 miles in 2021 and 28 miles for PHEVs. We estimate that electric vehicles have driven 68 billion miles on electricity since 2010, thereby reducing national gasoline consumption by 0.54% in 2021 and 2.5 billion gallons cumulatively through 2021. In 2021, PEVs used 6.1 terawatt-hours of electricity to drive 19.1 billion miles, offsetting 700 million gallons of gasoline. We find that this fuel switching reduced consumer fuel costs by $1.3 billion in 2021. Since 2010, 65% of PEVs sold in the United States have been assembled domestically, and over 110 gigawatt-hours of lithium-ion batteries have been installed in vehicles to date.

1 INTRODUCTION

The market share of plug-in electric vehicles (PEVs) in light-duty vehicles has grown over the last decade as costs of lithium-ion batteries dropped while energy density and charging rates improved (DOE 2021; Henze 2021). Argonne National Laboratory has been tracking the development of the U.S. PEV market since 2010, considering the total number of sales and the vehicle characteristics. This report quantifies the environmental and economic effects of the growing PEV market, and is the fifth in a series published annually. Much of the analytical approach within the present report follows that of the previous iterations, though estimations have been updated with improved data or methodology when possible.

While traditional gasoline- and diesel-powered internal combustion engines (ICE) are the most common light-duty drivetrain worldwide, alternative-fuel drivetrains are rapidly increasing in market share. PEV sales are among the fastest growing market shares worldwide, with over 6.7 million sales worldwide in 2021 (Irle 2022) and a cumulative total of over 16 million since 2010 (IEA 2022). PEVs get at least a portion of their energy from electricity, which is supplied to the vehicle through a charging cable. There are two types of PEVs: battery electric vehicles (BEVs) are powered exclusively by electricity, while plug-in hybrid electric vehicles (PHEVs) have a battery as well as a separate internal combustion engine for extended driving range. Another common acronym for electric vehicles is EV. This report uses the term "PEV" to explicitly distinguish these vehicles from hybrid electric vehicles (HEVs), which use gasoline as their sole fuel source (DOE and EPA 2022), and fuel cell electric vehicles (FCEVs), which typically use hydrogen as the energy carrier (DOE 2014).

Understanding the aggregate impact of electric vehicles is important when exploring electricity use and petroleum consumption. Electric utilities are working to understand the changes in electricity generation, demand, and required infrastructure (EEI 2022; Panossian 2022; Anwar 2022; Powell 2022). All 50 states submitted PEV infrastructure plans to the U.S. Departments of Energy and Transportation in order to receive funding through the National Electric Vehicle Infrastructure Program of the Bipartisan Infrastructure Law (DOE and DOT 2022). These PEV charging network plans were approved in September 2022 (FHWA 2022a). The growth of electric vehicles can offset petroleum consumption by conventional internal combustion engine vehicles, affecting oil prices and extraction (OPEC 2021). Refineries need to know the potential impact on demand for their refining mix; gasoline and diesel are the two most common end products in the United States (Davis and Boundy 2022).

Likewise, understanding characteristics of the vehicles is important at a high level. Enumerating the total capacity of batteries installed in PEVs is necessary to understand the battery supply chain and the future demands for battery recycling (Xu et al. 2020; Zhou et al. 2021). Estimates of vehicle cost, weight, and performance are useful for assessing automaker trends and consumer preferences in the electric vehicle market (EPA 2021). Evaluating the potential impacts of consumer tax incentives in the United States require knowledge of battery manufacturing supply chains (U.S. Congress 2022).

In this analysis, we present summary statistics for key metrics related to PEVs, and how most of these metrics have changed over time. Compiling data on vehicle sales and characteristics allows for a comprehensive assessment of the historical impacts of PEVs in the United States. Table 1 summarizes the high-level national impacts of these plug-in electric vehicles for PEV sales, electric vehicle miles traveled (eVMT), gasoline displacement, electricity consumption, and reductions in carbon dioxide emissions in each year from 2011 to 2021. As the market share and total number of on-road PEVs has increased, each of these aggregate metrics in Table 1 has grown since 2011. Through 2021, over 2.3 million PEVs have been sold in the United States and have driven nearly 70 billion miles, displacing more than 2.5 billion gallons of gasoline and nearly 20 million metric tons of greenhouse gases, and consuming 22 terawatt-hours of electricity.

TABLE 1 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road PEVs

Year	PEV sales (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	18	0.1	3	30	0.02
2012	53	0.3	13	100	0.08
2013	97	0.9	40	330	0.27
2014	119	1.8	73	610	0.50
2015	114	2.9	120	990	0.81
2016	160	4.0	160	1,400	1.10
2017	196	5.6	220	1,900	1.60
2018	331	8.3	310	2,800	2.30
2019	320	11.7	430	3,800	3.30
2020	308	13.0	480	4,200	3.70
2021	634	19.1	690	6,100	5.40
Total	**2,350**	**67.8**	**2,500**	**22,000**	**19.10**

Section 2 of this report highlights national scale impacts of the electric vehicle fleet, considering each of the metrics in Table 1 in greater detail. Section 3 explores how characteristics of PEVs have evolved over time, including driving range, energy efficiency, size, performance, and price. Section 4 addresses PEV supply chains, including characterization of total battery size and manufacturing supply chains, both historically and announcements for growth into the future. Section 5 summarizes key findings. Appendix A details the data sources used in this report and summarizes the methodology and key assumptions. Appendix B considers detailed sensitivity analysis on several assumptions to test the robustness of the results, including alternative methodologies for quantifying aggregate impacts, specifically comparing the updated methodology presented here based upon vehicle registrations with the methodology presented in previous reports (c.f., Gohlke and Zhou 2021) based upon sales dates.

2 NATIONAL-LEVEL IMPACTS

This section presents total national-scale metrics for PEVs, including vehicle sales, miles traveled, electricity consumed, gasoline displacement and greenhouse gas emissions. These numbers are then compared with total national-scale values for usage by all light-duty vehicles (LDVs) in order to contextualize the impacts of PEVs.

2.1 PEV SALES AND REGISTRATIONS

Over 630,000 plug-in electric vehicles were sold in the United States in 2021, more than double the sales total from 2020. Sales of all-electric BEVs grew 92% to over 457,000, while PHEV sales increased by 150% to 175,000. Relative to the total light-duty vehicle market, total PEV shares grew from 2.1% in 2020 to 4.2% in 2021, as the overall LDV sales increased by approximately 3% in 2021.

The historical trend in PEV sales is shown in Figure 1. Through 2021, a total of more than 2,300,000 PEVs have been sold, 64% of which have been BEVs. Before 2018, cumulative sales of PHEVs were slightly higher than of BEVs. In 2021, BEVs comprised 72% of the PEV market.

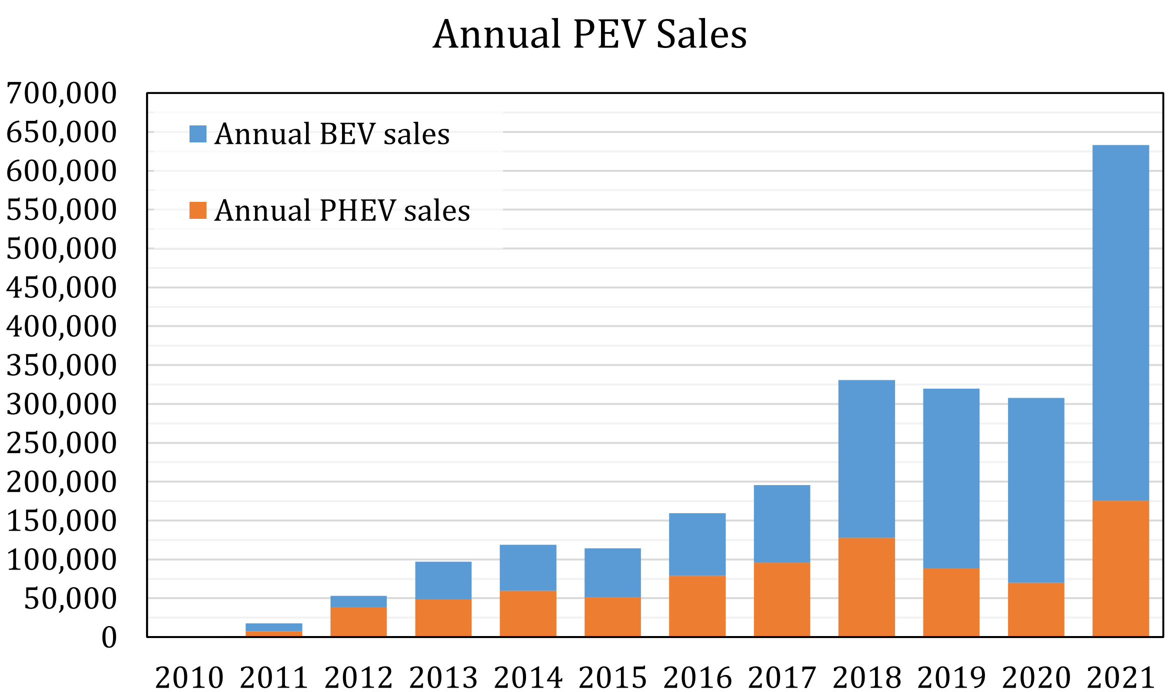

FIGURE 1 Annual sales of PEVs in the United States by year

From 2011 to 2021, annual PEV sales grew from fewer than 18,000 to more than 630,000, equivalent to an average year-over-year growth rate of 43%. As of 2021, fourteen models of PEVs have sold more than 30,000 units in the United States: Tesla Model 3, Tesla Model Y, Tesla Model S, Nissan Leaf, Chevrolet Volt, Toyota Prius, Chevrolet Bolt, Tesla Model X, Ford Fusion Energi, Chrysler Pacifica Hybrid, BMW i3, Ford C-Max Energi, Honda Clarity PHEV, and the Toyota RAV4 Prime. Of these, the Volt, Model S, Model 3, Leaf, Prius Prime, Model Y, and Bolt have all sold more than 100,000 units. The Tesla Model Y was the top-selling PEV in 2021, followed by the Tesla Model 3; 163,000 and 139,000 of these vehicles were sold in 2021, respectively. The top selling PHEV was the Toyota RAV4 Prime, with nearly 28,000 sales. The top-selling new models were the Ford Mustang Mach E and Jeep Wrangler 4xe, each of which sold 27,000 units.

Figure 2 shows the percentage of all PEV sales by each automaker. Tesla, with four models in the overall top ten of U.S. sales, has the most sales, with 40% of all of PEVs. General Motors, Toyota, Nissan, and Ford also each have at least 6% of domestic PEV sales.

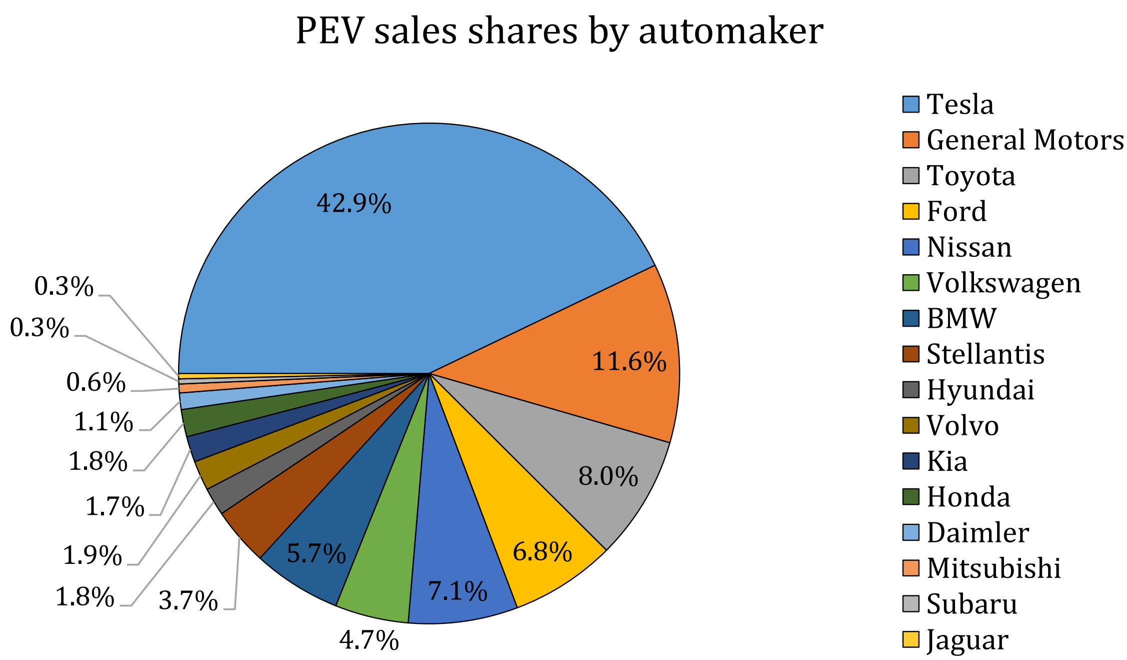

FIGURE 2 Sales shares of PEVs in the United States by manufacturer, 2011–2021

Most PEVs sold in the United States since 2010 are still on the road. As of December 31, 2021, 2.24 million PEVs were registered for use (Experian Automotive 2022). This is 4.6% lower than the total number of sales tracked by Argonne; the largest points of discrepancy come from vehicles that are no longer registered (largely due to scrappage such as from vehicle accidents) and from vehicles that were sold new late in 2021 and not yet registered. The state with the largest number of PEV registrations is California, with a total of 878,000 PEV registrations at the end of 2021. Florida (128,000), Texas (112,000), New York (96,000), and Washington (91,000) have the next-most registrations, as shown in Figure 3. Figure 4 shows the fraction of registered LDV which are PEVs for each state. California, Washington DC, Hawaii, Washington, Oregon, Vermont, and Colorado all have total PEV shares above 1%.

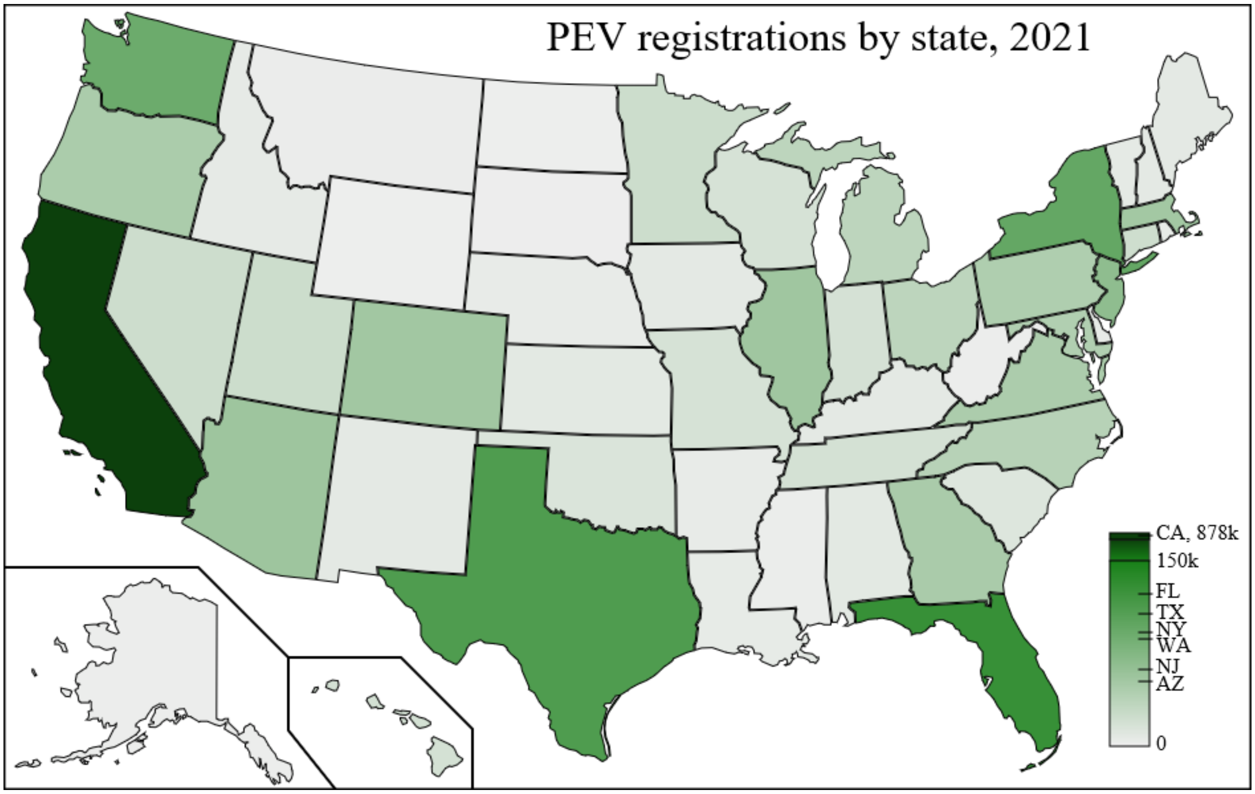

FIGURE 3 Number of registrations of PEVs by state, 2021

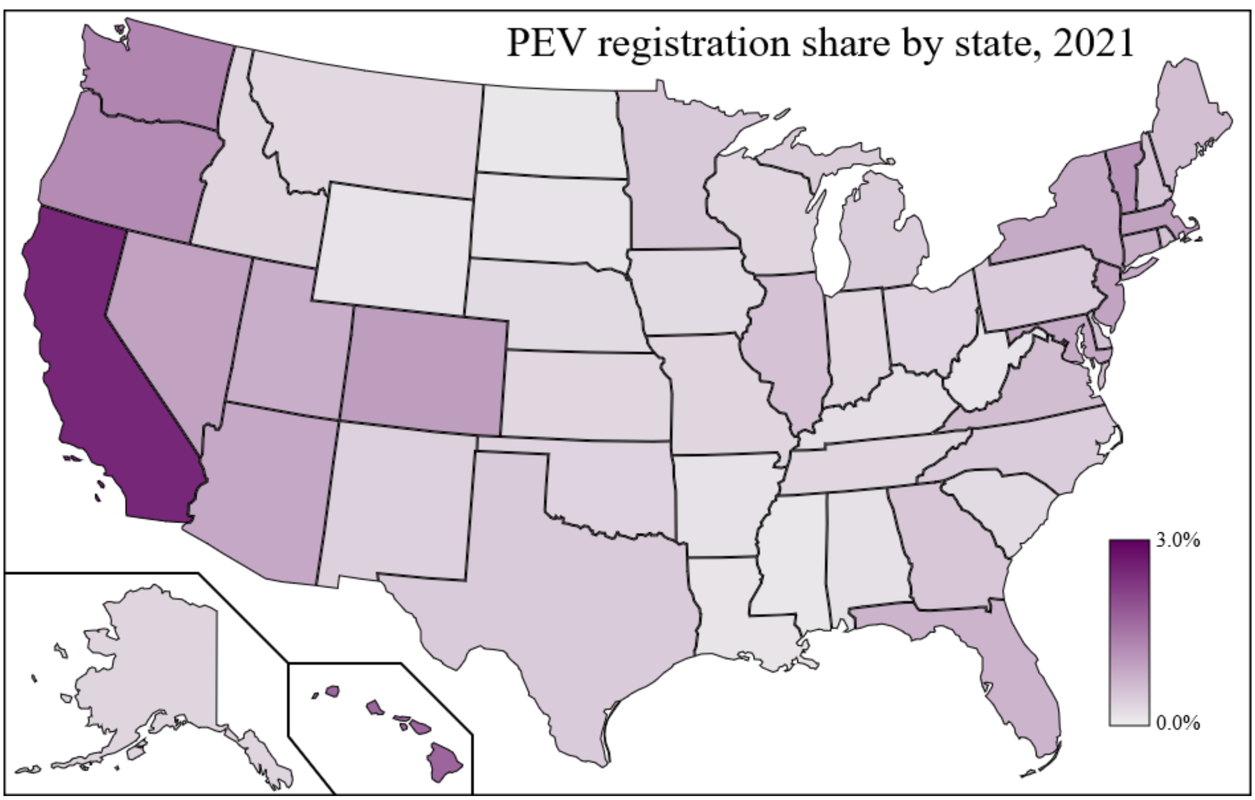

FIGURE 4 Registration shares of PEVs by state, 2021

2.2 ELECTRIC MILES TRAVELED

The total annual vehicle miles traveled (VMT) for each PEV depends on traveler behavior and the vehicle's all-electric range. In this analysis, each vehicle's total travel is scaled relative to a typical ICE vehicle (ICEV). PHEVs are assumed to drive the same total annual distance as ICEVs, with miles not supplied by electricity powered by gasoline like a hybrid. Conversely, the estimated annual mileage of each BEV is reduced relative to a comparable ICEV in order to account for the limited driving range, as described in Appendix A.

Given the total number of registered PEVs as well as the all-electric range and the effective utility factor for each vehicle, the total mileage driven in all-electric mode across the entire national LDV fleet can be estimated. Figure 5 shows the total eVMT by year in the United States. Through 2021, nearly 68 billion miles have been driven powered by electricity. In 2021, 19.1 billion miles on the road were driven by light duty electric vehicles using electric power; approximately 76% of this was driven by BEVs. PHEVs also drove an additional 4.2 billion miles in charge sustaining mode using gasoline.

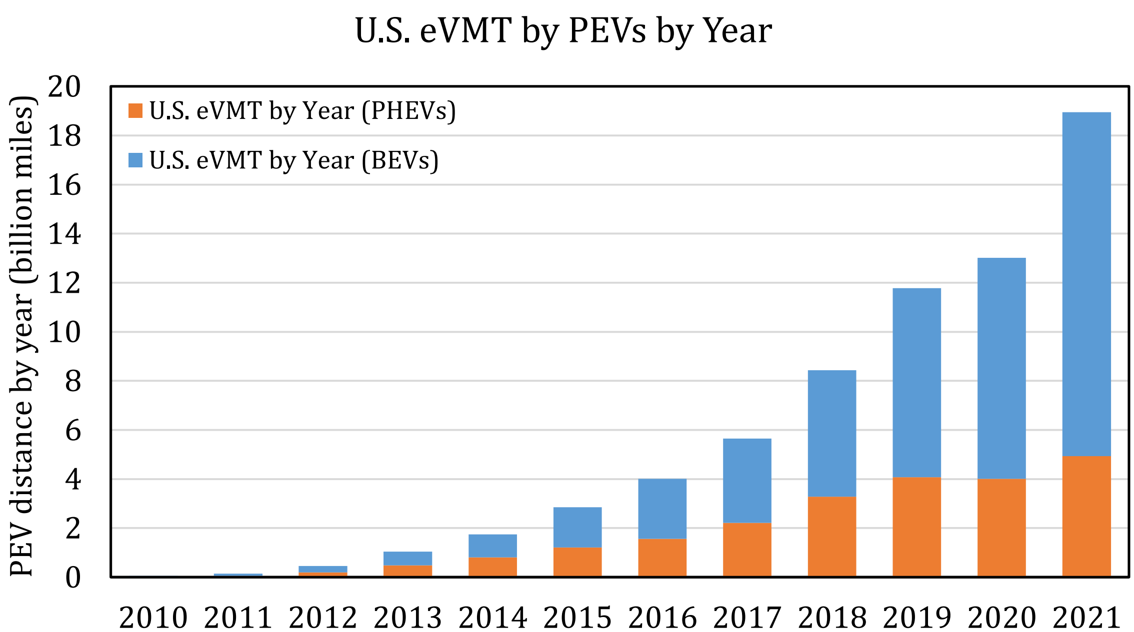

FIGURE 5 Electric vehicle miles traveled by LDVs by year

2.3 ELECTRICITY CONSUMPTION BY PEVs

Combining eVMT with knowledge of vehicle electricity efficiency allows us to determine the total electricity consumption by PEVs in the United States, shown in Figure 6. To find the total electricity consumption, the estimated eVMT in each year is multiplied by the electricity consumption per mile for each vehicle. For each vehicle model and model year, vehicle fuel efficiencies were gathered from the FuelEconomy.gov database (DOE and EPA, 2022). Through 2021, a total of 22.3 terawatt-hours of electricity have been consumed by PEVs. In 2021, the total electricity use for LDVs on the road was 6.1 terawatt-hours. In 2021, the average PHEV consumed 2,210 kilowatt-hours (kWh) of electricity, and the average BEV consumed 3,010 kWh of electricity, though these values include new vehicles which were not operated for the full calendar year.

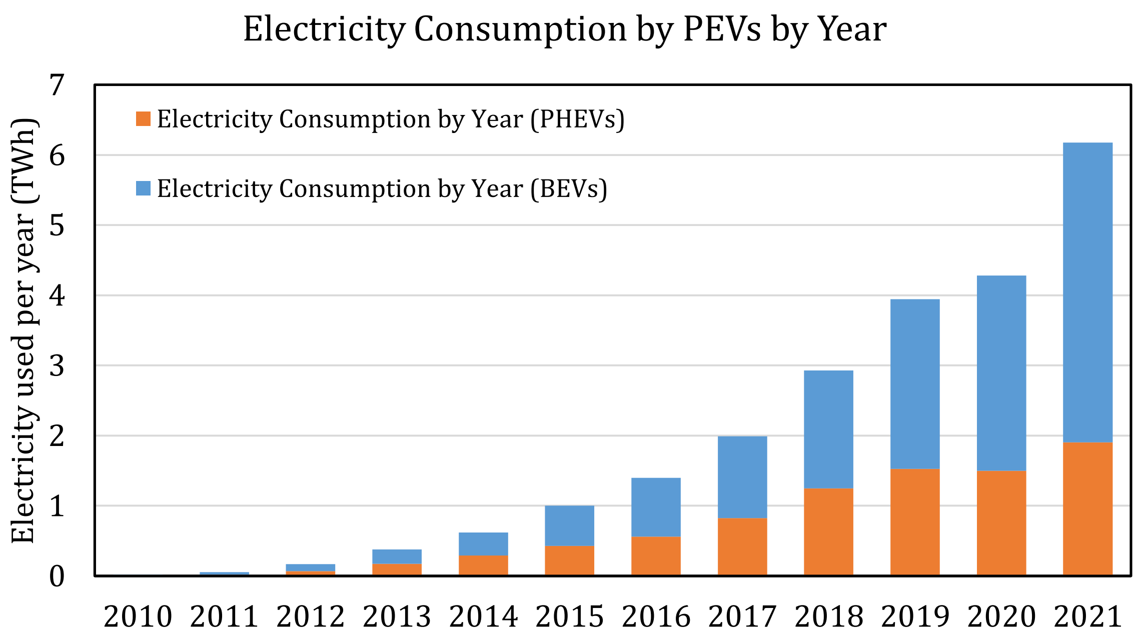

FIGURE 6 Electricity consumption by PEVs by year

2.4 GASOLINE CONSUMPTION REDUCTION

Use of electricity by PEVs displaces gasoline that would otherwise be used by an ICE vehicle. To estimate this reduction in gasoline consumption, we need to make assumptions about how each mile would have otherwise been traveled. We assume that every mile driven by an electric vehicle offsets exactly one mile that would have been driven by an ICEV. PEVs have lower per-mile operating costs than ICEVs (Burnham et al. 2021), but we do not model any rebound effect of additional induced VMT from the lower operating cost, or decreased demand from range anxiety (Chakraborty, 2022). For each PEV that is registered, we assume its displaced vehicle to be of the same size class and vintage, representing the most similar vehicle that would have been purchased when new. The U.S. Environmental Protection Agency (EPA) publishes distributions of fuel economy for two regulatory classes: "cars", which includes sedans and some crossover utility vehicles (CUVs) and sport utility vehicles (SUVs), and "light trucks", which includes the remainder of CUVs and SUVs, as well as pickup trucks and light-duty vans (EPA 2021). Previous iterations of this report made the conservative assumption that early adopters of electric vehicles are primarily interested in fuel economy and environmental benefits, and so assigned the comparable ICEV to be more fuel efficient than average. However, the growth of electric vehicles has been disproportionately in the luxury segment, and these vehicles may be more appropriately compared with larger, high-performance vehicles, justifying an assignment to less-fuel efficient ICEVs. Given these opposing factors, we simply assign the baseline vehicle to be the median of all vehicles of the same age in the same regulatory size class. Appendix B examines the quantitative impact of varying the fuel economy of this reference vehicle, ranging from vehicles of comparable size in the 25^{th} to 75^{th} percentile of fuel economy.

The total gasoline displacement by year is graphed in Figure 7. In 2021, 690 million gallons of gasoline were offset by PEVs, with 70% of this total offset by BEVs. In 2021, the average on-road BEV offset 330 gallons of gasoline, and the average PHEV offset 270 gallons, though, as with the electricity consumption data presented in Section 2.3, these values include new vehicles with less than one entire year of driving. Cumulatively, through 2021, PEVs have offset over 2.5 billion gallons of gasoline, 1,570 million gallons by BEVs and 970 million gallons by PHEVs. This analysis counts all gasoline usage that is offset by PEVs. Specifically, the analysis considers both eVMT and gasoline-fueled VMT (gVMT) from operation of PHEVs in charge-sustaining mode (i.e., using only gasoline). For PHEVs operating in charge-sustaining mode, the engines are also generally more efficient than the comparable ICEV engine due to the fuel efficiency benefits of hybridization. Thus, there are typically fuel savings for PHEVs in both charge-sustaining and charge-depleting operational models.

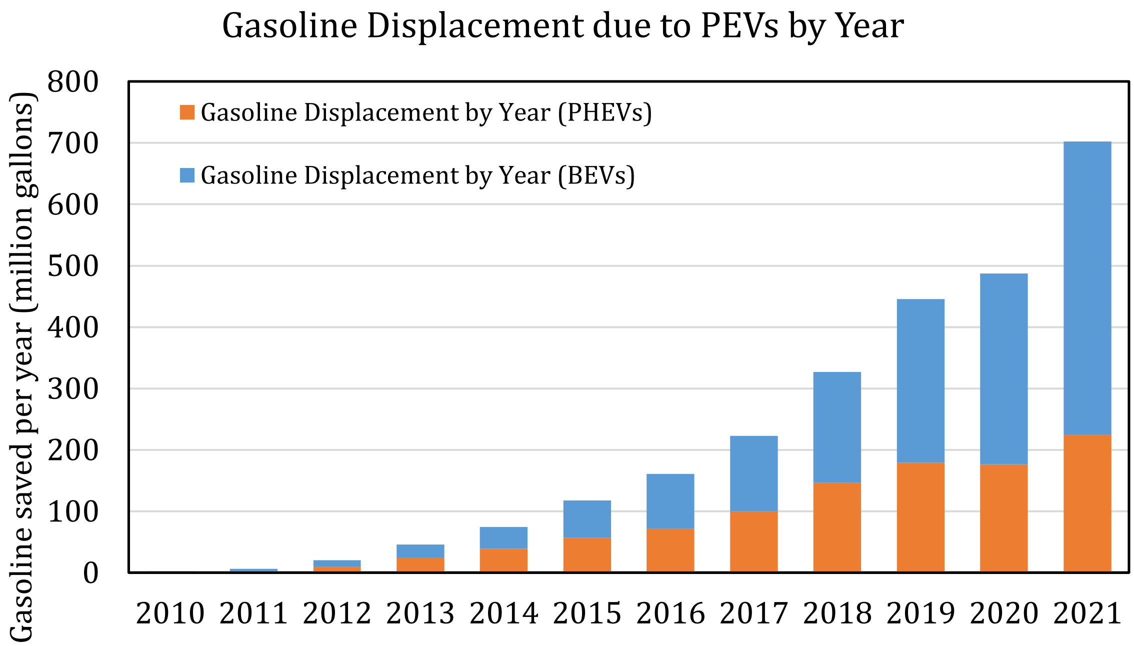

FIGURE 7 Gasoline displacement from ICE vehicles by LDV PEVs by year

2.5 GREENHOUSE GAS EMISSIONS

Operation of PEVs can reduce greenhouse gas (GHG) emissions relative to use of conventional ICE vehicles. The magnitude of this reduction depends on the carbon intensity of the electricity grid used to supply the electricity for the PEVs. A recent analysis by Argonne National Laboratory considered regional variations in the electricity generation mix across the country as well as in the distribution of registrations of PEVs (Gohlke et al. 2022).[1] This analysis found that the registration-weighted average operational emissions for PEVs were 110 grams of CO_2-equivalent GHG emissions per mile in 2021. This regionally-derived analysis is 13% lower than a simple national average due to PEVs being disproportionately registered in locations with lower-emitting electricity grids and higher shares of renewable electricity. After accounting for regional differences in electricity generation and registration shares for PEVs, the weighted national average emissions rate for electricity has dropped from 187 grams CO_2-equivalent per mile to 110 grams CO_2-equivalent per mile over the previous decade due to the shifting mix of electricity generation and improvements in PEV efficiency. Over the same timespan, emissions for the comparable ICEV has improved from 441 grams/mile to 382 grams/mile. Comparing the net electricity-grid emissions with those from gasoline combustion, PEVs reduced GHG

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1 This calculation is for fuel-cycle emissions only; that is, it excludes emissions from the production of the vehicles. The majority of emissions come from the operation, rather than the manufacturing, of both ICEVs and PEVs. A recent study found that vehicle-cycle emissions from a midsize gasoline ICEV were about 10% of the total lifetime emissions, and about 30% for a midsize BEV (Kelly et al., 2022). Including these indirect vehicle-cycle emissions in a full lifecycle assessment still nets GHG reductions (Wolfram et al., 2021).

emissions by 5.4 million metric tons in the United States in 2021, and nearly 20 million metric tons cumulatively, shown in Figure 8.

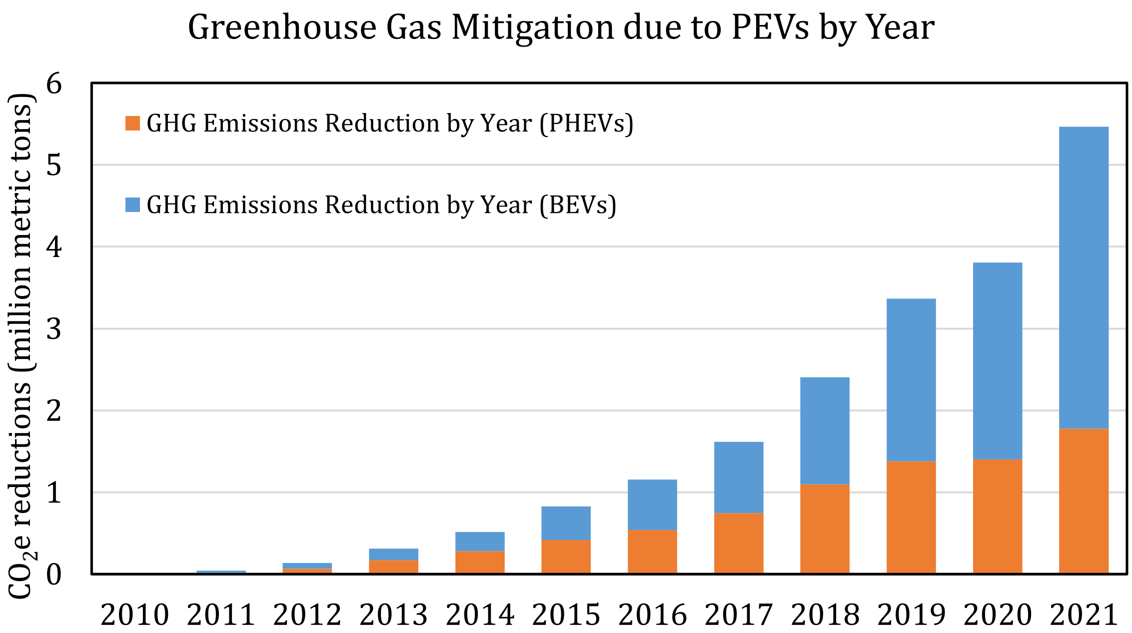

FIGURE 8 Annual GHG emissions reductions due to LDV PEV by year

2.6 FUEL COST REDUCTIONS

Across the United States, gasoline vehicles cost more to operate than electric vehicles. The national average for fueling an electric vehicle tends to be approximately one-third the cost-per-mile of a conventional gasoline ICEV. In this analysis we assume that all electric vehicle charging occurs at home, and use the average annual residential electricity rate for each state (EIA 2022a), and compare it to the average gasoline cost in each state (EIA 2022b). (Appendix B explores alternative costs for electricity using public chargers.) We find 6.4 cents-per-mile savings for BEVs and 4.7 cents-per-mile savings for PHEVs, for a total average fuel cost savings of 5.7 cents/mile in 2021. Across all vehicles, this totals to $1.34 billion dollars in consumer savings in 2021. The magnitude of this cost savings is highly dependent on both gasoline and electricity prices. Because of this, there are large spatial variations across the United States, ranging from over 7.9 cents/mile in Washington (with high gasoline prices and low electricity prices) to 2.7 cents/mile in Massachusetts (with high electricity prices).

Figure 9 shows the historical trends in both aggregate and per-mile fuel cost savings for PEVs by year since 2011. These calculations all account for the distribution of vehicle registrations at the state level in each year as well as the state energy prices. The per-mile costs are strongly correlated with changes in energy costs, particularly for gasoline, while the aggregate cost savings have increased in each year due to the increase in number of PEVs registered and used. Lower fuel prices in 2020 resulted in an average savings of 3.2 cents per mile, while higher fuel prices and less-efficient comparable gasoline vehicles in 2011 yielded operational savings of 8.1 cents per mile.

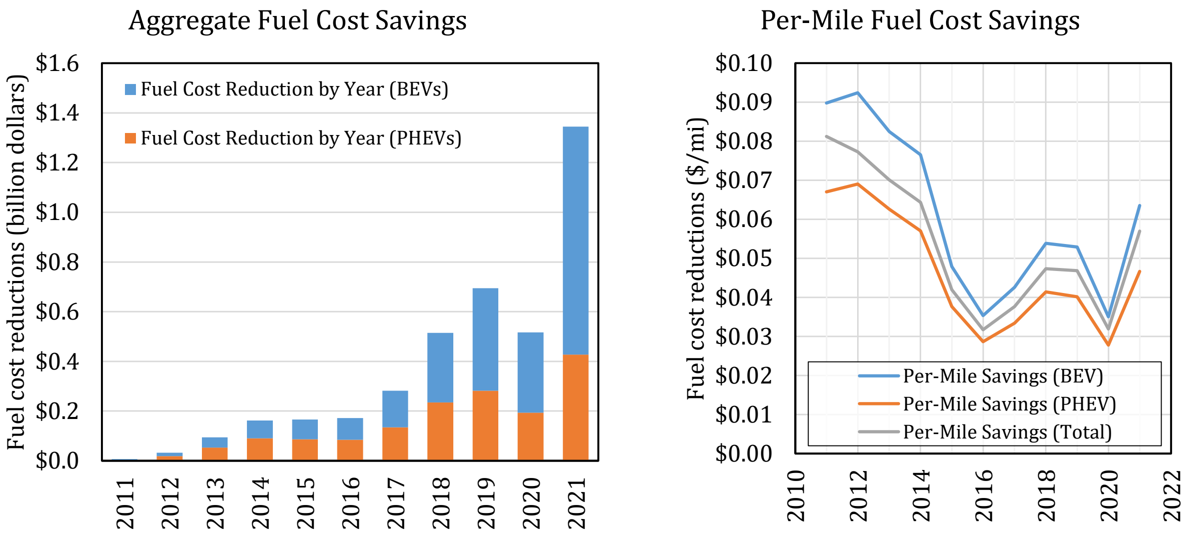

FIGURE 9 Fuel cost savings due to PEVs. Left side: annual aggregate fuel cost savings. Right side: per-mile fuel cost savings.

2.7 CONTEXTUAL COMPARISONS

PEVs are a growing share of the light-duty vehicle market and are having increasing impacts on the transportation and energy sectors. Figure 10 highlights how these impacts have changed, comparing the quantities from PEVs for total number of on-road vehicles, miles driven, electricity consumption, and gasoline reduction with corresponding total national values.[2] In 2020, PEVs comprised 0.64% of the 253 million light-duty vehicle registrations (FHWA 2021). Nearly 3 trillion miles are driven by light-duty vehicles in the U.S. each year (FHWA 2021); in 2020 0.51% of that total was powered by electricity. In 2020, the total electricity use for LDVs on the road was 4.2 terawatt-hours. This compares with a total of 3,856 terawatt-hours (EIA 2022c), or 0.11% of the total national electricity generation. In 2020, 480 million gallons of gasoline were offset by PEVs, equivalent to 0.40% of the 118 billion gallons of gasoline used in the United States that year (EIA 2021). In 2021, PEVs in the United States offset 700 million gallons, which is equivalent to 46,000 barrels of petroleum per day. Bloomberg New Energy Finance estimated a worldwide reduction of about 200,000 barrels per day for passenger vehicles in 2021 (Cheung and O'Donovan 2022), implying that approximately one-quarter of petroleum reductions attributable to PEVs are for vehicles operated in the U.S. In 2020, light-duty vehicles emitted 934 million metric tons of CO_2-equivalent (EPA 2022c); PEV were directly responsible for emissions of 2.3 million metric tons, contributing 0.25% of the total, but had a net reduction

2 For total light-duty vehicle registrations, VMT, and greenhouse gas emissions, 2020 is the latest year with full data availability from public sources as of the writing of this report (November 2022), so Figure 10 uses extrapolated values of LDV registrations and LDV VMT to estimate through 2021.

of 3.7 million metric tons after accounting for displaced gasoline consumption, yielding a 0.40% reduction relative to counterfactual ICE vehicles.

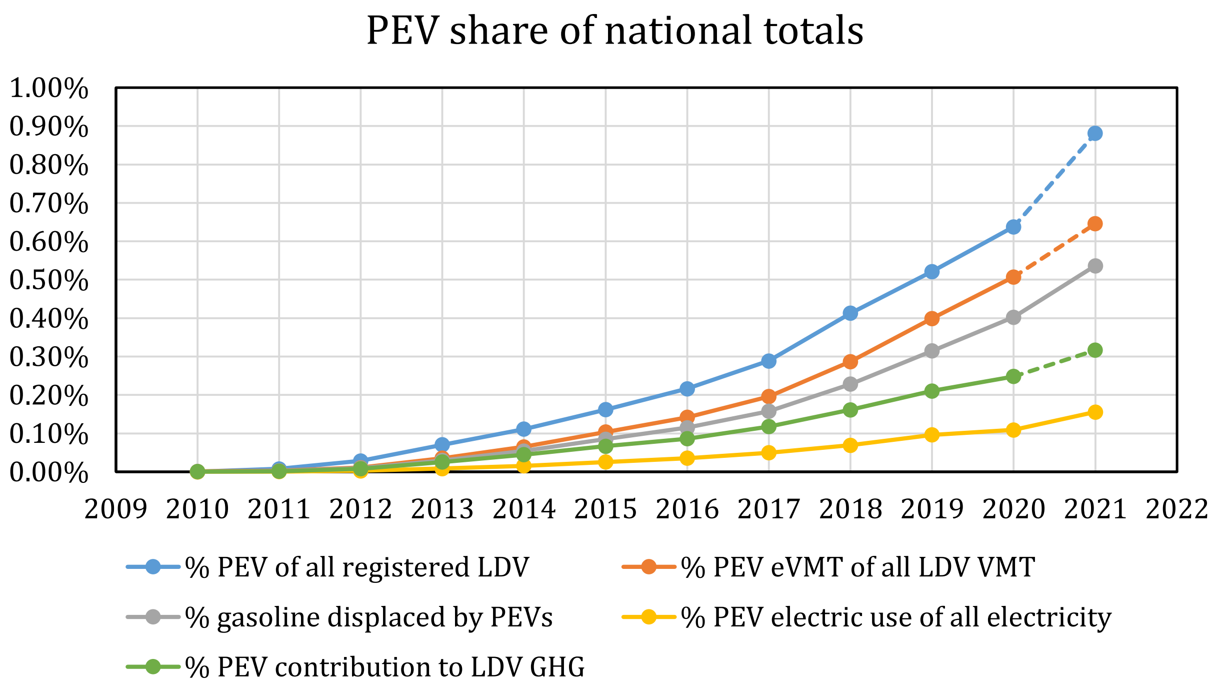

FIGURE 10 Portion of key national metrics attributable to PEVs in the United States by year, 2010–2021

3 VEHICLE CHARACTERISTICS

In addition to the total national-scale impacts of PEVs presented in Section 2, specific trends within the PEV market can be examined, including all-electric range, energy efficiency, vehicle size, performance, battery size, and manufacturing location.

3.1 ALL-ELECTRIC RANGE

The average range of PEVs has increased since 2010. This is largely due to the introduction and increased consumer preference for longer-range BEVs, which have become more economical due to the reduced cost of batteries. Figure 11 shows the average sales-weighted all-electric range for new vehicles (left side) and for all on-road vehicles (right side). PHEVs have consistently averaged between 20 and 35 miles of all-electric range while the average range of all on-road BEVs has more than tripled from approximately 70 miles to over 245 miles. The sharp growth in all-electric range for BEVs that can be seen in early 2013 reflects the introduction of the Tesla Model S, with a range of up to 265 miles, while the increase evident in 2018 can be largely attributed to high sales of the Tesla Model 3 with a range of up to 310 miles. In 2021, the sales-weighted range for new PEVs was 220 miles – 28 miles for PHEVs and 290 miles for BEVs. This represents a modest decline from the previous year due to the greater share of PHEVs.

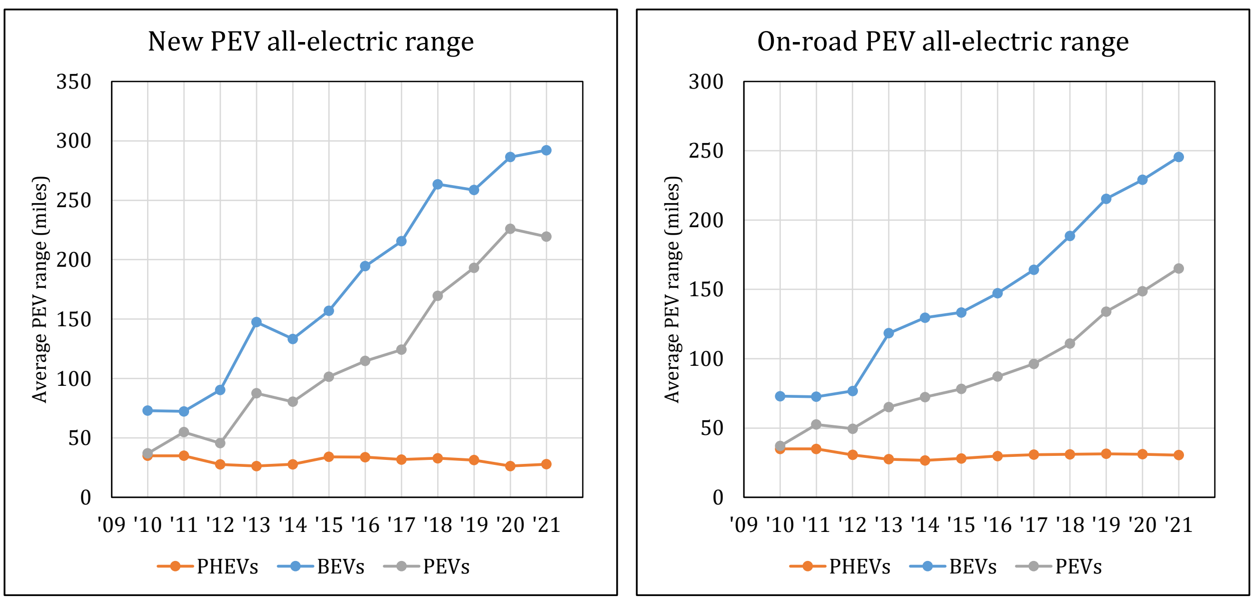

FIGURE 11 All-electric range for PEVs. Left side: sales-weighted average of range in new vehicles. Right side: stock-weighted average range for all on-road PEVs.

3.2 ENERGY EFFICIENCY

Figure 12 shows the average (distance-weighted) energy efficiency of vehicles running on electricity for new vehicles (left) and for the entire on-road fleet of PEVs (right).[3] Since 2010, BEVs have become more efficient, on average, while PHEVs have become much less efficient since 2020. In 2020, the market for PEVs shifted heavily toward SUVs, leading to an increase in fuel consumption for PHEVs. Largely due to the efficiency of the Tesla Model Y, this shift had only minor impact on the average electricity consumption for BEVs.

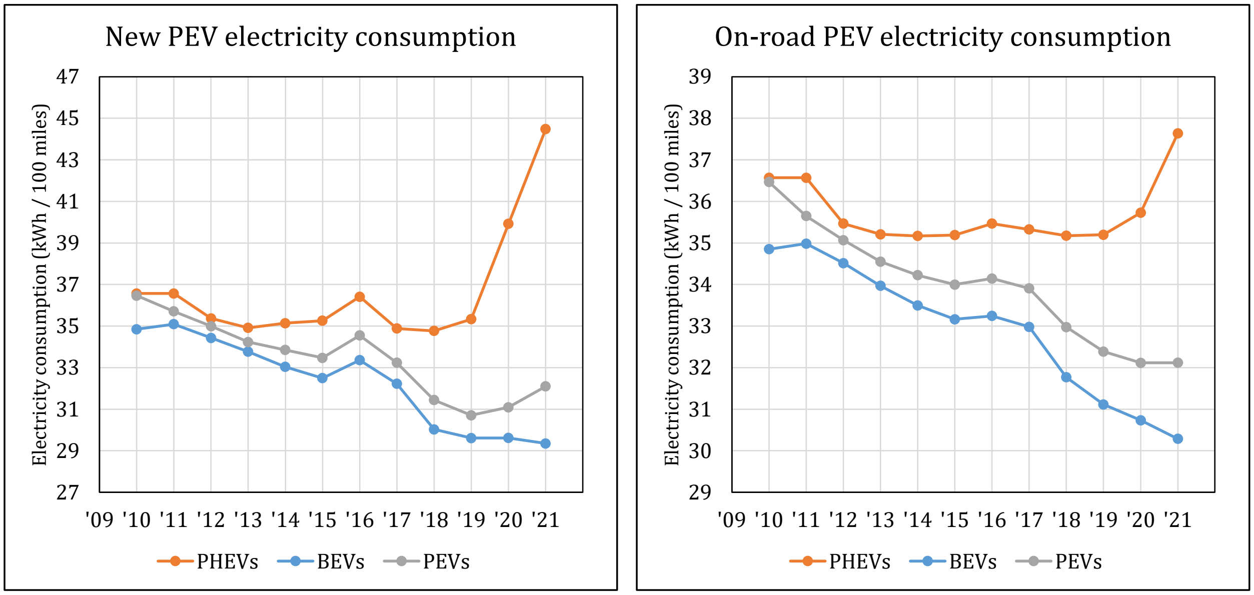

FIGURE 12 Electric efficiency for PEVs. Left side: distance-weighted average efficiency for new vehicles. Right side: distance-weighted average for all on-road vehicles.

For new vehicles sold in 2021, BEVs used 29.4 kWh per 100 miles driven, PHEVs averaged 44.5 kWh per 100 miles, and the fleetwide average was 32.1 kWh per 100 miles. In model year 2021, the most efficient vehicle in the FuelEconomy.gov database is the Tesla Model 3 Standard Range Plus, using 24.1 kWh / 100 miles. The next most efficient vehicles in the FuelEconomy.gov database are the Hyundai Ioniq BEV and the Toyota Prius Prime PHEV, each consuming just under 26 kWh /100 miles when operating on electricity (DOE and EPA, 2022).

The average electricity consumption of the entire PEV fleet has dropped from nearly 36 kWh per 100 miles to approximately 32 kWh per 100 miles. BEVs sold in the United States have generally been more efficient than PHEVs. As of December 2021, the average on-road PHEV consumed 37.6 kWh per 100 miles driven in charge-depleting (all-electric) mode, while

3 A distance-weighted average (rather than a sales-weighted average) is used to give a proper comparison of electricity consumption of the entire PEV fleet.

the average on-road BEV consumed 30.3 kWh per 100 miles.[4] The fleet-average electricity consumption for PHEVs increased by over 2 kWh per 100 miles from 2019 to 2021 due to the increased electricity consumption by newer, larger PHEVs. In terms of miles per gallon of gasoline equivalent (MPGe), where 33.7 kilowatt-hours of electricity is equivalent to one gallon of gasoline (EPA 2011), the average PEV fuel economy has increased from 94 MPGe to 105 MPGe.

3.3 SIZE CLASS AND VEHICLE WEIGHT

Figure 13 shows PEVs sorted by size class, from 2010 through 2021. Historically, the most common PEV size class has been a midsize car since 2011, which includes the Nissan Leaf, Toyota Prius Prime, and Tesla Model 3. This is followed by small four-wheel drive SUVs such as the Tesla Model Y, compact cars, which are more prominent for PHEVs, such as the Chevrolet Volt, and by large cars, such as the Tesla Model S BEV. Sales for sport utility vehicle (SUV) PEVs are growing; small SUVs were the top selling electric vehicle class for the first time in 2021, followed by midsize cars, small station wagons, and standard four-wheel drive SUVs.

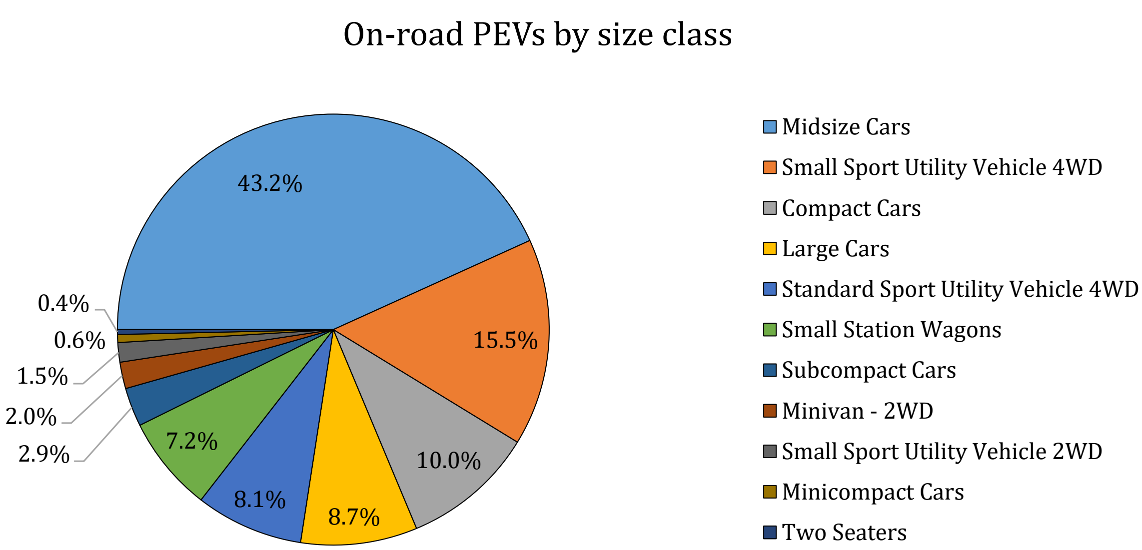

FIGURE 13 Cumulative sales of PEVs by EPA size class

The EPA splits LDVs into five different vehicle types: sedans/wagons, car SUVs, truck SUVs, minivans/vans, and pickup trucks (EPA 2021). Vehicles defined as sedans and wagon by the EPA make up 72% of cumulative PEV sales since 2010, and 26% of PEV sales have been SUVs. In 2021, sedans and wagons were less than half of total PEV sales in the U.S. for the first time, at 42%. Car SUVs and cars each comprised 48% of BEV sales in 2021, with the remainder being truck SUVs. Truck SUVs were 45% of PHEV sales, followed by cars at 25%, car SUVs at

4 The total per-mile energy consumption of PHEV is higher when accounting for miles powered by the ICE.

16%, and the remainder as minivans/vans. This growth of SUV PEVs brings the market for PEVs more into alignment with the overall LDV market, in which over half of vehicles were SUVs in 2020 (EPA 2021). Figure 14 shows the annual change in vehicle type from 2010 to 2021.

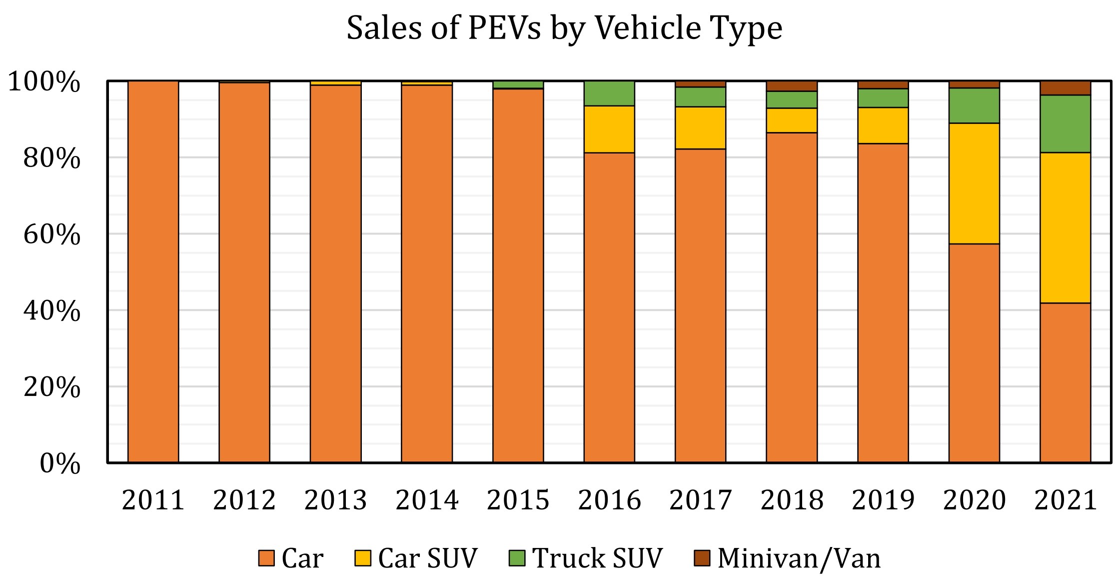

FIGURE 14 Changes in sales mix of plug-in electric vehicle type from 2011 to 2021

The EPA collects data on vehicle weights as part of the fuel economy testing process. The EPA maintains a publicly accessible database of the equivalent test weight of each vehicle, classified into 125- and 250-pound groups (EPA, 2022a).[5] The sales-weighted average of these equivalent test weights for PEVs has increased from 3,800 pounds in 2011 to 4,600 pounds in 2021. Over that timeframe, the sales-weighted average equivalent test weight has increased from 3,600 pounds to 4,600 pounds for BEVs, and from 4,000 to 4,800 pounds for PHEVs. This weight increase is due to increased battery capacity in BEVs and due to larger average size classes for both BEVs and PHEVs. There was a notable increase in vehicle weight from 2019 to 2021, especially for PHEV, as the total share of PEV SUVs increased. Since 2015, the average PEV weight has been greater than the average weight across all light-duty vehicles, even though the total share of SUVs and pickup trucks is higher in the general population.

5 Because of this grouping of vehicles in the EPA database, the equivalent test weight group for each vehicle is similar to, but not exactly the same as, its test weight basis. On average, the equivalent test weight is about 300 lb heavier than the listed curb weight.

3.4 VEHICLE PERFORMANCE

Performance of electric vehicles has on average increased since 2010, as measured by electric motor power (in kilowatts) and by the acceleration time from 0 to 60 miles per hour (mph). Figure 15 shows the average total electric motor size and acceleration for PEVs sold in each year. For each of these metrics, much of the increase in vehicle performance for BEVs was initially due to Tesla. The average motor size for Tesla dropped in 2021 due to the sales growth of the rear-wheel drive variant, which only has one motor. For many all-wheel drive electric vehicles, there are separate motors for front and rear wheels, resulting in a greater total motor power. In 2021, the average motor size for non-Tesla BEVs (205 kW) nearly reached that of Tesla (230 kW). In 2021, the average motor size for PHEVs reached 100 kW; PHEVs have an additional gasoline-powered engine for propulsion, and therefore have less need for a larger electric motor.

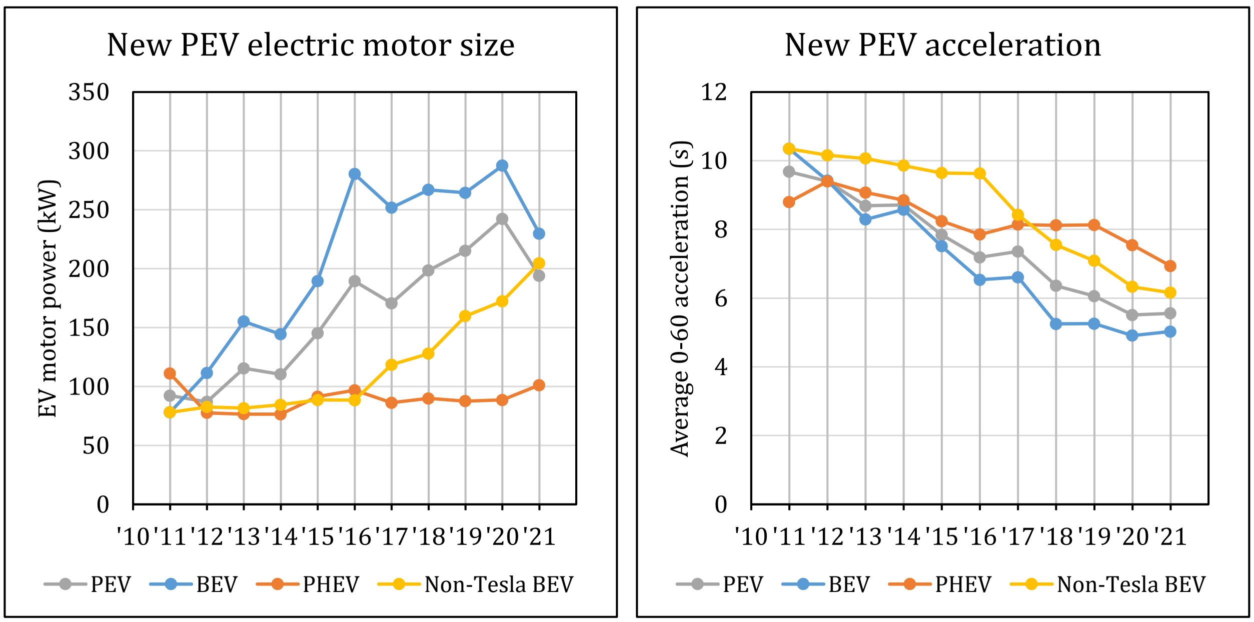

FIGURE 15 Average performance indicators for PEVs sold in each year

As PEV electric motors have become more powerful, vehicle acceleration has improved. The average time for a PEV to reach 60 mph is below 6 seconds. As with the electric motor power, much of the change since 2011 comes from Tesla vehicles. The fastest commonly available PEVs is the Tesla Model S Plaid, which can reach 60 mph in 2.0 seconds. The average 0–60 mph time for PHEVs had been consistently between 8 and 9 seconds since 2013, though the average acceleration improved to 6.9 seconds in 2021. Through 2016, the sales-weighted average 0–60 mph time for a non-Tesla BEV was 10 seconds, though this has dropped to 6.2 seconds in 2021. This overall improvement in average PEV acceleration rates has multiple causes, including increased availability of models with faster acceleration and some specific models becoming quicker as technology improves.

3.5 VEHICLE PRICE

Figure 16 shows the sales-weighted average manufacturer's suggested retail price (MSRP) for PEVs from 2010–2021.[6] This value includes the base MSRP for each model that is distinguishable in the FuelEconomy.gov database, but does not include additional optional features and packages which may bring the price higher. Therefore, this is not necessarily the cost a consumer will pay for the vehicle (and does not include state or federal tax incentives) but is a price that can be referenced as a benchmark for each vehicle and compared year-over-year. The average cost of BEVs has gone up since 2010, while the average cost of PHEVs has remained mostly flat since then. The average MSRP for BEVs peaked in 2016 and has declined since then. In 2021, the weighted MSRP decreased for PEVs from $52,200 to $51,000. BEV exhibited a modest decrease from $54,300 to $53,100 while PHEV increased less than 1% from $45,000 to $45,400. This overall decrease is despite the shift from cars to generally more-expensive SUVs in the PEV market, shown in Figure 14.

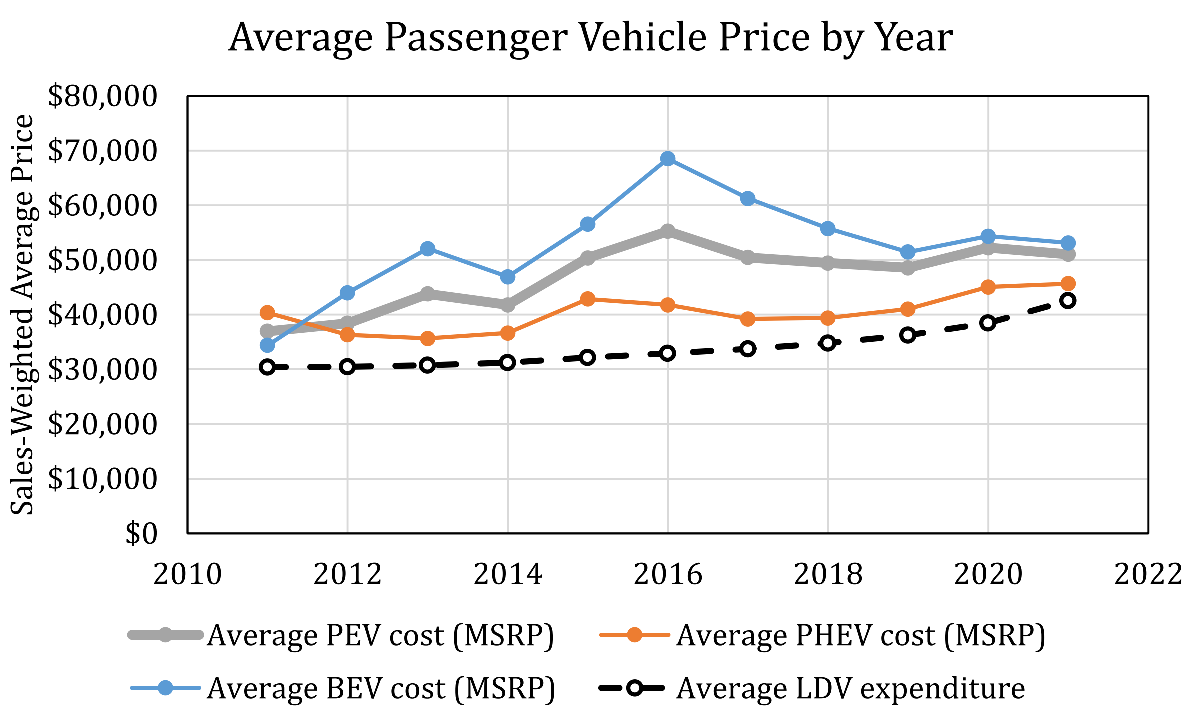

FIGURE 16 Average MSRP for PEV sold from 2010 to 2021; average expenditure for light-duty vehicles included for comparison

Figure 16 also shows the average consumer expenditure for all light-duty vehicles as a dashed black line, using data from the Bureau of Economic Analysis (BEA 2022). The average expenditure does represent the price paid by the consumer, including taxes. In 2021, the average

6 Values here are nominal dollars, not inflation-adjusted. From 2011 to 2020, the Consumer Price Index (CPI) increased by 1.9% per year, so a cost in 2011 would need to be increased by 20% to be adjusted for inflation to 2021$ (BLS, 2022).

expenditure for LDVs increased by 11%, and so the gap between the MSRP for PEVs and the average expenditure for LDVs decreased. In 2020 the difference of the PEV MSRP to a conventional vehicle transaction price was $13,800, while in 2021, this difference was $8,500. Comparison of MSRP to vehicle transaction price is indirect, so these observations may partly reflect conventional vehicles selling at and above MSRP, a factor that is distinct from historic norms (Hailes 2022; Henry 2022). This atypical pattern results in part from a continued upsizing in passenger vehicles, though prices increased for both cars and light trucks.

In 2021, purchases of PEVs were eligible for a Plug-In Electric Drive Motor Vehicle federal tax credit of up to $7,500 (IRS, 2009). This tax credit has been superseded by the enactment of the Inflation Reduction Act in August 2022 creating a Clean Vehicle Credit (U.S. Congress 2022; DOE 2022a). Tesla and General Motors have both sold more than 200,000 PEV, reaching the threshold for the previous tax credit to be phased out (IRS, 2018; IRS, 2019). Every other model of BEV was eligible for the full $7,500 tax credit in 2021, while PHEV tax credits ranged from $4,500 to $7,500 depending on battery size. Accounting for this OEM-specific credit, the average BEV sold in 2021 was eligible for a $1,850 credit in 2021 and the average PHEV was eligible for a $6,500 credit.

4 VEHICLE SUPPLY CHAIN

4.1 VEHICLE MANUFACTURING AND ASSEMBLY

Most electric vehicles that have been sold in the United States were assembled in the United States, as shown in Figure 17. 81% of BEVs and 33% of PHEVs have been assembled in the United States. Most of the remaining PEVs sold in the United States were assembled in Japan, Germany, and Mexico. A higher fraction of PEVs have been assembled domestically than ICE vehicles since 2011. In 2021, 64% of PEV were assembled in the United States, including 79% of BEV; for comparison, 46% of all LDV were assembled in the United States, based on import data from the Department of Commerce and sales data from Wards Auto (USITC 2022; Wards 2022).

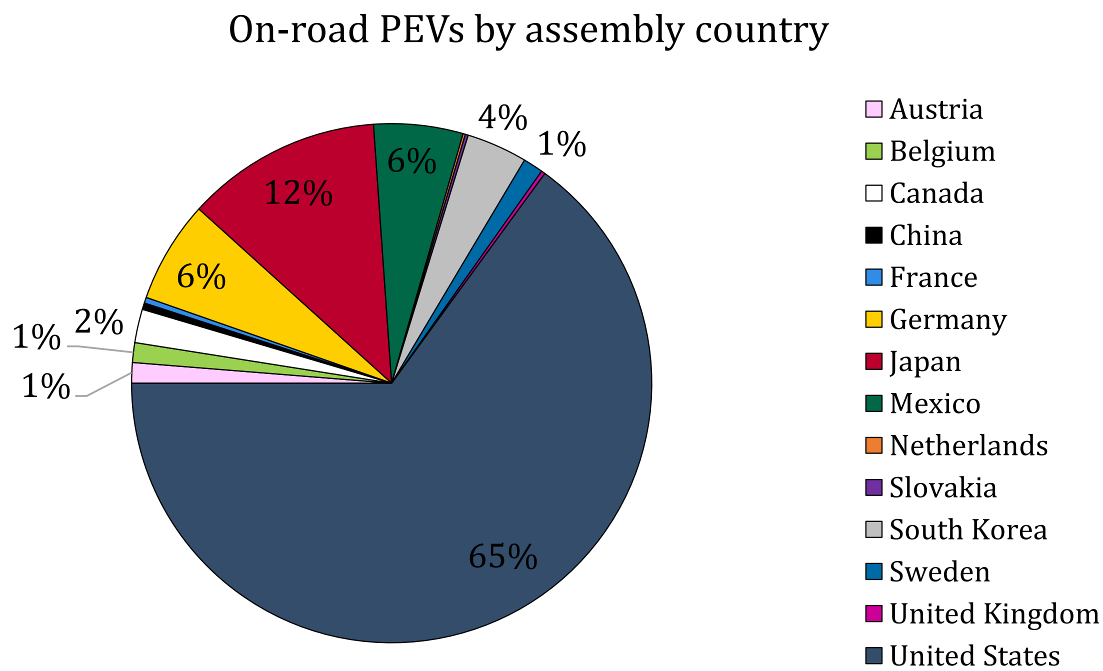

FIGURE 17 Assembly location for PEVs sold in the United States through 2021

Figure 18 shows how assembly location and vehicle content has changed over time. In 2011 and early 2012, most PEVs sold in the United States were assembled in Japan, led by the Nissan Leaf and Toyota Prius Plug-in. By the end of 2012, the Nissan Leaf was being produced in Tennessee and additional models (from Ford and Tesla) were being produced in the United States. Since 2014, about one-third of PEVs have been assembled in foreign countries. In 2021, 64% of PEVs were assembled in the United States.

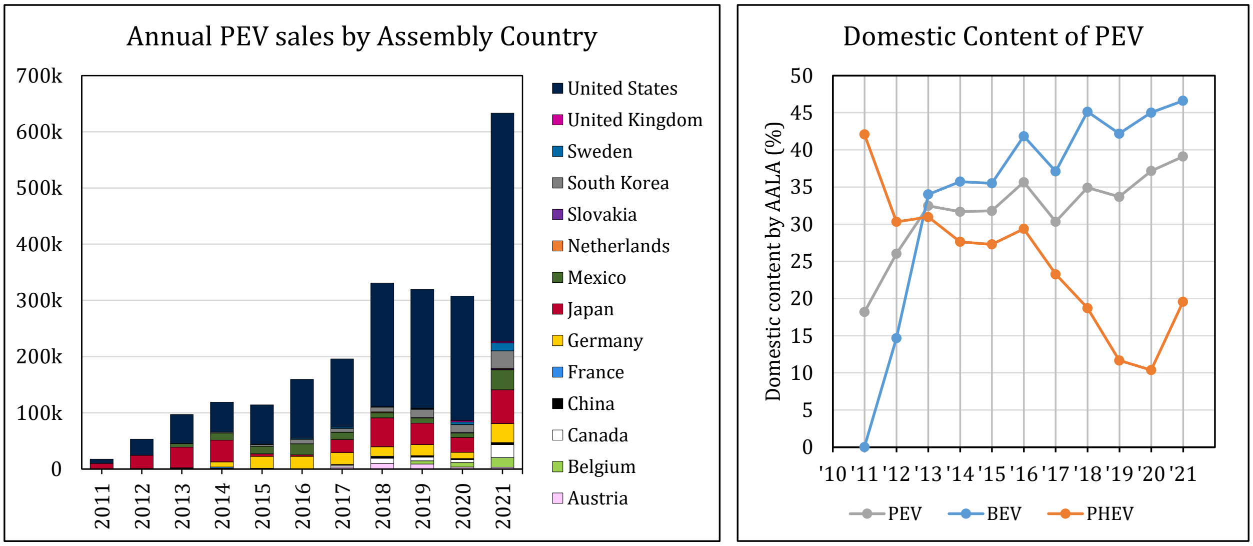

FIGURE 18 Assembly location by year and annual sales-weighted AALA domestic content for PEVs sold in the United States from 2010 to 2021

The fraction of vehicle components that are produced domestically (here defined as both United States and Canada) come from the American Automobile Labeling Act (AALA) reports that are compiled by the National Highway Traffic Safety Administration (NHTSA) for each vehicle model (NHTSA 2022). Figure 18 shows the sales-weighted average of these AALA values for PEVs sold in the United States. This figure shows that the total amount of domestically sourced materials in electric vehicles has grown since 2011, with strong growth from 2011 to 2013 for BEVs. In 2013, about one-third of components in both BEVs and PHEVs were domestically sourced. Since then, the fraction of domestic content in PHEVs has declined, largely due to an increasing selection of models produced throughout the world, reaching only 10% in 2020 before rebounding to 20% in 2021. The increase in fraction of domestic content in BEVs since 2011 was initially due to the relocation of assembly of Nissan Leafs to the United States, and then due to the growth in sales by Tesla. For the BEV, shares have generally continued to increase, beginning in early 2013 with the Tennessee-based production of the Nissan Leaf, and then increasing since 2016 as Tesla became the top-selling PEV automaker in the U.S., producing vehicles in their California plant.

4.2 BATTERY CAPACITY

Since 2010, the commercially available PEVs in the United States have used lithium-ion batteries for energy storage. These batteries are comparatively lightweight, and batteries with capacities of up to 100 kWh have been included in PEVs.

The aggregate battery capacity in PEVs sold in the United States is over 110 gigawatt-hours (GWh) through 2021. Table 2 shows total battery capacity by year for BEV and PHEV from 2010 through 2021; new battery capacity was nearly 36 GWh in 2021. Nearly half of all battery capacity for PEVs was added between 2020 and 2021. Though BEVs comprise only 64% of the total PEV market since 2010, 90% of all battery capacity has been installed in BEVs in the United States. The average BEV battery capacity reached 73 kWh in 2021, while the average PHEV reached 14.6 kWh, after averaging between 12–13 kWh since 2015.

TABLE 2 Lithium-Ion Battery Capacity for New BEV and PHEV by Year

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
BEV capacity (total GWh)	0.2	0.5	2.2	2.3	2.9	4.9	6.4	15.0	15.8	17.6	33.4	101.2
BEV capacity (average kWh)	23.7	33.6	44.9	39.2	46.9	60.7	63.7	73.8	68.5	74.3	73.0	
PHEV capacity (total GWh)	0.1	0.4	0.5	0.6	0.7	1.0	1.2	1.6	1.1	0.8	2.6	10.7
PHEV capacity (average kWh)	16.0	11.7	11.0	10.8	12.7	12.4	12.1	12.8	12.3	12.1	14.6	
Total PEV capacity (GWh)	0.4	0.9	2.7	3.0	3.6	5.9	7.5	16.6	16.9	18.5	36.0	111.9

The core components of lithium-ion batteries are the anode and the cathode. Most lithium-ion batteries have a graphite anode, though a few vehicles (e.g. Mitsubishi i-MiEV, Honda Fit) have used lithium titanate instead (Blomgren, 2017). The cathode is the most expensive component of the lithium-ion battery (Pillot and Sanders, 2017), and there are numerous competing chemistries for the cathode active material. The most common cathode chemistries for lithium ion batteries for automotive uses are $Li[Ni_{1-x-y}Co_xAl_y]O_2$ (NCA), $Li[Ni_{1-x-y}Mn_xCo_y]O_2$ (NMC), $LiMn_2O_4$ (LMO), and $LiFePO_4$ (LFP). For a detailed description of the relative merits of each of these chemistries, see, e.g., Berman et al. (2018), Andre et al. (2015) and Schmuch et al. (2018). There are trends toward reducing cobalt in favor of increased nickel content in NMC batteries to reduce costs (Berman et al., 2018). It is generally not reported what stoichiometry battery cathodes use in each PEV, and occasionally even the type of active material is not publicly known. Tesla has most frequently used NCA batteries, while most other automakers have been using NMC batteries. To reduce costs and usage of critical materials, automakers have begun to transition to using LFP batteries, most notably Tesla, which has begun to use LFP in its shorter-range Model 3 and Model Y.

End-of-life vehicle scrappage is an opportunity for recovery of the battery materials. Based on historical trends, and assuming that PEVs have been scrapped at similar rates to ICE vehicles of the same vintage, about 3.1% of lithium-ion batteries in PEVs (approximately 3.5 gigawatt-hours) has been scrapped as of December 2021.

4.3 BATTERY ASSEMBLY

Understanding the battery supply chain is particularly important for the strategic planning and development of a battery recycling infrastructure to secure critical materials supply. Argonne National Laboratory recently published a comprehensive assessment of the lithium-ion battery supply chain for PEVs in the United States (Zhou et al., 2021). Following the methodology in that report, we summarize the manufacturing and production locations of lithium-ion battery cells and packs by make and model for PEVs sold in the U.S. from 2010 to 2021.

In this analysis, we find that the batteries used in PEVs sold in the U.S. have been largely domestically sourced. Since 2010, over half of all PEVs sold have cells which were produced in the U.S., as have over 70% of all battery packs. In terms of total energy capacity (in Watt-hours), 57% of battery cells have been manufactured and 84% of battery packs have been assembled in the U.S. This is larger than the share for vehicles, as domestically-produced PEVs have higher-capacity batteries, on average. In 2021, 65% of battery cells and 73% of battery packs were domestically produced, with the majority of domestic production being used in Tesla vehicles. Starting in 2023, the Inflation Reduction Act ties eligibility for each make and model for the Clean Vehicle Tax Credit to the North American value of battery component manufacturing and assembly (U.S. Congress 2022).

Historically, Japan and South Korea have been the two largest foreign suppliers of the cells in PEV sold in the U.S. market. However, in 2021, Poland became the largest country of origin, with LG Chem supplying batteries to the Ford Mustang Mach-E and several models from BMW, Volkswagen Group, and Volvo (Seredynski 2020; Kane 2022a). In 2021, China became the source of the fourth-most battery cells, largely due to the use of batteries with lithium iron phosphate ($LiFePO_4$, or LFP) cathodes in the Tesla Model Y.

Figure 19 shows a Sankey flow diagram for manufacturing of PEV sold in the United States, including production locations of battery cells and battery modules and final assembly location as described in Section 4.1, in terms of total battery capacity in GWh. For most vehicles, the supply chain is regionalized; European cell production often leads to assembly of the packs and final vehicles in Europe as well. Many Asian cells are imported to North America for assembly into U.S.-made packs and U.S.-assembled vehicles. The countries with the most production of cells, packs, and vehicles are shown in Table 3. Note that in Table 3, the units are in terms of total number of vehicles – a smaller battery pack in a PHEV is counted equally to a larger battery pack in a BEV.

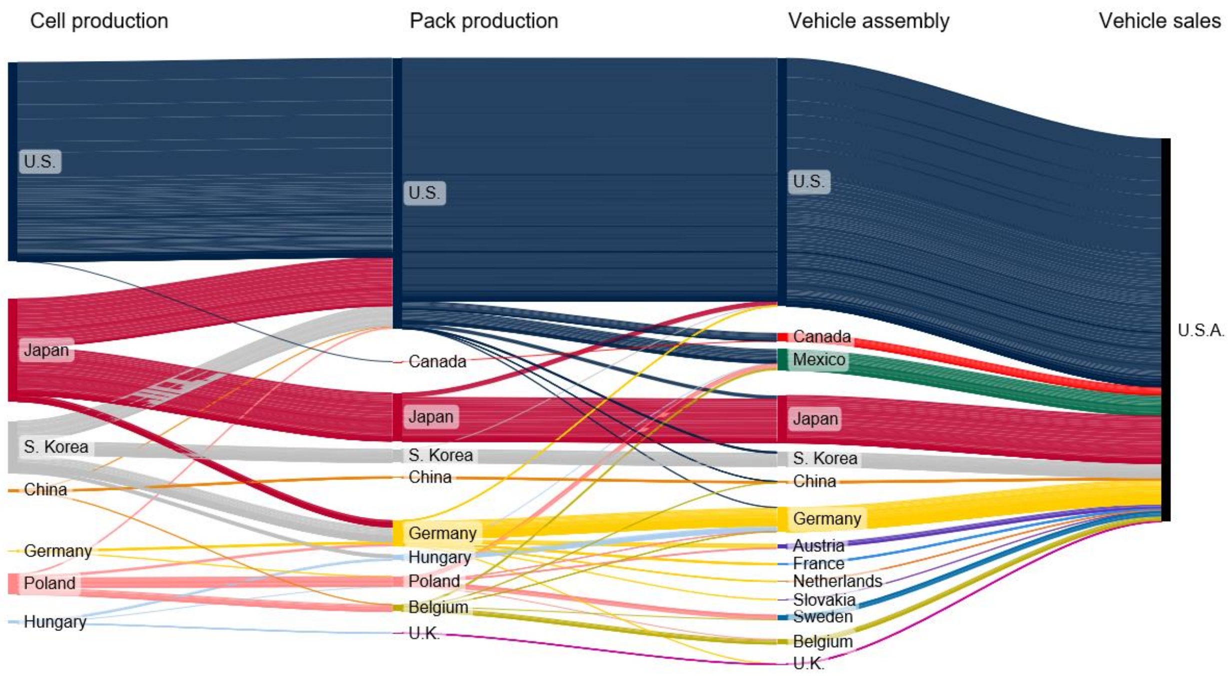

FIGURE 19 Sankey flow diagram showing manufacturing location for cells, packs, and vehicles for PEVs sold in the United States from 2010 to 2021 (GWh)

TABLE 3 Production Locations for Lithium-Ion Battery Cells, Packs, and Vehicles (Thousand Vehicles)

Country	Cell (2021)	Cell (cum.)	Pack (2021)	Pack (cum.)	Veh. (2021)	Veh. (cum.)
Belgium	0	0	23	41	16	29
Canada	0	0	0	0	23	49
China	12	18	4	9	4	10
Germany	3	9	34	159	31	150
Hungary	4	19	6	37	0	0
Japan	116	632	87	295	60	290
Mexico	0	0	0	0	39	130
Poland	89	128	45	63	0	0
South Korea	46	322	32	81	32	89
United Kingdom	0	0	1	2	3	6
United States	362	1,220	402	1,660	406	1,520
Other	0	0	0	0	21	75
Total Vehicle Counts	630	2,350	630	2,350	630	2,350

Figure 20 shows a similar diagram as Figure 19, grouped by manufacturing company, in terms of GWh of battery capacity. In Figure 20, the flow colors represent the manufacturer of the cell, with the seven largest cell producers shown. Panasonic and LG Chem are the two largest battery suppliers for PEVs in the U.S. market, combining to produce 90% of all batteries used. Much of Panasonic's production is used in Tesla vehicles, followed by Toyota and Ford, while LG Chem historically has supplied a large number of different automotive original equipment manufacturers (OEMs). From the OEM side, Volkswagen and Ford have been comparatively willing to source batteries from a variety of battery companies, while Nissan, Tesla, and General Motors largely stuck to a single source through 2021. Figure 20 shows that there is a variety of business models for battery pack production: some packs are developed by the cell producers, others by automotive OEMs, others by joint ventures between the two (e.g., Primearth or Ultium), and still others from third parties (e.g., Bosch or Draexlmaier).

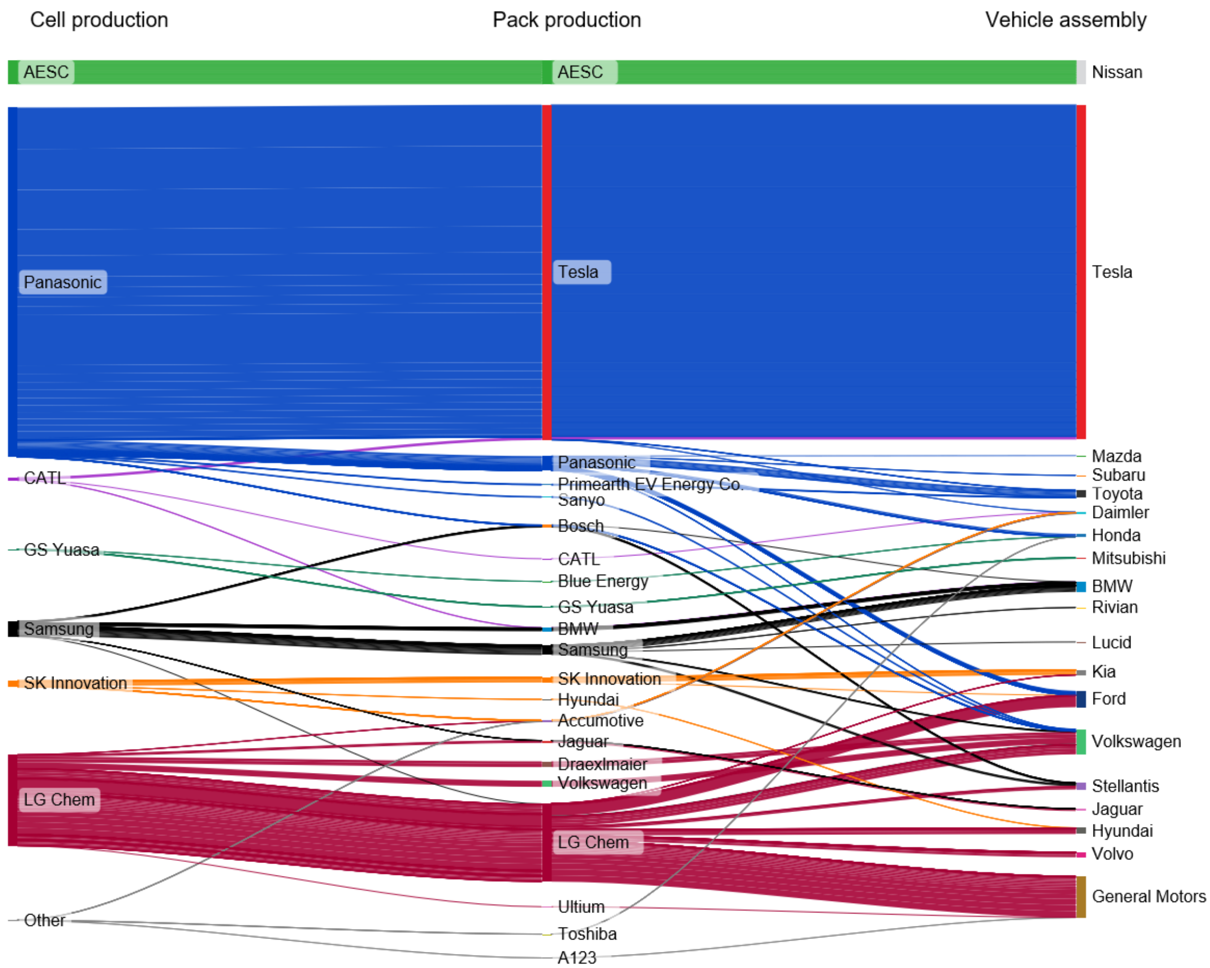

FIGURE 20 Sankey flow diagram showing manufacturing company for cells, packs, and vehicles for PEVs sold in the United States from 2010 to 2021

4.4 BATTERY PLANT ANNOUNCEMENTS

Over the past several years, many OEMs have announced plans to build factories for PEV batteries across the world, including in North America. Most of the announced battery plant projects aim to start production by the second half of the 2020's. This wave of planned battery plants will increase the battery manufacturing capacity in North America from less than 100 GWh in 2021 to approximately 1,000 GWh by 2030, as shown in Figure 21. The vast majority of this announced capacity is for manufacturing of battery cells, though a few plants are dedicated solely to assembly of packs and modules. In Figure 21, estimates of capacity through 2021 are based on actual, existing plants, while estimates through 2030 are based on tracking public announcements of planned facilities (added atop the 2021 actual net capacity data). Note that capacities of some factories were estimated based on their investments and the numbers of vehicles they serve. This production volume is roughly equivalent to the capacity needs of 10 to 13 million BEVs per year. Much of the existing capacity has historically been from the Tesla Gigafactory in Nevada, though over ten plants of similar size have been announced nationwide. Future domestic battery manufacturing is accelerated in part by investments in research and development by the U.S. Department of Energy (DOE). In October 2022, DOE announced a set of 21 projects receiving a combined $2.8 billion through the Bipartisan Infrastructure Law (DOE 2022b). These projects support new, retrofitted, and expanded facilities to commercially produce battery materials and demonstrate new approaches in manufacturing.

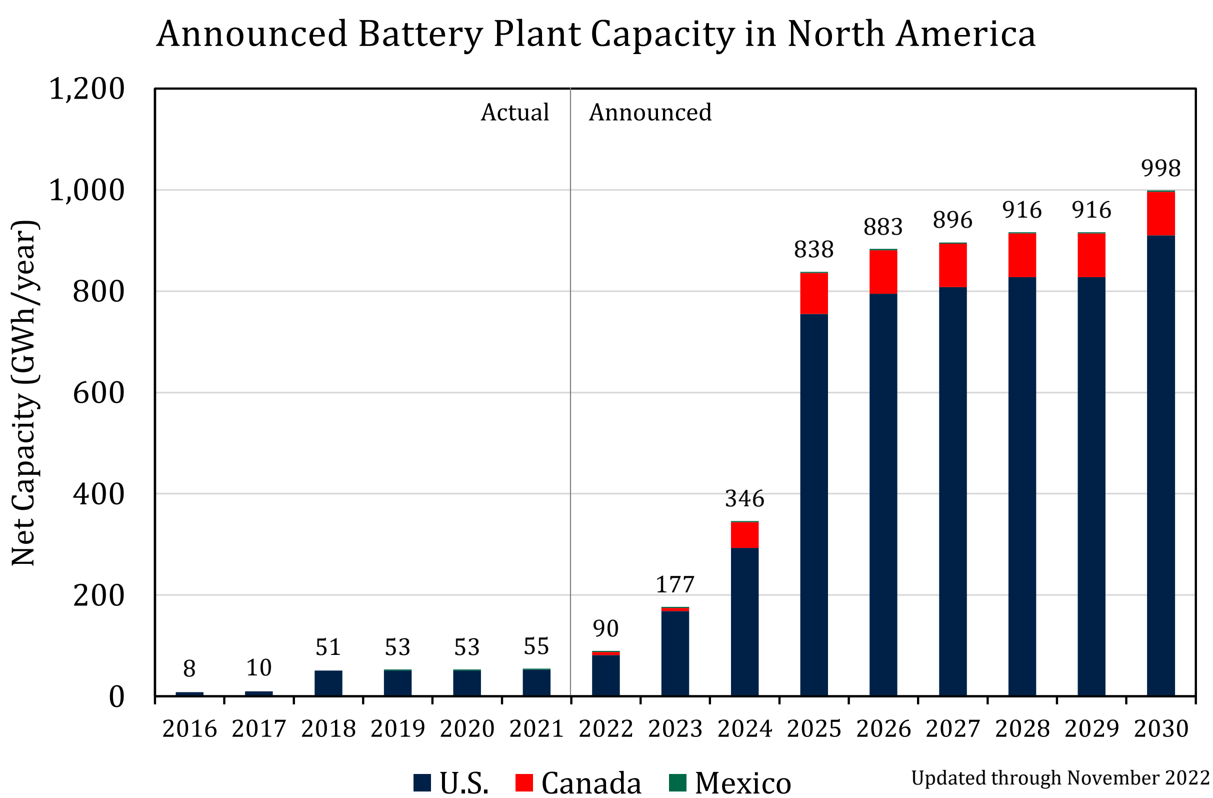

FIGURE 21 Announced capacity for battery plants in North America, as of November 2022

Many states and provinces in North America will have forthcoming battery plants. Co-located with the broader automotive industry, much of the proposed development is in the eastern United States, between Georgia and Michigan. In the U.S., Kentucky, Tennessee, Georgia, and Michigan will see the highest growth in battery manufacturing capacity. There are many OEM and joint ventures that have chosen to locate their battery projects in these states. These include Ford, SK Innovation, and LG Energy Solutions. Outside of the U.S., Canada sees a growing number of PEV battery plants in Ontario, and Mexico has an announced project in Guadalajara, Jalisco. Figure 22 shows a map of the planned plants, aggregated at the state/province level. This map also overlays existing light-duty vehicle assembly plants (Automotive News 2022), which are also centralized in the eastern part of the country.

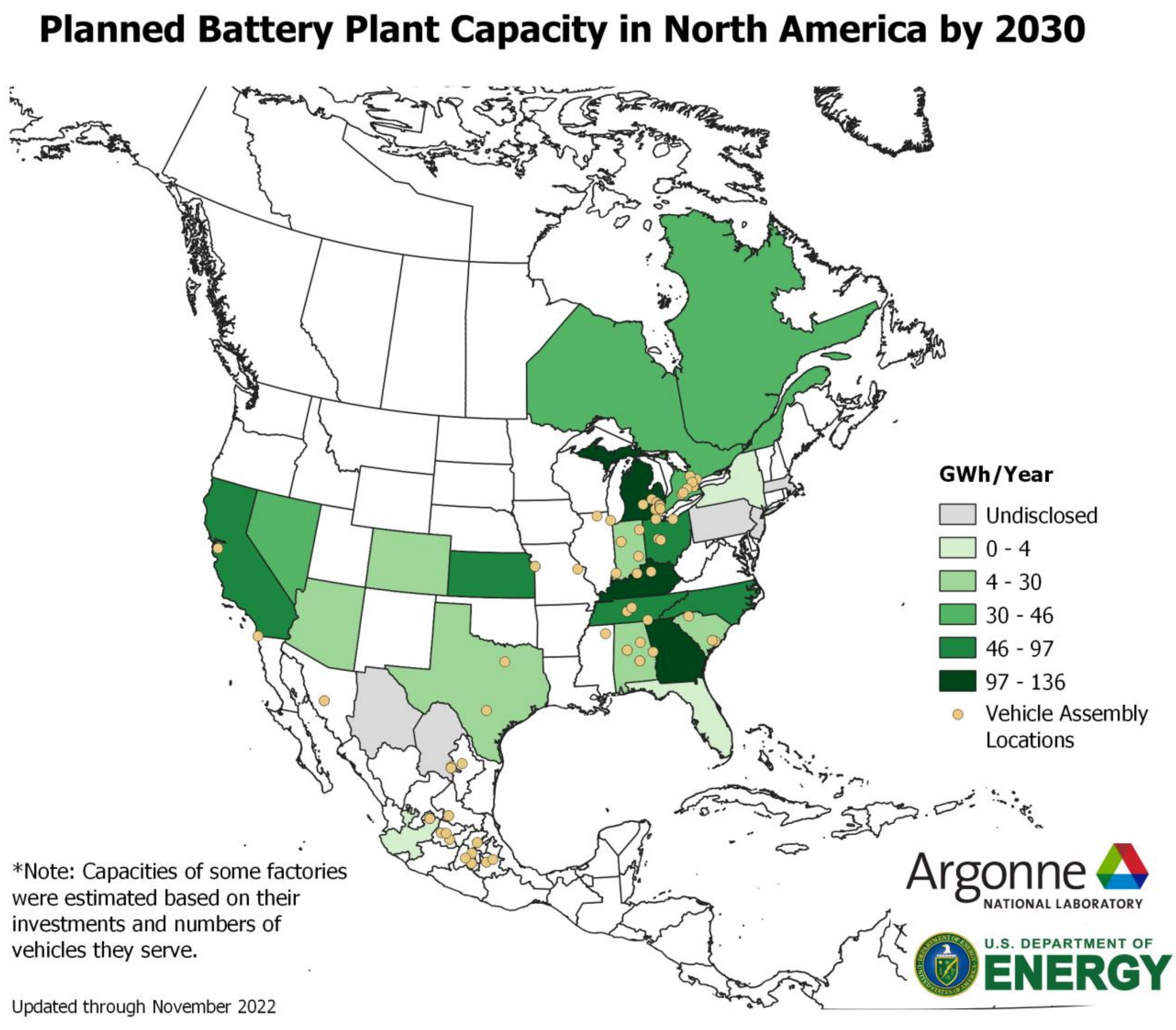

FIGURE 22 Planned battery plant capacity by state in 2030 (GWh/year), as of November 2022

5 CONCLUSIONS

Since light-duty plug-in electric vehicles have been widely available in the United States, more than 2.3 million PEVs have been sold, driving nearly 68 billion miles on electricity. These 68 billion eVMT consumed 22 terawatt-hours of electricity. PEVs reduce gasoline consumption by replacing gasoline-fueled VMT with electricity, in the case of BEVs, and in the case of PHEVs, by utilizing hybrid powertrains which use both gasoline and electricity. Use of these vehicles has led to a total nationwide reduction of 2.5 billion gallons of gasoline from 2011 to 2021, with this fuel shift translating to an emissions reduction of nearly 20 million metric tons of GHGs. In 2021 alone, electric vehicles reduced gasoline consumption by nearly 700 million gallons, offsetting 5.5 million metric tons of GHGs, and reducing consumer fuel spending by approximately $1.4 billion. Table 4, below reproduces Table 1 from the introduction, summarizing the total impacts of PEVs by year from 2011 to 2021. Tables 5 through 8 present the same metrics for smaller groups of vehicles. Tables 5 and 6 present the impact metrics for BEV and PHEV, respectively. Similarly, Tables 7 and 8 present the same metrics delineated by cars and non-cars (CUVs, SUVs, vans, and pickup trucks).

TABLE 4 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road PEVs (Duplication of Table 1)

Year	PEV sales (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	18	0.1	3	30	0.02
2012	53	0.3	13	100	0.08
2013	97	0.9	40	330	0.27
2014	119	1.8	73	610	0.50
2015	114	2.9	120	990	0.81
2016	160	4.0	160	1,400	1.10
2017	196	5.6	220	1,900	1.60
2018	331	8.3	310	2,800	2.30
2019	320	11.7	430	3,800	3.30
2020	308	13.0	480	4,200	3.70
2021	634	19.1	690	6,100	5.40
Total	**2,350**	**67.8**	**2,500**	**22,000**	**19.10**

TABLE 5 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road BEVs

Year	PEV sales, BEV (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	10	0.1	2	20	0.01
2012	15	0.1	6	50	0.04
2013	48	0.5	19	180	0.12
2014	59	0.9	35	320	0.23
2015	63	1.7	60	560	0.40
2016	80	2.5	87	830	0.61
2017	100	3.5	120	1,200	0.86
2018	203	5.2	180	1,700	1.30
2019	231	7.8	270	2,400	2.00
2020	238	9.2	310	2,800	2.40
2021	458	14.4	480	4,400	3.70
Total	**1,500**	**45.9**	**1,600**	**14,500**	**11.60**

TABLE 6 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road PHEVs

Year	PEV sales, PHEV (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	8	0.0	1	10	0.01
2012	39	0.1	7	50	0.05
2013	49	0.4	21	150	0.15
2014	59	0.8	38	290	0.28
2015	52	1.2	55	430	0.42
2016	79	1.6	70	560	0.54
2017	96	2.2	95	770	0.75
2018	128	3.1	140	1,100	1.10
2019	89	3.9	170	1,400	1.40
2020	70	3.8	170	1,400	1.40
2021	176	4.7	210	1,700	1.80
Total	**840**	**21.9**	**970**	**7,800**	**7.50**

TABLE 7 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road Cars

Year	PEV sales, Car (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	18	0.1	3	30	0.02
2012	53	0.3	13	100	0.08
2013	96	0.9	39	330	0.26
2014	118	1.7	72	600	0.49
2015	112	2.8	110	970	0.80
2016	130	3.9	150	1,300	1.10
2017	161	5.2	200	1,700	1.50
2018	286	7.5	280	2,400	2.10
2019	267	10.4	380	3,300	2.90
2020	176	11.2	400	3,500	3.20
2021	265	14.5	520	4,400	4.10
Total	**1,680**	**58.7**	**2,200**	**18,700**	**16.60**

TABLE 8 Annual Sales of New PEVs, and Total Annual eVMT, Gasoline Reduction, Electricity Consumption, and CO_2 Emissions Reduction by On-Road Trucks, Utility Vehicles, and Vans

Year	PEV sales, Truck (thousands)	eVMT (billion miles)	Gasoline reduction (million gallons)	Electricity consumption (gigawatt-hours)	CO_2 emissions reduction (million metric tons)
2011	0	0.0	0	0	0.00
2012	0	0.0	0	0	0.00
2013	1	0.0	0	5	0.00
2014	1	0.0	1	10	0.01
2015	2	0.0	1	14	0.01
2016	30	0.2	6	64	0.04
2017	35	0.4	17	180	0.10
2018	45	0.8	31	320	0.20
2019	52	1.2	50	510	0.34
2020	131	1.9	71	730	0.51
2021	369	4.6	170	1,700	1.20
Total	**844**	**9.1**	**340**	**3,500**	**2.40**

On average, electric vehicles have become more fuel efficient and have acquired longer all-electric driving ranges as technology has advanced. This improvement in efficiency has occurred even while performance metrics (such as vehicle power or acceleration) have improved as well. In recent years, PHEVs have become less efficient, however, while BEVs have become more efficient. Historically, midsize and compact cars were the most commonly sold PEVs, but plug-in electric SUVs have become more popular as models become available.

Electric vehicles present the opportunity to save consumers money. In this work, we find 6.6 cents-per-mile savings for BEVs, and 4.9 cents-per-mile savings for PHEVs, for a total average fuel cost savings of 5.9 cents/mile in 2021. Across all vehicles, this totals to $1.4 billion in consumer savings in 2021. PEVs have also been found to have lower maintenance and repair costs than conventional vehicles (Burnham et al. 2021). However, PEVs do tend to have higher purchase costs than conventional vehicles, though this cost differential appears to be shrinking and may be further reduced with the Clean Vehicle Credit and Advanced Manufacturing Production Credit established by the Inflation Reduction Act.

Most of the PEVs on the road were assembled in the United States, and many of the battery packs and cells were built in the U.S. as well. Nearly two-thirds of PEVs have been assembled in the United States, and 40% of the total content is domestically sourced. Over 110 GWh of battery capacity has been installed in PEVs since 2010, with nearly half of this total occurring since 2020. Automakers and battery companies have made announcements to build factories for batteries across the world, including in North America, in order to satisfy projected growth in PEV sales.

APPENDIX A DATA AND METHODOLOGY

The data used in this assessment is compiled from a broad set of sources. Including these data in one report allows for convenient reference and harmonization of assumptions on vehicle use. Vehicle counts come from both vehicles in operation (VIO) registration data and from sales data. In this report, we distinguish two types of metrics:

- Aggregate impact metrics which are based on use intensity (as in Section 2)
  - These terms are used to quantify eVMT, gasoline reduction, electricity consumption, and emissions reductions, as presented in Table 1 or in Section 5.
  - Quantified using VIO data.
- Metrics based on vehicle characteristics (as in Sections 3 and 4).
  - These are quantified by sales-weighted averages (typical vehicle characteristics) or in aggregate terms (such as total battery capacity).
  - Calculated using initial vehicle sales data.

Data Sources

VIO registration data for light-duty vehicles is licensed from Experian Automotive (2022). Sales estimates for this analysis come from Argonne National Laboratory (ANL 2022), which are compiled from other sources including Wards Auto (Wards 2022), Inside EVs (Inside EVs 2020), and HybridCars (Cobb 2018). Most of these sales estimates are informed by quarterly reports by automakers, though some automakers do not present sufficient information to determine exact sales numbers of each make and model. Within a model, it is possible for multiple variants which have distinct features of relevance within this report, such as high-capacity and low-capacity versions, or performance and standard trim levels. A parallel report (Schwartz et al., 2021) details estimated sales mixes for the individual variants of each of these models, using detailed registration data from twenty states, and this information has been supplemented using VIO registration data from Experian Automotive.

The all-electric range, vehicle efficiency, size class, and electric motor power come from the FuelEconomy.gov database, managed by the U.S. Department of Energy (DOE) and Environmental Protection Agency (EPA) (DOE and EPA 2022). The carbon intensity of electricity comes from the eGRID database from the EPA (EPA 2022b), considering the local variations in electricity generation and vehicle registrations, as described in Gohlke et al. (2022).

The manufacturer's suggested retail price (MSRP) of each model comes from FuelEconomy.gov, automaker websites, and from Car and Driver magazine (Car and Driver 2022). Vehicle curb weight comes from a mix of Car and Driver magazine, the Canadian Vehicle Specifications database (CARSP 2021), and directly from the automaker websites and brochures. The EPA (2022a) publishes equivalent vehicle test weight for each vehicle, and often includes information on gross vehicle weight rating (GVWR) and curb weight. Vehicle assembly and origin of parts come from American Automobile Labeling Act (AALA) data from the National Highway Traffic Safety Administration (NHTSA) (NHTSA 2022), and are supplemented by manufacturer press releases and news stories. Vehicle acceleration and battery capacity for each vehicle were established through a mix of data compiled by InsideEVs (Kane 2022b), press releases, news stories, and information on manufacturer websites.

Quantification Methodology

The average annual vehicle travel for each vehicle make and model was estimated considering all-electric vehicle range and vehicle vintage. We note that since PEVs are an emerging technology, these vehicles are on average newer than the average ICE vehicle, with an average age of only 3.2 years as of December 2021. According to mileage schedules from NHTSA and the EPA (Lu, 2006; EPA, 2016; NHTSA and EPA, 2018), the average ICE car is driven approximately 13,000–14,000 miles per year in its first three years. Therefore, as a baseline for this report, an annual baseline driving distance of 13,500 miles per vehicle, or 1,125 miles per month, is used. We prorate the annual VMT for newly sold vehicles to account for less than a full year of driving. VIO data includes the model year (MY) of a given vehicle, but not the date of initial sale. For newly-sold vehicles where the model year is the calendar year, we assume that vehicles are on the road for an average of 0.5 years; for vehicles of later MY (e.g. MY2022 sold in 2021), we assume these are on the road for an average of 0.125 years.

We adjust this annual per-vehicle VMT in two ways. First, we make an adjustment to account for the distance driven using electricity. PHEVs can travel using a mix of gasoline and electricity. Because of the flexibility of a secondary fuel source, PHEVs are assumed to drive the same total distance as ICE vehicles, i.e., 13,500 miles per year. For PHEVs, the utility factor represents the fraction of total mileage run on electricity rather than gasoline. This utility factor is a function of the battery size; a battery with a longer all-electric range will have a higher fraction of miles driven using electricity. The utility factor for PHEVs in this report comes from the Society of Automotive Engineers (SAE) J2841 standard (SAE, 2010), specifically the multi-day individual utility factor (MDIUF). The PHEV utility factor matches reasonably well with empirical data for the average vehicle (c.f. Gohlke and Zhou 2018 or Raghavan and Tal 2022), though there are naturally variations of travel across all owners of a specific type of vehicle. BEVs do not have a utility factor, as 100% of their driving is all-electric. To account for the correlation of annual driving distance with driving range, we adjust the annual mileage for each vehicle dependent on its reported all-electric range, as if there is an effective utility factor for eVMT. This analysis uses the square of the utility factor for PHEVs as the effective utility factor for BEV, which has good agreement with real-world studies (c.f. Gohlke and Zhou 2018). The utility factor for PHEVs and effective utility factor for BEVs are shown in Figure 23 in terms of the total annual driving distance, relative to a baseline of 13,500 miles per year.

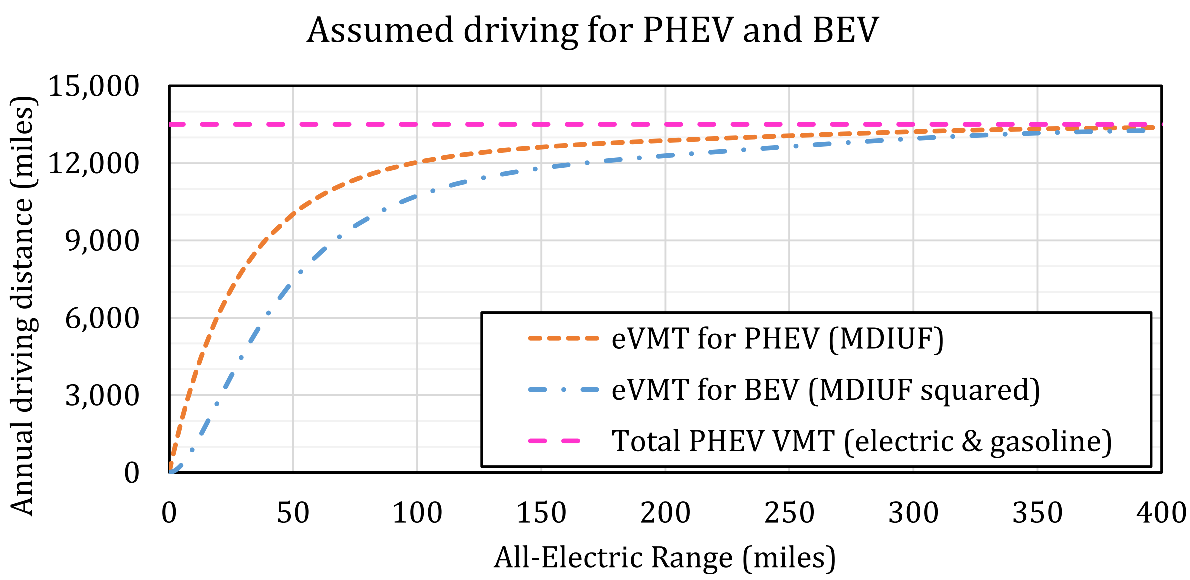

FIGURE 23 Annual electric vehicle miles assumed to be traveled by PEV type and range; total PHEV VMT included for comparison

The second adjustment for VMT holds for all vehicle powertrains. In 2020, due to COVID-19 pandemic, total VMT dropped in the United States by 11%, and for 2021, the total VMT was 1% lower than in 2019 (FHWA 2022b). For these two years, we assume a proportional decrease in annual VMT for each PEV equal to the total nationwide reduction, adjusting both eVMT and gVMT.

Given the total VMT for each PEV in each year, we quantify the total energy consumption using the vehicle efficiency from the FuelEconomy.gov database. We assume a mix of 57% highway driving and 43% city driving, matching the EPA methodology believed to best describe real-world driving (EPA 2021).

We then estimate the counterfactual gasoline consumption by an ICE vehicle that would have been purchased instead of the PEV. As our baseline, we considered the typical counterfactual vehicle to have a fuel consumption in the 50th percentile of vehicles in the same regulatory class (car or light truck) and of the same model year, using data from the EPA Automotive Trends database (EPA 2021). As noted in Section 2.4, there are reasons a buyer's second choice may be more or less efficient than the average ICE vehicle, and so we considered alternative cases, shown in Appendix B.

We use the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model to quantify the CO_2-equivalent GHG emissions per gallon of gasoline and for electricity from different fuel sources (ANL 2021). To determine historical electricity mixes, we use the 26 different subgrids within EPA's eGRID, assigning the relevant mix for each vehicle in each year based on the zip code in which PEV is registered (Gohlke et al. 2022). Comparing the actual electricity consumption (and gasoline for PHEVs) with the hypothetical gasoline consumption allows us to quantify gasoline displacement and carbon dioxide emissions reductions by PEV.

Methodology Updates

Relative to the annual assessment report published last year (Gohlke and Zhou 2021), this analysis makes the following changes:

- Calculations of key metrics using annual VIO data rather than monthly sales data
- Inclusion of gasoline from PHEV operating in charge-sustaining mode; including comparison of this gasoline consumption with a counterfactual ICE vehicle
- Switching default counterfactual vehicle to 50th percentile ICE vehicle within same regulatory class, rather than using 75th percentile ICE vehicle in the same size class
- Switching the ratio of city:highway driving from 55:45 to 43:57
- Update of electricity grid mix, and use of regionally resolved electricity grid emissions
- Quantification of fuel cost savings by state
- Addition of historical vehicle supply chain analysis and planned manufacturing facilities, extending methodology of Zhou et al. (2021)
- Removal of comparison of total capacity of different battery cathode active materials
- Removal of third-party references to American-made vehicle rankings

APPENDIX B ALTERNATIVE ASSUMPTIONS AND SENSITIVITY ANALYSES

This section explores variations in the input data and assumptions to examine the robustness of the results. This was done in detail in a previous iteration of this report (Gohlke and Zhou, 2018) and many results here reference that work. The largest variations in the results come from assumptions ICE vehicle replacement, and we also consider impacts variations in assumed traveler behavior. For ease of comparison with previous iterations of this report, we also include a side analysis using the previous methodology. The impacts of the biggest potential changes are summarized below in Table 9.

Comparable ICE Vehicles

As described in Section 2.4, the reduction in gasoline attributed to PEVs depends on the ICE vehicle that each PEV is assumed to replace. As our baseline, we considered the average displaced gasoline vehicle to have a fuel consumption in the 50th percentile of vehicles in the same regulatory class (car or light truck) and of the same model year from the EPA Automotive Trends database (EPA 2021).[7]

Xing et al. (2021) used survey responses of new PEV buyers from MY2011–2014 on their second-choice vehicle, and developed a model to consider hypothetical vehicle replacement. As a point of comparison, their simulations found that the average counterfactual fuel economy of an ICEV was 28.9 miles per gallon (mpg) in 2014. While this is more efficient than the LDV market as a whole in 2014, this is largely due to the prevalence of cars rather than SUVs in the PEV market. Through 2014, over 99% of PEV sold were cars, rather than light trucks, as shown in Figure 14 and Tables 7 and 8. Using data from the EPA Automotive Trends database (EPA 2021), the counterfactual sales-weighted fuel economy for the 50th percentile vehicle is 28.2 mpg, while the 75th percentile is 31.0 mpg and 25th percentile is 24.8 mpg. Therefore, the 50th percentile for fuel economy is a valid starting point.

Buyers of electric vehicles may be more interested in fuel conservation for economic or environmental reasons, and so we considered side cases where the fuel economy of the counterfactual vehicle is better than similarly sized vehicles of the same model year. On the other hand, vehicles with similar performance levels may be a more apt comparison for displaced gasoline vehicles. New ICE vehicles with high acceleration tend to be larger with worse fuel economy than the average vehicle, so we also considered vehicles with lower fuel economy as a side case as well. Specifically, we considered replacement ICE vehicles at the 25th and 75th percentiles for fuel economy.

7 The EPA classifies some utility vehicles as cars and some as trucks, based on a detailed examination of the vehicle characteristics. Each model of PEV was considered individually in this analysis; models classified by the EPA as “Car SUVs” were compared to the fuel economy for all cars, while “Truck SUVs” were compared against the fuel economy for all light trucks.

In these analyses, the total eVMT and electricity consumption do not vary, as they are functions only of the PEV characteristics. Considering a counterfactual ICE fuel economy in the 25th percentile leads to increased estimates of gasoline savings (13% higher) and GHG reductions (18% higher). On the other hand, if PEVs are replaced by ICE vehicles in the 75th percentile of fuel economy, our estimates for gasoline and GHG reductions would be lower by 11% and 15%, respectively, as shown below in Table 9.

Traveler Behavior

The baseline VMT in this study was fixed at 13,500 miles/year. As noted in Appendix A, this corresponds to the average distance driven by a comparable ICE vehicle (Lu, 2006). Tuning this parameter affects all vehicles equally and acts as a simple linear scaling factor for eVMT, electricity consumption, gasoline displacement, and GHG emissions.

A non-uniform impact comes from potential reduction of vehicle use as the vehicle ages. NHTSA has a vehicle mileage schedule for estimated travel by age of vehicle, based on historical ICEV data (Lu, 2006). Translating this vehicle mileage schedule (for cars) to the PEV sales since 2010 yields a 5.1% reduction in VMT from 2010 through 2021. It is unknown if this methodology translates to eVMT driven by PEVs.[8] Using data from the 2017 National Household Travel Survey (NHTS), BEVs exhibit no clear reduction in mileage for vehicles dating back to 2011, while PHEVs show a decrease in mileage using NHTS's best estimate, but an increase in mileage when relying on self-reported mileage. In either case, the sample size for each of these vehicles is small.

The fraction of PHEV VMT driven on electricity is determined by a utility factor, and BEVs have an effective utility factor in this report, which can be thought of as representing driver reluctance to fully discharge the battery or use BEVs for long-distance trips. These behavioral factors are strongly dependent on the vehicle make and model, and average values are used in this report. A previous iteration of this report (Gohlke and Zhou, 2018) explored these utility factors in depth. In that report, using the SAE Fleet Utility Factor resulted in 6% lower eVMT, while the utility factors from the World Harmonized Light Vehicles Test Procedure increased eVMT by up to 16%.

We assume a mix of 57% highway driving and 43% city driving, matching the EPA methodology believed to best describe real-world driving (EPA 2021). It is possible that this ratio is less applicable for PEVs than for conventional gasoline ICE vehicles. PEVs are currently disproportionately owned in urban and suburban locales, which tend to have less long-distance driving than rural areas. Additionally, short-range electric vehicles may be preferentially used for

8 There are logical reasons that the eVMT could either be reduced or stay the same as the vehicle ages. For BEVs, a reduction in VMT is identical to a reduction in eVMT though travel behavior for BEV is not the same as ICE vehicles. For PHEVs, only a fraction of the miles are electrified; in particular, the first miles of most trips. If long-range travel is reduced as the vehicle ages, this does not impact the eVMT and instead raises the effective utility factor. If, conversely, fewer trips are taken, but at a proportionally longer distance, this would lower eVMT. Additionally, battery degradation can cause the all-electric range of PEVs to decrease as the vehicle ages, which would lower the potential eVMT.

city commutes. If so, this would generally slightly overestimate electricity consumption, and electric vehicles are often more efficient in city driving than in highway driving. Using a 45/55 highway/city driving mix would decrease PEV electricity consumption by about 1%.

Fuel Costs

The baseline analysis (as presented in Section 2.6) assumes state averages for gasoline and electricity costs. For electricity costs, this analysis assumes the average residential charging. However, unlike gasoline fueling, there are multiple options available for charging, electric vehicle charging can take place at public charging stations or at home. This makes estimating consumer costs more difficult. In a recent analysis, Borlaug et al. (2020) assumed 81% home charging and 19% public charging, and quantified the costs of charging in this scenario for each state, including installation costs of electric vehicle supply equipment (EVSE). For BEV, public charging was further distinguished by charging power, accounting for higher expected costs of high-power charging. We use the charging costs by state, weighting for different charging power for PEV usage in 2021, we find per-mile savings of 5.5 and 5.1 cents-per mile relative to comparable gasoline vehicles, for BEV and PHEV respectively. This yields aggregate savings approximately 6% lower than the baseline analysis ($1.26 billion rather than $1.34 billion in 2021). This analysis likely overestimates average charging costs paid by users of PEVs, as many owners charge using workplace charging or other reduced-cost options, and several automakers have offered free public charging as a purchase incentive (Rogers 2022).

Methodological Changes

This report uses a new methodology for calculating total eVMT and energy use from electric vehicles as compared with previous editions of the report. As listed in Appendix A, the major differences are:

- use of registration data rather than sales data;
- change in comparable ICE vehicle;
- inclusion of gasoline savings for PHEVs operating in charge-sustaining mode; and
- city/highway driving assumptions.

Use of vehicle sales (previous methodology) instead of vehicle registrations (current baseline methodology) results in a total increase of eVMT of 4–5%. The major causes for this change are the implicit inclusion of scrappage in the registration data, and the greater temporal resolution in the date a vehicle is placed into service afforded by sales data. Analysis with vehicle sales has the benefit of a higher temporal resolution, considering vehicle sales monthly. However, many automakers have stopped releasing monthly sales information, instead using quarterly results. Additionally, sales data rarely indicates the model year for a given vehicle, making it difficult to assign vehicle attributes to each vehicle. Conversely, vehicle registration data has state-level, allowing electricity emissions and fuel costs to be calculated with higher resolution.

Total fuel consumption has a comparable change to eVMT. The electricity consumption is 3–4% higher with the sales-based analysis. Changing the methodology has a larger impact on gasoline displacement, with the older methodology estimating around 6% higher than the registration-based update.

Quantification of greenhouse gases has the largest impact from updating the methodology. Estimates of total emissions are 26% lower, using the older methodology. This increase in GHG mitigation in the newer modeling has three major causes. First, about half of this difference is from switching from a national-average grid to a registration-location-weighted grid, as described in Gohlke et al. (2022). Second, the new methodology accounts for reductions in emissions for PHEV while they are operating in charge-sustaining mode. While this operational mode still uses gasoline, the hybridized powertrain tends to use less than the counterfactual ICEV would have. Finally, the change of counterfactual vehicle from the 75th percentile in fuel economy to the 50th percentile leads to larger emissions reductions.

Table 9 shows how each calculation would be different when using the previous methodology, considering both the cumulative totals of each metric for 2010 through 2021 and 2021 alone.

TABLE 9 Comparison of Key Metrics for Different Assumptions

Metric	Baseline	25th percentile LDV MPG	75th percentile LDV MPG	Previous methodology
eVMT (billion miles, cumulative)	67.8	67.8	67.8	71.0 (+4.8%)
eVMT (billion mile, 2021 only)	19.1	19.1	19.1	19.9 (+4.1%)
gVMT (billion miles, cumulative)	19.0	19.0	19.0	N/A
gVMT (billion mile, 2021 only)	4.5	4.5	4.5	N/A
Electricity usage (GWh, cumulative)	22,300	22,300	22,300	23,100 (+3.8%)
Electricity usage (GWh, 2021 only)	6,120	6,120	6,120	6,320 (+3.2%)
Gasoline displacement (million gallons, cumulative)	2,530	2,910 (+14.9%)	2,220 (-12.4%)	2,680 (+5.7%)
Gasoline displacement (million gallons, 2021 only)	690	800 (+14.9%)	610 (-12.3%)	740 (+6.9%)
GHG reductions (MMT CO_2e, cumulative)	19.1	23.1 (+23.1%)	15.7 (-17.8%)	14.1 (-26.1%)
GHG reductions (MMT CO_2e, 2021 only)	5.4	6.5 (+20.6%)	4.5 (-17.1%)	4.0 (-24.7%)

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