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ELECTRIC VEHICLES IN THE U.S.: PROGRESS TOWARD BROADER ACCEPTANCE

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16. Abstract

This report examines the current status and recent progress regarding various technical and public acceptance-related issues that have historically hindered the more widespread acceptance and adoption of plug-in electric vehicles (PEVs), which includes both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). As a reference for comparison, information for current gasoline-powered internal combustion engines is also presented where appropriate.

The main issues explored in this report include:

- vehicle availability, including sales trends and costs
- fuel economy, GHG emissions, and petroleum usage
- batteries, charging time, driving range, and range anxiety
- charging infrastructure availability and smart charging
- public opinion and government support

Overall, recent advances and improvements in several of these areas have led to PEVs becoming increasingly more competitive with conventional gasoline-powered internal combustion engine (ICE) vehicles. Furthermore, future costs of the vehicles and fuel, coupled with rising public interest and increasing numbers of charging locations, are expected to make such vehicles even more capable of replacing ICE vehicles for the majority of U.S. drivers in the relatively near future.

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plug-in electric vehicle, PEV, battery electric vehicle, BEV, plug-in hybrid electric vehicle, PHEV, greenhouse gases, internal combustion engine, batteries, energy density	Unlimited

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Abbreviations used in this report

Abbreviation	Definition
AC	alternating current
ANL	Argonne National Laboratory
BEV	battery electric vehicle
Btu	British thermal units
CAFE	corporate average fuel economy
CD	charge depleting
CO_2	carbon dioxide
CS	charge sustaining
DC	direct current
EV	electric vehicle (any type)
EVSE	electric vehicle supply equipment
g	gram
gal	U.S. gallon
GGE	gasoline gallon equivalent
GHG	greenhouse gas
hr	hour
ICE	internal combustion engine
kg	kilogram
km	kilometer
kWh	kilowatt-hour
L	liter
lb	pound
mi	mile
min	minute
mpg	miles per U.S. gallon
mpge	miles per U.S. gallon equivalent
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
quad	quadrillion Btu
V2G	vehicle-to-grid
V	volt
VMT	vehicle miles of travel
Wh	watt-hour
ZEV	zero-emission vehicle

Contents

Introduction

Currently, electricity accounts for just 0.1% of all transportation-related energy consumption in the U.S., while 92% of transportation-related energy consumption is still derived from petroleum (0.03 and 25.7, respectively, out of a total 27.9 quads[1] consumed for transportation) (LLNL/DOE, 2017). However, in recent years, sales of plug-in electric vehicles (PEVs)—both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—have begun to accelerate, with sales of each vehicle type increasing by more than 700% since 2011 (AFDC, 2017g). This rapid increase in sales for these relatively new (and still evolving) vehicle technologies was due in part to the need for automobile manufacturers to begin to meet the increasingly stringent requirements to lower CO_2 and other greenhouse gas (GHG) emissions (and the corresponding performance gains in fuel economy) to help comply with current and future CAFE standards.[2] Zero-emission vehicles (ZEVs) such as BEVs have played an important role in recent years to help manufacturers achieve their CAFE targets; California and several other states have recently required the sale of such vehicles (Carley, Duncan, Esposito, Graham, Siddiki, and Zirogiannis, 2016).

Battery electric vehicles (BEVs) operate entirely on electricity stored in on-board battery systems that are charged from the main electrical grid, usually via a special high-voltage charging station and using special electrical connectors. Plug-in hybrid electric vehicles (PHEVs) can also operate on electricity stored in on-board battery systems that are charged from the main electrical grid or by an internal combustion engine (ICE), but with the option of switching to the internal combustion engine for power when the battery runs low. Example illustrations of the key differentiating components for each vehicle type are shown in Figure 1 (AFDC, 2017e, 2017f). The advantage offered by PEVs over conventional ICE vehicles is their ability to operate on little to no petroleum (depending on the vehicle design and operating mode). Correspondingly, little to no CO_2 emissions are associated with such vehicles when calculating CAFE compliance.

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[1] One quad (one quadrillion Btu) is equal to approximately 8 billion U.S. gallons of gasoline or 293 billion kWh of electricity.

[2] In March of 2017, the EPA and NHTSA officially announced that the midterm review of CAFE targets for model years 2022-2025 would be re-reviewed (EPA/NHTSA, 2017), reversing the decision to confirm the targets set by the previous administration (EPA, 2017c). Therefore, it is possible that the CAFE targets for 2022-2025 could be altered or eliminated during the upcoming midterm re-review.

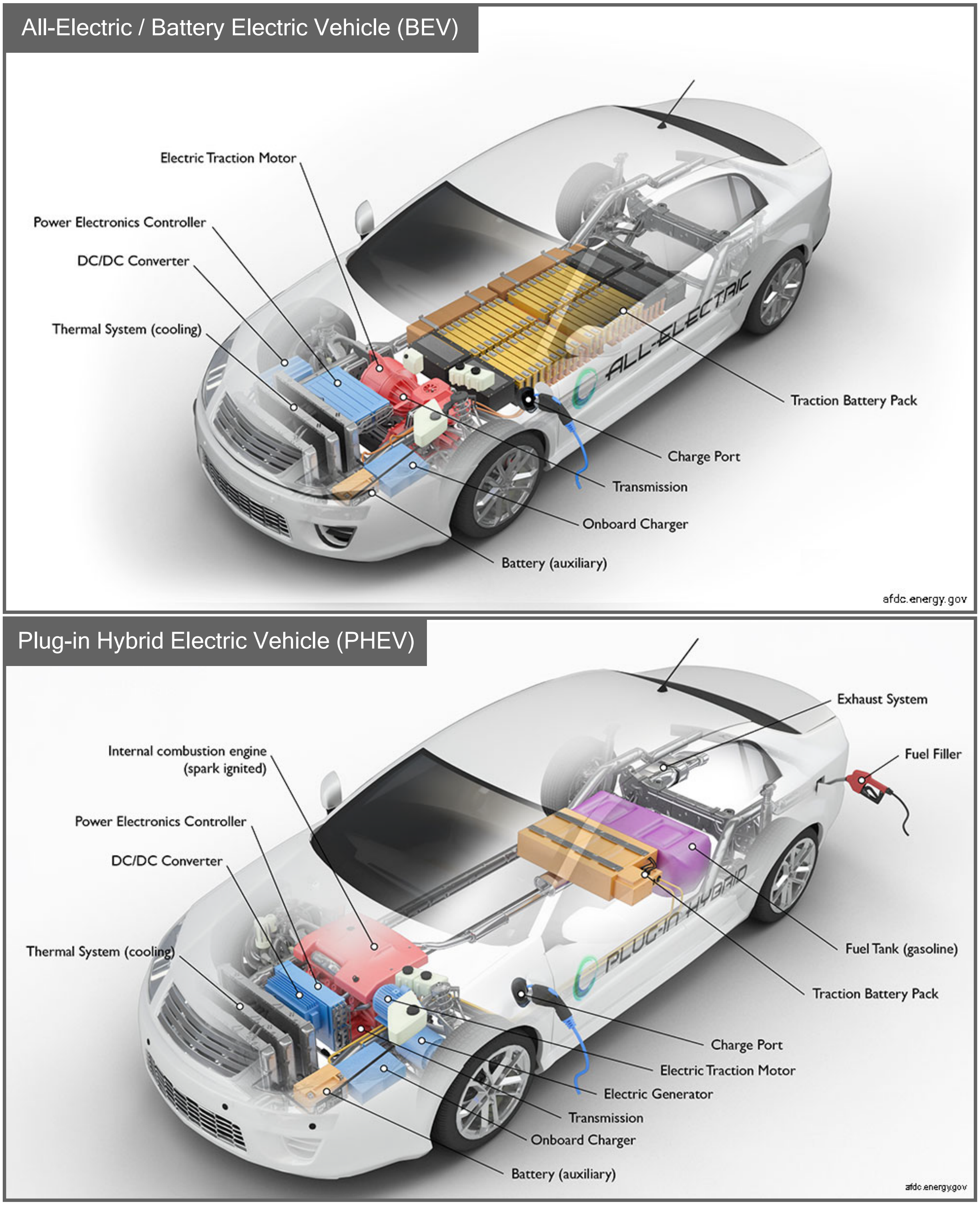


Figure 1. Illustrations of the key differentiating components for all-electric vehicles (called battery electric vehicles, or BEVs, in this report) and plug-in hybrid electric vehicles (PHEVs) (AFDC, 2017e, 2017f).

The main advantages and disadvantages of each PEV type are listed below in Table 1 (EEA, 2016).

Table 1
Main advantages and disadvantages of each PEV type over conventional ICE vehicles (EEA, 2016).

Vehicle type	Advantages	Disadvantages
BEV	• Higher fuel efficiency • Lower fuel cost • Home/workplace recharging • Low engine noise • Zero tailpipe emissions (ZEV)	• Higher vehicle price • Fewer recharging stations • Long recharge times • Short driving range • Eventual battery disposal
PHEV	• Higher fuel efficiency • Lower fuel cost (for electricity) • Home/workplace recharging • Many refueling stations (for gas)	• Higher vehicle price • Technologically complex • Semi-long recharge times • Eventual battery disposal

The current state of the major barriers that have hindered the large-scale adoption of PEVs by consumers thus far—driving range, charging time, and vehicle price—will be examined and discussed, and comparisons of electric vehicles relative to gasoline-powered vehicles and other available vehicle types will be presented where applicable. As a reference for comparing the current state of PEVs, information for current ICE vehicles and gasoline as a fuel will also be presented.

Vehicles

Vehicle availability and sales trends

BEVs have been generally been available for sale to the public in the U.S. since 2008, with the majority of models being introduced within the past six years. For model year 2017, 14 unique models of BEV are offered for sale by 13 different automobile manufacturers (EPA, 2017a). Table 2 shows the recent history of BEV availability by manufacturer and model year. In total, 19 automobile manufacturers have offered 86 models (by company and model year) of BEVs for sale in the U.S. since model year 2008.

Table 2
Number of individual models of battery electric vehicles (BEVs) available in the U.S., by company and model year (EPA, 2017a).

Company	Model year							*Total*
	2011	2012	2013	2014	2015	2016	2017	
BMW				1	1	1	2	*5*
Chevrolet				1	1	1	1	*4*
Coda Automotive		1	1					*2*
Fiat			1	1	1	1	1	*5*
Ford	1	2	1	1	1	1	1	*8*
Honda		1	1	1				*3*
Hyundai							1	*1*
Kia				1	1		1	*3*
Mercedes-Benz				1	1	1	1	*4*
Mitsubishi		1	1	1	1	1	1	*6*
Nissan	2	1	1	1	1	1	1	*8*
Scion			1	1				*2*
Smart			1	1	1	1	1	*5*
Tesla	1	1	1	1	1	4	11	*20*
Toyota		1	1	1				*3*
Volkswagen					1	1	1	*3*
Total	*4*	*8*	*10*	*13*	*11*	*13*	*23*	***82***

PHEVs became available to the general public in the U.S. starting in 2011, with the majority of models being introduced within the past four years. For model year 2017, 22 unique models of PHEVs are offered for sale by 12 different automobile manufacturers (EPA, 2017a).

Table 3 shows the recent history of PHEV availability by manufacturer and model year (from 2011 through 2017). In total, 13 automobile manufacturers have offered 69 models (by company and model year) of PHEVs for sale in the U.S. since model year 2011.

Table 3
Number of individual models of plug-in hybrid electric vehicles (PHEVs) available in the U.S., by company and model year (EPA, 2017a).

Company	Model year							*Total*
	2011	2012	2013	2014	2015	2016	2017	
Audi					1	1	1	*3*
BMW				2	2	3	4	*11*
Cadillac				1	1	1	1	*4*
Chevrolet	1	1	1	1	1	1	1	*7*
Chrysler							1	*1*
Ford			2	2	2	2	2	*10*
Honda				1	1			*2*
Hyundai							2	*2*
Kia							1	*1*
Mercedes-Benz					1	2	3	*6*
Porsche				1	3	2	4	*10*
Toyota		1	1	1	1	1	1	*6*
Volvo						1	2	*3*
Total	*1*	*2*	*4*	*9*	*13*	*14*	*23*	***66***

While there have historically been more BEV models available from more individual companies than PHEVs (82 versus 66, respectively), there are currently equal numbers of BEV and PHEV models available for model year 2017 (23 for both). Companies that offer both vehicle types tend to have more models of PHEVs available than BEVs.

Figure 2 illustrates the recent sales trends for both vehicle types. Figure 3 shows the international PEV sales trends for recent years in several major automotive markets (accounting for approximately 95% of global PEV sales) (DOE, 2016a). Both figures show the rapid increase in sales of PEVs in recent years, especially for China and Western Europe.

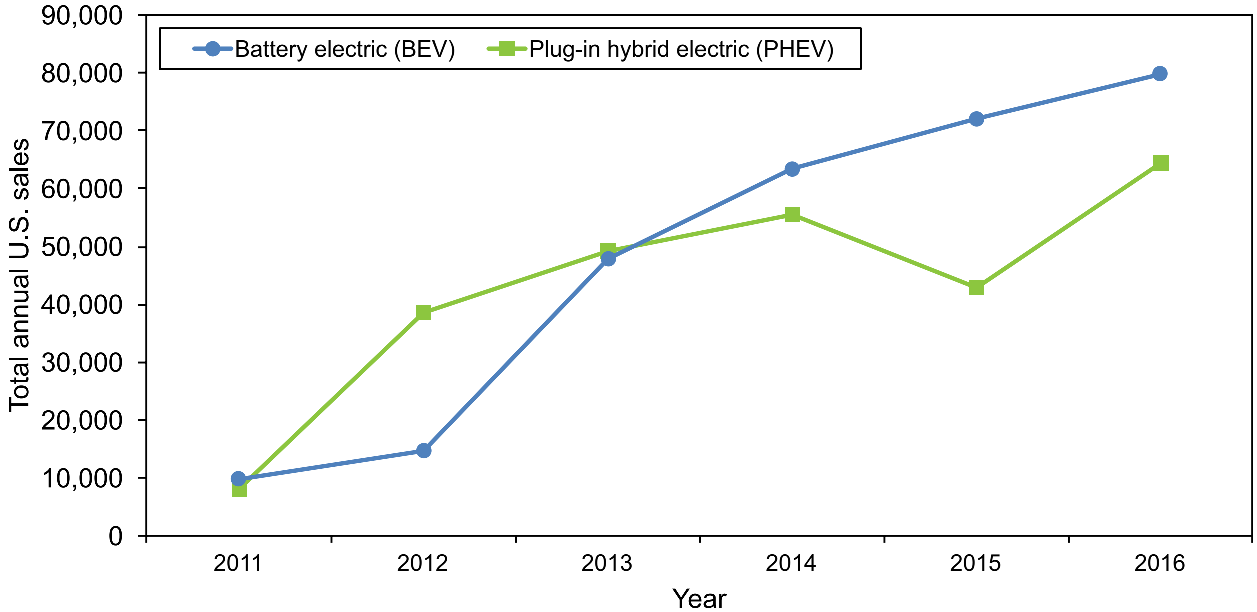


Figure 2. Sales trends for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) from 2011 to 2016 (AFDC, 2017g).

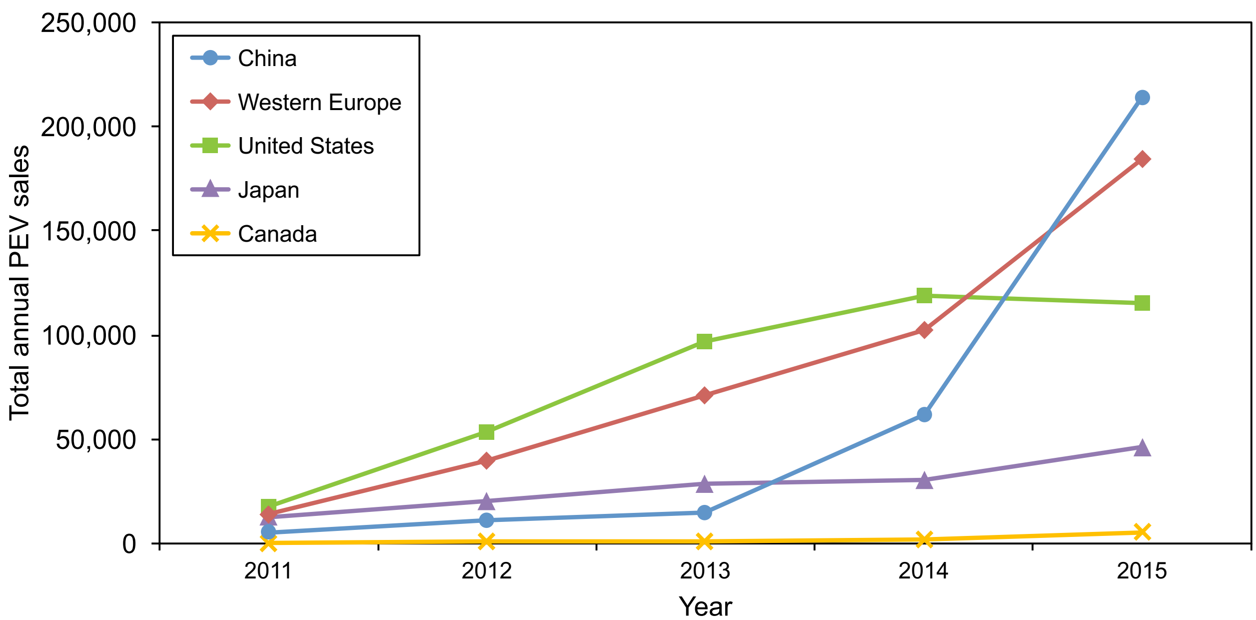


Figure 3. International sales trends for plug-in electric vehicles (PEVs) from 2011 to 2015 (DOE, 2016a).

In keeping with these trends, sales of PEVs are expected to continue climbing in the coming years. An analysis by the U.S. Energy Information Administration (EIA) projects that BEV sales in the U.S. will significantly surpass PHEV sales, totalling approximately twice the volume of BEVs as PHEVs by 2050 (EIA, 2017b). (However, a recent study by Axsen and Kurani [2013] suggests that more initial success may be achieved in gaining market share through the sale of small-battery PHEVs rather than BEVs. This pattern has already been observed in Europe, with PHEVs outselling BEVs by a wide margin [EEA, 2016].) By 2025, the EIA analysis estimates that electric vehicle sales will make up about 9% of all light-duty vehicle sales. Figure 4 shows the projected sales estimates for BEVs and PHEVs from 2018 to 2050 (EIA, 2017b).

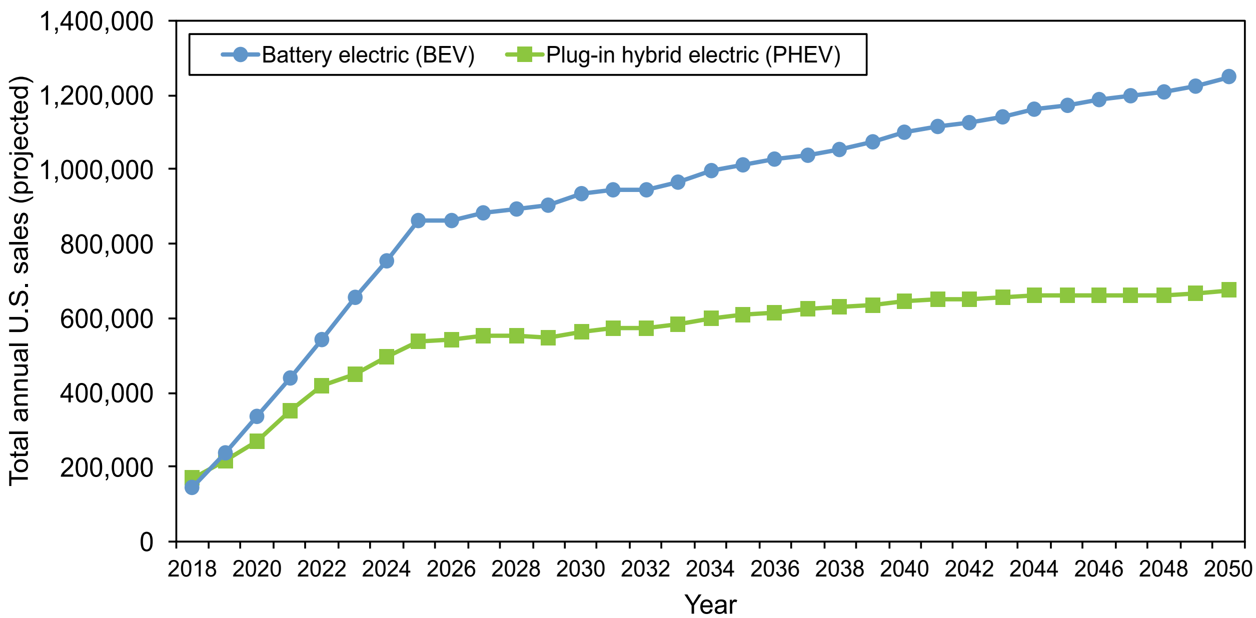


Figure 4. Projected sales estimates for BEVs and PHEVs in the U.S., 2018 to 2050 (EIA, 2017b).

Vehicle prices

The cost of PEVs has historically been higher, mostly due to the cost of developing the advanced technology and manufacturing required for such vehicles and their batteries (Wolfram and Lutsey, 2016). However, the median cost[3] of PEVs relative to the average cost of all new vehicles have slowly dropped, and for model year 2017, the differential between median vehicle costs was less than $10,000. A comparison of median new vehicle costs in the U.S. for the 2017

[3] The PEV costs discussed here have not been reduced by any of the available state or federal incentives, including the $7,500 (maximum) federal tax credit. Therefore, the actual cost of purchasing a PEV would likely be lower than the costs discussed here after including all available incentives.

model year for each vehicle type is shown in Figure 5. The prices of PEVs are expected to become comparable to prices for the average ICE vehicle in the next several years, especially in Europe (Forbes, 2017; Wolfram and Lutsey, 2016).

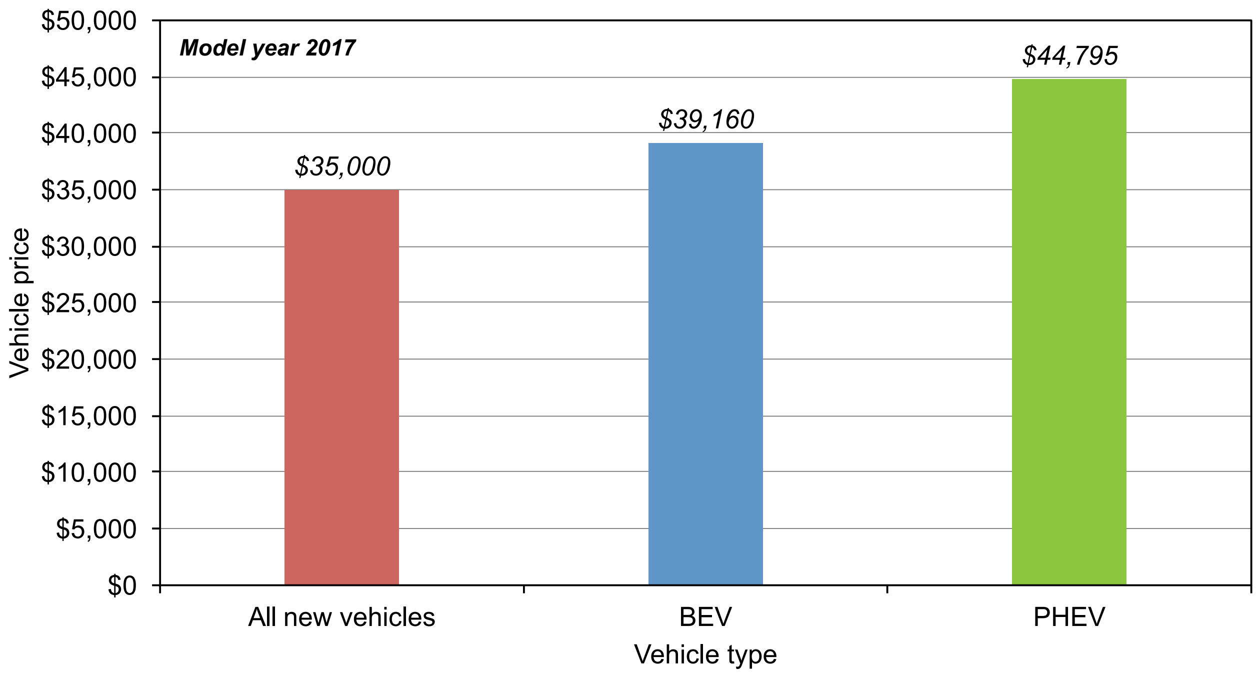


Figure 5. Median new vehicle prices for model year 2017 in the U.S., by vehicle type (Automotive News, 2016; Green Car Reports, 2017a, 2017b).

Vehicle fuel economy

The average fuel economy[4] of modern BEVs has always been substantially better than comparable conventional ICE vehicles. Compared to the average fuel economy of 22.8 mpg for current ICE vehicles,[5] the average available fuel economy of BEVs is more than 4.5 times higher, averaging 103.0 mpge (miles-per-gallon equivalent). Furthermore, the range of minimum and maximum fuel economies for each vehicle type do not overlap; ICE vehicles range from 11 to 39 mpg, and BEVs from 72 to 136 mpge.

When operating in charge-sustaining (CS) mode with only gasoline being consumed, PHEV efficiency performance averages 33.8 mpge, falling slightly above that of ICEs, but well

[4] Fuel economy of electric vehicles is expressed in miles-per-gallon-equivalent (mpge). The calculation of mpge is based on the equivalent mpg that would be required for a gasoline-powered ICE to emit the same level of GHGs, based on the average amount of GHGs emitted to generate each unit of electric energy (e.g., kWh).
[5] Average (non-sales-weighted) combined city/highway window sticker values for model year 2017 (EPA, 2017a).

below BEVs; when operating in charge-depleting (CD) mode, these vehicles average 80.1 mpge, slightly below most BEVs. Argonne National Laboratory estimates that PHEVs are operated approximately 50% of the time in each mode (ANL, 2015). A comparison of fuel-economy trends by model year for each vehicle type is shown in Figure 6.

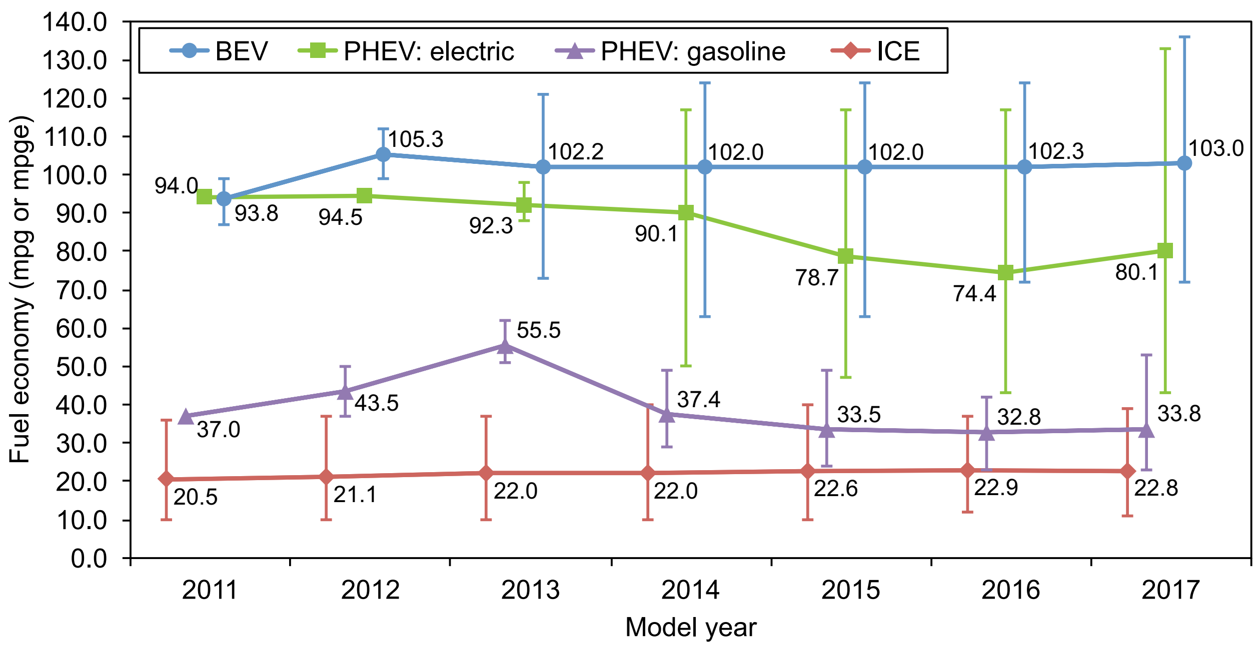
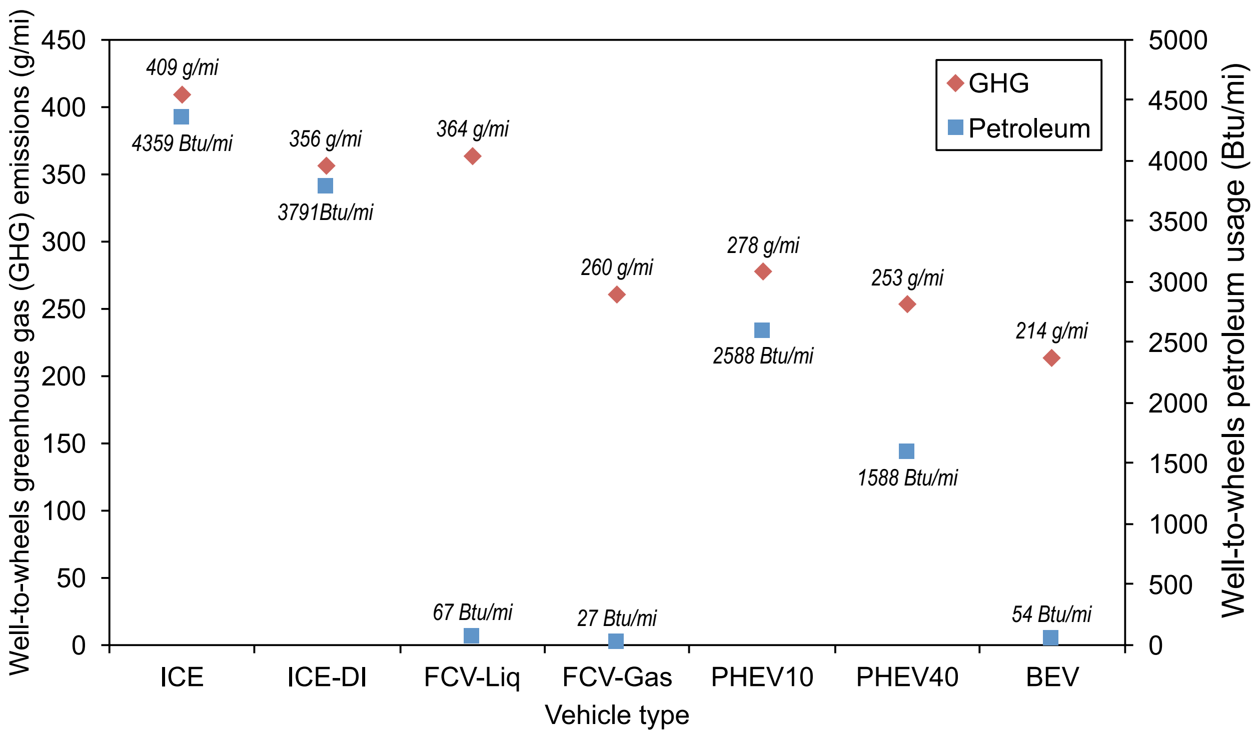


Figure 6. A comparison of fuel-economy trends (combined city/highway window-sticker value [EPA, 2017a]) by model year for each vehicle type. The symbols mark the average fuel-economy value for each vehicle type, while the ranges represent the minimum and maximum fuel-economy values. The graphs for the different vehicle types within each model year have been staggered to help illustrate any overlap between each set of fuel economy values.

Well-to-wheels GHG emissions and petroleum usage

The following well-to-wheels calculations use the GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation; 2015 release) developed by Argonne National Laboratory for model year 2015 passenger cars to calculate GHG emissions and petroleum usage during vehicle operation (ANL, 2015). Well-to-wheels calculations estimate the GHG emissions resulting from: (1) the production and delivery (well-to-pump), and (2) the final consumption (pump-to-wheels) of a particular fuel or energy source. As such, well-to-wheel results do not include GHG emissions or petroleum usage during the vehicle manufacturing process. A comparison of well-to-wheels GHG emissions and petroleum usage for each vehicle type is shown in Figure 7.



<u>Notes:</u> ICE = gasoline-powered, spark-ignited ICE
ICE-DI = gasoline-powered, spark-ignited ICE with direct fuel injection
FCV-Liq = fuel-cell vehicle using liquid hydrogen
FCV-Gas = fuel-cell vehicle using gaseous hydrogen
PHEV10 = PHEV capable of at least 10 miles on battery power alone
PHEV40 = PHEV capable of at least 40 miles on battery power alone

Figure 7. A comparison of well-to-wheels GHG emissions and petroleum usage for each vehicle type based on the GREET model (ANL, 2015). For comparison, two types of PHEV are modeled. Results for fuel-cell vehicles (FCVs) have also been included to show the relative performance of both nonhydrocarbon-based alternative-fuel-powered vehicles that are available to the public (i.e., electricity and hydrogen).

Based on the average mix of renewable and nonrenewable electric power sources in the U.S.,[6,7] the average well-to-wheels GHG emissions for BEVs is the lowest, at 214 g/mi. The corresponding values for two different PHEV implementations—PHEV10 and PHEV40—range

[6] The implications of this average mix of electric power sources is discussed in the *Fuel production and renewable power sources* subsection on pages 23-24 of this report.
[7] Well-to-wheel GHG emissions and petroleum usage by BEVs occurs almost entirely during the well-to-pump stage (i.e., electricity generation and transmission), with no GHG emissions occurring at the vehicle (i.e., pump-to-wheels), and negligible petroleum usage at the vehicle for lubrication, etc.

from 253 to 278 g/mi, respectively. Gasoline-powered vehicles produce the most GHGs per mile, ranging from 356 to 409 g/mi, depending on the specific type of ICE (direct fuel injection versus conventional port fuel injection, respectively). The results of this GREET model indicate that a typical BEV emits approximately half the amount of GHGs as a typical fuel-injected ICE. A study by the European Environment Agency (EEA, 2016) estimates that BEV GHG emissions could be reduced by a factor of 10 if completely renewable power sources were used.

When total well-to-wheels petroleum usage is compared (in British thermal units [Btu]), there are also significant improvements for both PEV types versus conventional ICE vehicles. For example, BEVs use the least amount of petroleum at 54 Btu/mi, with a typical PHEV40 vehicle model ranking the second lowest in usage at 1588 Btu/mi, and a typical PHEV10 vehicle model using the third lowest amount at 2588 Btu/mi. Predictably, gasoline-powered vehicles use considerably more petroleum per mile, with direct fuel injection ICEs averaging 3791 Btu/mi and traditional fuel-injection ICEs averaging 4359 Btu/mi. While the PHEV40 consumes 29 times the amount of petroleum a typical BEV consumes, a typical fuel-injected ICE still consumes nearly 3 times the amount of petroleum as a PHEV40 (and around 80 times as much as a BEV). Future development of PHEV models with longer electric-only ranges will further improve the overall PEV emissions and petroleum-consumption advantages over ICEs, while also narrowing the gap between BEV and PHEV electric-only driving ranges and efficiency.

Driving range, charging time, and range anxiety

The average driving range of current BEVs is less than half that of PHEVs operating in combined gasoline and electric mode (187 miles versus 462 miles, respectively) (EPA, 2017a). However, BEVs significantly outdistance the range of current PHEVs operating in electric-only mode (i.e., charge depleting), achieving more than 7 times the range on average (187 miles versus 26 miles, respectively) (EPA, 2017a). Figure 8 shows the average driving ranges of each vehicle type and operating mode, as well as the range of minimum and maximum distances, for each recent model year. While the combined gas and electric ranges of PHEVs tend to be much greater than BEVs, in recent years the BEV with the longest outperforms the PHEV with the overall shortest range by a large margin (335 miles versus 180 miles, respectively); conversely, the PHEV with the longest range when operating in electric-only mode can now outdistance the BEV with the lowest range by 38 miles (97 miles versus 59 miles, respectively).

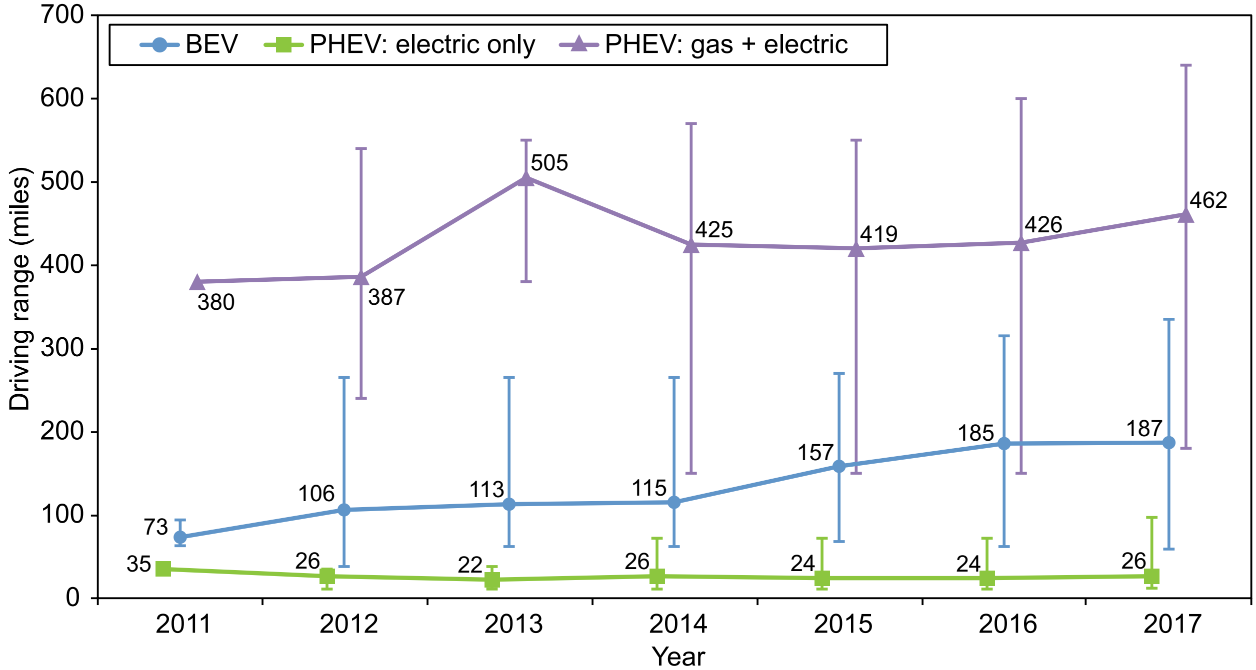


Figure 8. A comparison of average driving distances by model year for each vehicle type and (for PHEV) operating mode. The symbols mark the average driving range for each vehicle type and driving mode, while the ranges represent the minimum and maximum driving ranges (EPA, 2017a). The graphs for the different vehicle types within each model year have been staggered to help illustrate any overlap between each set of driving ranges.

For a discussion of the current challenges related to charging time versus driving range, see Schoettle and Sivak (2016). As described in SAE (2011), charging performance approaching that of DC Level 3 (<10 min to charge to 80%) would generally alleviate the limitations (in terms of both performance and public acceptance) imposed by long charging times for BEVs relative to most other vehicle/fuel combinations. However, charge times for recent models of BEVs and PHEVs have converged somewhat, with BEV charge times improving to just under double the required charging time for a PHEV (4.8 hours versus 2.8 hours, respectively). Figure 9 shows the recent trends for charging times by vehicle type. While BEVs require approximately twice as much charging time, on average they are capable of more than seven times the driving range of PHEVs, as previously illustrated in Figure 8 (187 miles versus 26 miles, respectively). Furthermore, the slowest charging PHEV (5 hours) now requires about the same amount of time as the average BEV (4.8 hours), and the best BEV (3.5 hours) is approaching the charge time of the average PHEV (2.8 hours).

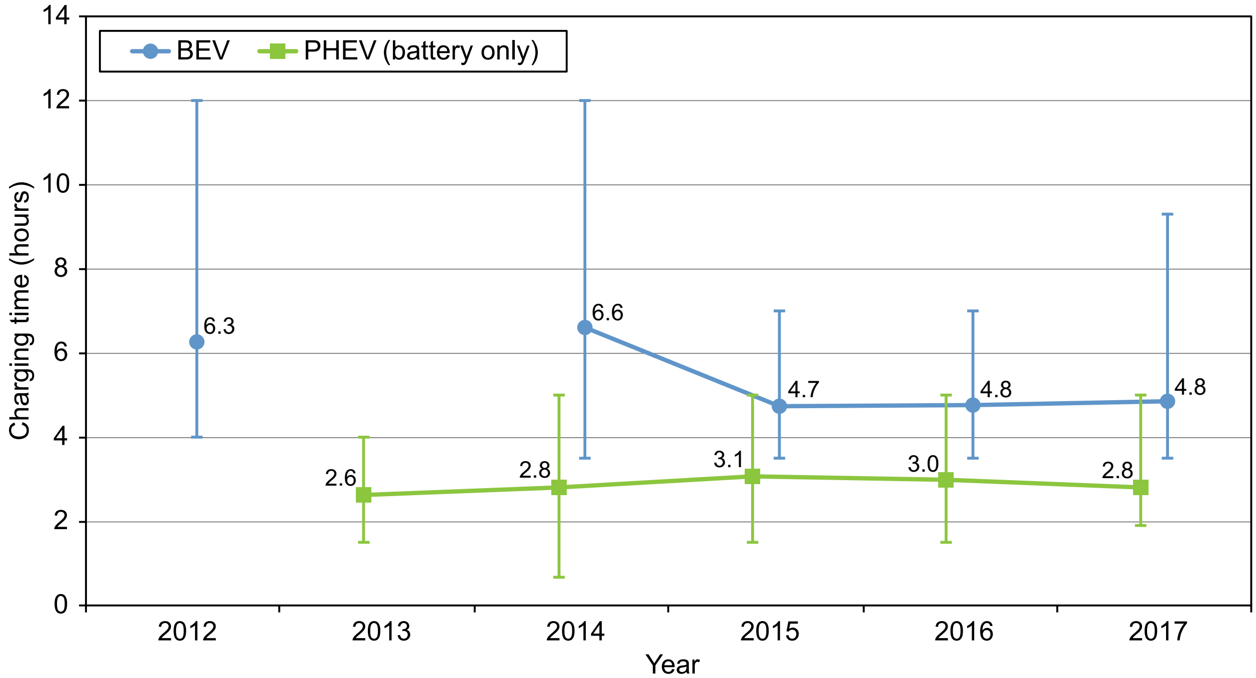


Figure 9. A comparison of average charging times (in hours @ 240V) by model year for each vehicle type. The symbols mark the average charging time for each vehicle type, while the ranges represent the minimum and maximum charging times (EPA, 2017a). The graphs for the different vehicle types within each model year have been staggered to help illustrate any overlap between each set of charging times. Data were not available for years with missing values.

Recent improvements in range and charging times for both vehicle types move closer to wider acceptance based on the ability to satisfy the daily driving requirements of most drivers while lessening the overall range anxiety that plagued PEVs (particularly BEVs) when first introduced. Two separate studies concluded that the current performance (or expected near future performance) of BEVs and PHEVs is now more capable of meeting the daily travel needs (based on daily vehicle miles of travel [VMT]) of a majority of U.S. drivers. FHWA estimates that BEVs with a range of at least 120 miles would be able to cover 99% of all household vehicle trips (FHWA, 2016). An analysis conducted by Argonne National Laboratory (Elgowainy, Han, Poch, Wang, Vyas, Mahalik, and Rousseau, 2010) estimated that a PHEV with an all-electric range of 30 miles (PHEV30) would be able to replace more than half (54%) of all daily VMT for trips by U.S. drivers operating on battery power only (i.e., charge depleting or CD mode). Figure 10 reproduces Figure 3.8 (based on data in Table 3.4) from that report, showing the model developed by ANL and the corresponding percentages of daily VMT in the U.S. that could be replaced with PHEVs operating in CD mode, based on various PHEV driving ranges in CD mode. Based on the ANL analysis, a PHEV40 would be capable of replacing around 62% of daily VMT in the U.S., while a PHEV100 would be able to replace around 89% of daily VMT.

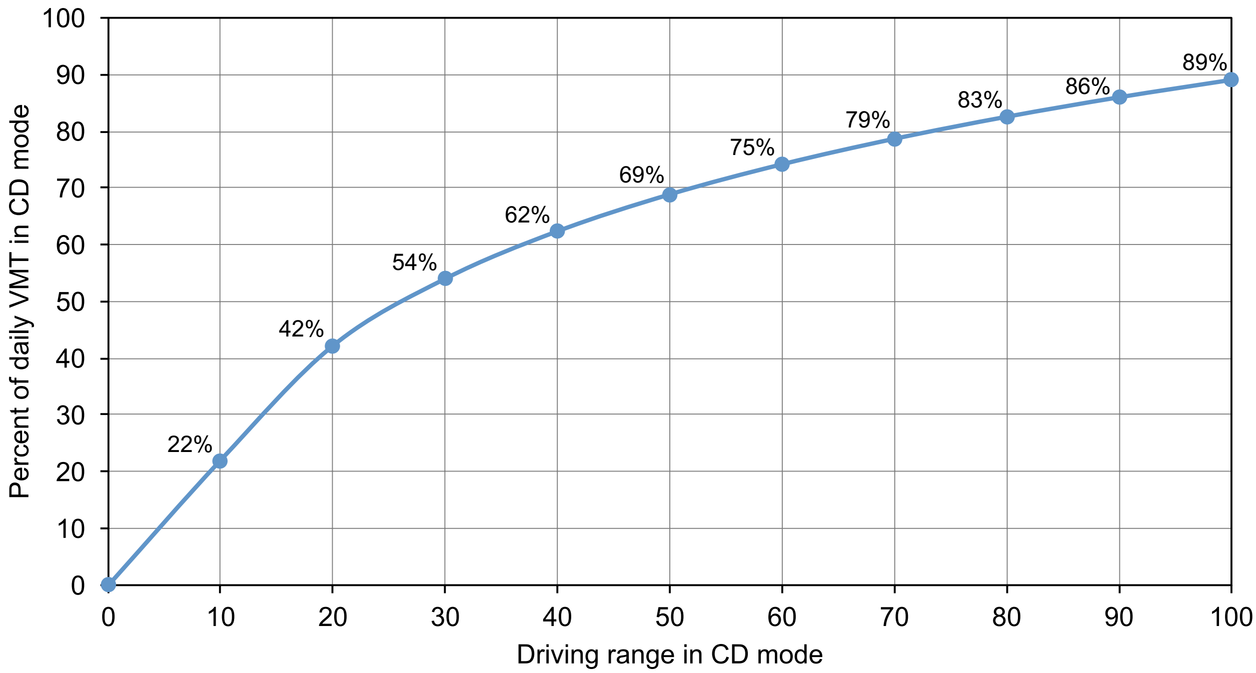


Figure 10. Percentage of daily VMT available for replacement by a PHEV in CD mode (reproduced from Elgowainy et al., 2010).

Energy density and battery cost

Current automotive lithium-ion battery packs contain approximately 1.1 MJ/L (300 Wh/L) (OECD/IEA, 2016), or 1/32 the volumetric energy density of a similar volume of liquid gasoline. The energy per mass (i.e., gravimetric density or specific energy) of relatively heavy batteries remains at approximately 0.5 MJ/kg (150 Wh/kg) (DOE, 2013; Young, Wang, Wang, and Strunz, 2013), compared with 44 MJ/kg for gasoline, which translates to 88 times less energy density by mass than gasoline. However, achieving equal energy density may not be required, as several estimates suggest that achieving 350 Wh/kg or better (still more than 30 times less energy dense than gasoline) would enable BEVs to generally replace gasoline-powered ICE vehicles for most U.S. drivers (DOE, 2013; Nature, 2015). One study estimates that the ability of batteries to equal gasoline performance as an energy source may occur as soon as 2045, primarily due to future powertrains with greater efficiency and less mass than comparable ICE vehicles (Vijayagopal, Gallagher, Lee, and Rousseau, 2016).

Matching the rapid increase in battery energy density has been the rapid decrease in battery cost. Battery cost ($/kWh) dropped by 80% over six years, to around $250/kWh in 2015, and then to approximately $200/kWh by 2016 (McKinsey, 2017; OECD/IEA, 2016). Several estimates expect the cost to drop below $200/kWh in the next several years (McKinsey, 2017; OECD/IEA, 2016), although some manufacturers claim to have already achieved this goal (Electrek, 2017).

Summary of key vehicle-specific aspects of BEVs and PHEVs

Table 4 summarizes several key vehicle-specific aspects of battery electric vehicles and plug-in hybrid electric vehicles. Current ICE vehicle technology is presented for comparison to the alternative vehicle types.

Table 4
Relevant aspects of vehicle performance for model year 2017 battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV).

Aspect	Current ICE	Battery electric (BEV)	Plug-in hybrid electric (PHEV)
Fuel type	Gasoline	Electricity	Gasoline + electricity
Number of vehicle models available	283	23	23
Average vehicle price	$35,000	$39,160	$44,795
Average fuel economy	22.8 mpg	103.0 mpge	33.8 mpge (gasoline) 80.1 mpge (electric)
Fuel economy range	11 – 39 mpg	72 – 136 mpge	23 – 53 mpge (gasoline) 43 – 133 mpge (electric)
Effective cost per mile	$0.10	$0.04	$0.07 (gasoline) $0.05 (electricity)
Well-to-wheels GHG emissions (g/mi) [8]	356 – 409	214	253 – 278
Well-to-wheels total petroleum usage (Btu/mi) [8]	3791 – 4359	54	1588 – 2588
Driving range (average)	475 mi	187 mi	26 mi (electric) 462 mi (combined)
Driving range (min – max)	381 – 716 mi	59 – 335 mi	12 – 97 mi (electric) 180 – 640 mi (combined)
Time to refuel/recharge	~ 5 min	~ 30 min, 80% charge (DC Level 2) ~ 5 hr, 100% charge (AC Level 2)	~ 5 min (gasoline) ~ 3 hr, 100% charge (electricity; AC Level 2)
Availability of qualified mechanics	Yes	Limited	Limited
Availability of qualified emergency responders	Yes	Yes	Yes
Vehicle maintenance issues [9]	-	• Lower maintenance than ICE • Possible battery replacement required during vehicle lifetime	• Similar routine maintenance as for ICE • Possible battery replacement required during vehicle lifetime • More technologically complex than ICE or BEV

[8] GREET 2015 release, using default settings for model year 2015 passenger cars (ANL, 2015).
[9] AFDC (2014).

Charging infrastructure

Current and future availability

With the ability to tap into the existing electrical grid, the electricity required for BEV charging is readily available in most commercial and residential settings. However, for the more advanced AC Level 2 (current standard) and DC Fast Charging,[10,11] installation of special charging equipment is required. Approximately 16 thousand public charging stations (individual charging sites) offering nearly 43 thousand charging outlets (individual charging connectors/plugs) are currently available across the U.S. (AFDC, 2017a). As is evident in Figure 11, the number of publicly available charging stations has grown rapidly since 2011. For comparison, there are approximately 112 thousand individual gasoline stations covering all 50 states and the District of Columbia (U.S. Census Bureau, 2015).

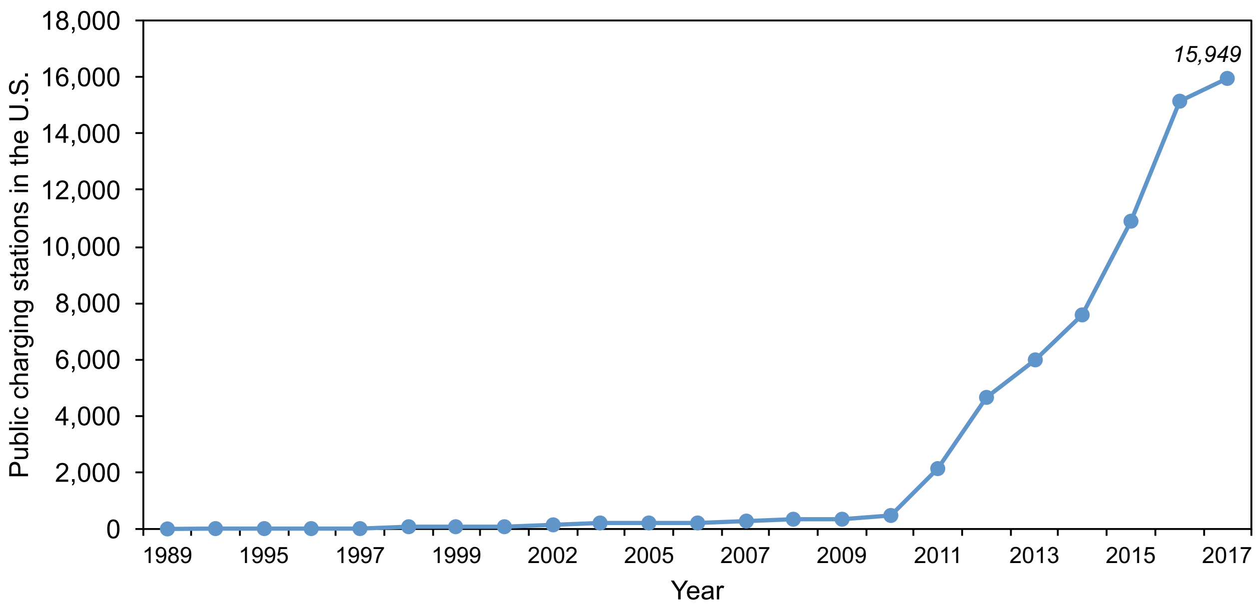


Figure 11. Public charging stations available in the U.S. (as of May 22, 2017) (AFDC, 2017a).

Table 5 summarizes the availability of charging levels at public stations in the U.S., while Figure 12 shows the breakdown of connector types (and related charging levels) available at

[10] For detailed descriptions of each charging level and type of connector, see AFDC (2017b) and SAE (2011). For a summary of international standards and charging equipment, see Green Transportation (2017).
[11] DC Fast Charging is expected to replace AC Level 2 charging as the prevailing standard for future vehicles (IHS Markit, 2013).

these stations. While J1772 with AC Level 2 is currently the most common connector and standard combination in the U.S., various forms of DC Fast charging (although with varying connector types) are offered at 36% of public stations, making up 13% of all public charging connections. (This discrepancy is due to the fact that stations offering multiple connection types tend to offer more of some types than others.)

Table 5
Charging levels and number of physical connections available at public stations in the U.S. (as of May 22, 2017) (AFDC, 2017a). Note: Some stations offer more than one level of charging.

Charging standard (level)	Stations	Connections
AC Level 1	1,482	2,924
AC Level 2	14,433	34,148
DC Fast	2,080	5,607
Inductive (wireless)	63	81

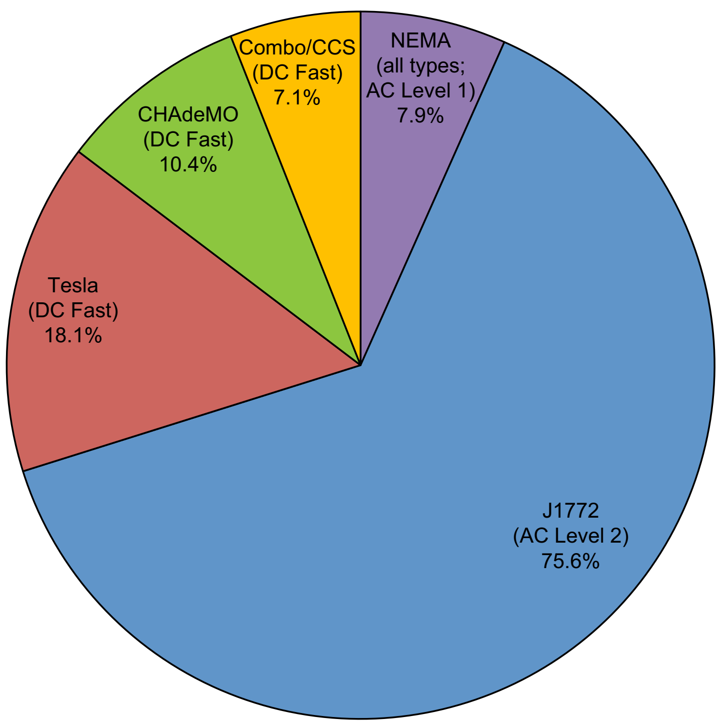


Figure 12. Percentage of public charging stations in the U.S. offering each connector type and associated charging level (as of May 22, 2017) (AFDC, 2017a). (Inductive or wireless charging, while still requiring specially equipped vehicles and EVSEs, is not shown here because it does not require a unique physical connection.) Note: Some stations offer more than one connector type.

Figure 13 shows the general distribution of public charging stations within the U.S., by state. The distribution of charging stations across the U.S. is strongly positively correlated with state population size, $r(49) = 0.867$, $p < .001$, as states with larger overall populations tend to have proportionally more public charging stations. Furthermore, within each state, public charging stations also tend to cluster around large population centers, dropping in density in less populous, more rural areas. Figure 14 illustrates the high density of public charging stations around population centers (and correspondingly low density of stations in more rural areas) for an example region and metropolitan area—the western U.S. (top pane) and the Los Angeles metropolitan area (bottom pane).

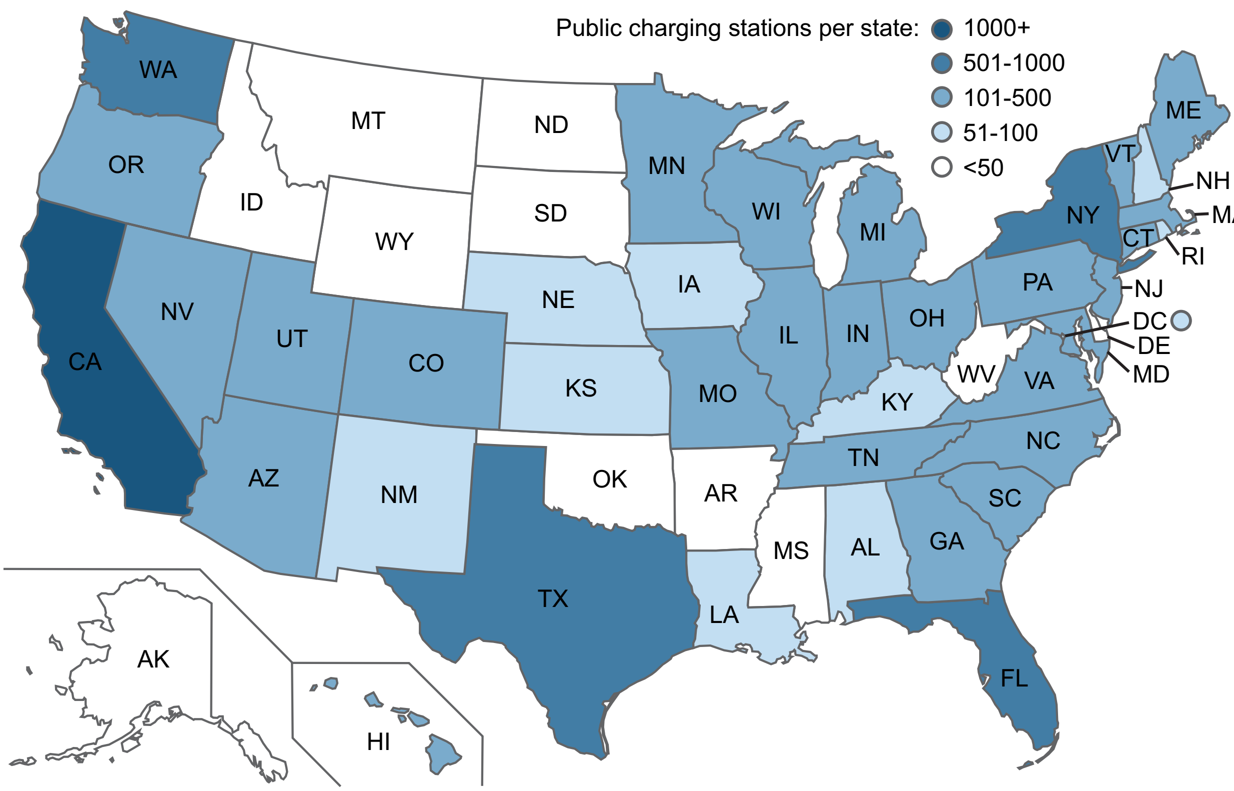


Figure 13. Distributions of public charging stations within the U.S., by state (AFDC, 2017a).

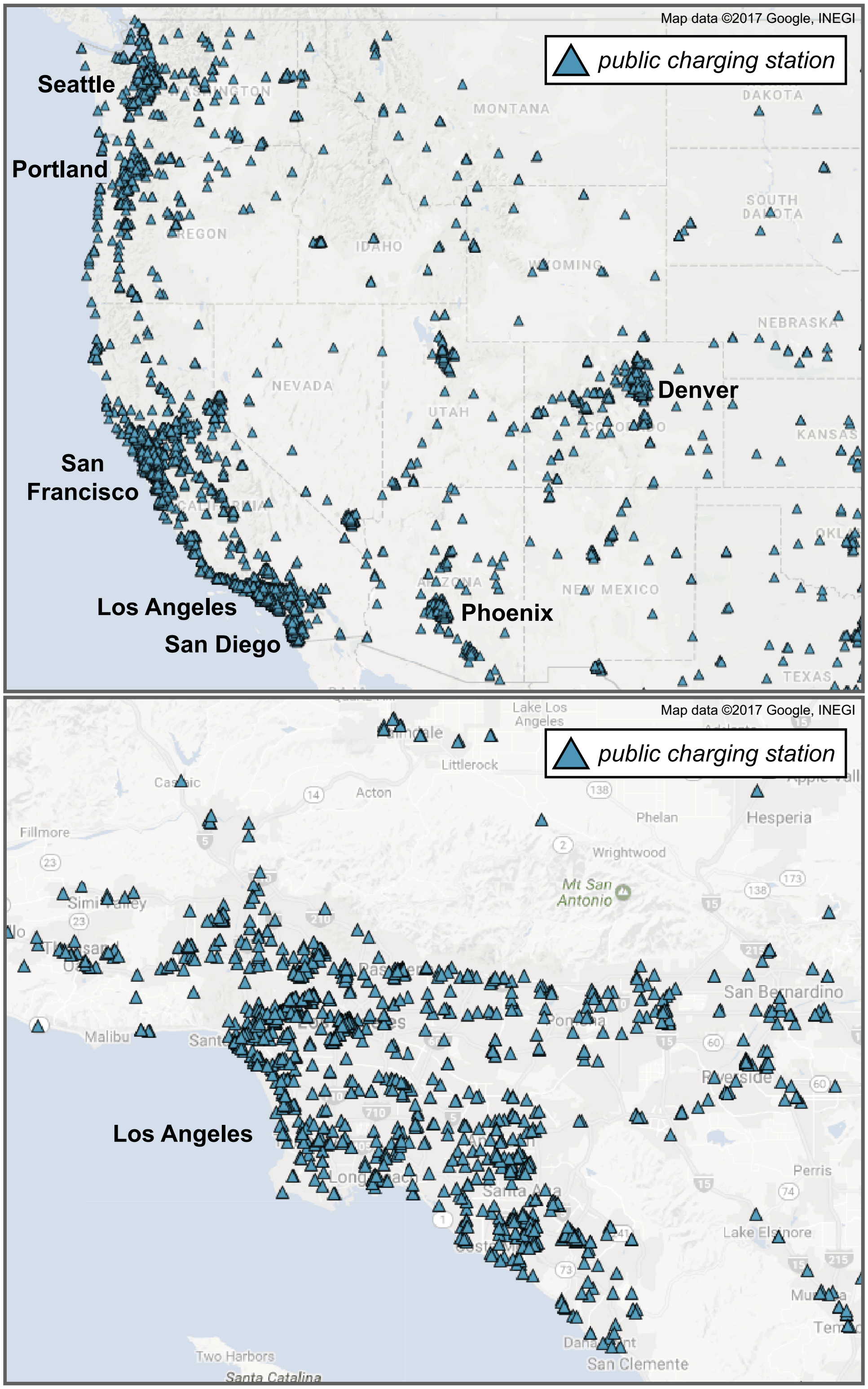


Figure 14. Distributions of public charging stations relative to population centers versus rural areas (Top pane: western U.S., bottom pane: Los Angeles metropolitan area) (AFDC, 2017a). In each pane, examples of large population centers have been labelled.

Expansion of the BEV charging network is relatively inexpensive, costing approximately $1,000 for home-based charger installation, and ranging from approximately $5,000 to $50,000 for public charging station units (Green Car Reports, 2016; Inside EVs, 2014; Plug In America, 2017; Wolfram and Lutsey, 2016). For comparison, the cost of installing a gasoline station is typically in the range of $1 million to $2 million (NPC, 2012).

General availability of public charging stations may prove to be more important for BEVs than PHEVs, as drivers of PHEVs may often rely on the on-board ICE to power the vehicle when the battery runs low; there is also evidence that PHEV users tend to charge mostly at home, in the evening, relying less frequently on public charging than BEV users (DOE, 2014; Kelly, MacDonald, and Keoleian, 2012; Tal, Nicholas, Davies and Woodjack, 2013).

Fuel pricing trends and effective cost per mile

Because units of sale are not standardized across different fuel types (gallons of gasoline versus kWh of electricity), fuel pricing poses a challenge for customer acceptance and understanding when comparing different vehicles and fuel types. Furthermore, the conversion factors to the gasoline-gallon equivalent (GGE: the amount of an alternative fuel required to equal the energy in one gallon of gasoline) are generally not known or easily understood by most consumers.

For BEVs, 33.7 kWh of battery power is equal to the energy in 1 gallon of gasoline (AFDC, 2014). With a national average price of approximately $0.128/kWh and GGE conversion factor of 0.031 (GGE = kWh x 0.031; DOE [2017]), the current fuel cost[12] for charging a PEV is $1.21/GGE (AFDC, 2017). The average fuel economy for model year 2017 BEVs is 103.0 mpge, resulting in an effective cost per mile of $0.04. Analogously, the cost per mile for PHEVs is $0.05 when operating electrically in CD mode with an average fuel economy of 80.1 mpge, and $0.07 when operating on gasoline in CS mode with an average fuel economy of 33.8 mpge. For current gasoline-powered ICE vehicles, an average fuel economy of 22.8 mpg, coupled with a fuel price of $2.38 per gallon (AFDC, 2017d), results in a cost of $0.10 per mile. The average effective fuel cost per mile for current ICEs is approximately two and a half

[12] Per the AFDC (Department of Energy): "Electric prices are reduced by a factor of 3.4 because electric motors are 3.4 times more efficient than internal combustion engines" (AFDC, 2017d).

times the cost of operating a BEV, two times the cost of a PHEV operating only on battery power, or one and a half times the cost of operating a PHEV on gasoline.

Examples of the preceding calculations are shown below:

$$Fuel\ cost_{BEV} = \left(\frac{\$0.128/kWh}{0.031\ GGE/kWh}\right)/3.4\ = \$\mathbf{1.21/\mathit{GGE}}$$

$$Cost\ per\ mile_{BEV} = \left(\frac{\$0.128/kWh}{0.031\ GGE/kWh}\right)/103.0\ mpge = \ \$\mathbf{0.04/\mathit{mile}}$$

In addition to considerably lower fuel costs per mile, PEVs also have the advantages of price stability (i.e., lack of volatility) and projected slow increases in overall price. Figure 15 shows the recent price trends for both fuel types going back to April 2000, illustrating the significant volatility of gasoline prices during that time relative to electricity prices (AFDC, 2017d). From April 2000 through January 2017, the maximum price fluctuation for electricity (percentage difference between the minimum and maximum price per GGE) was 62% ($0.50) versus 253% ($2.80) for gasoline. Figure 16 shows the fuel prices for both fuel types projected out to 2050 (EIA, 2017a). The EIA projects that the price of electricity (in 2016 $/GGE) will increase by less than $0.50 over the next 30 years (possibly even decreasing toward the end of that period), while the price of gasoline is expected to increase by more than $1.00 per gallon during that same time.

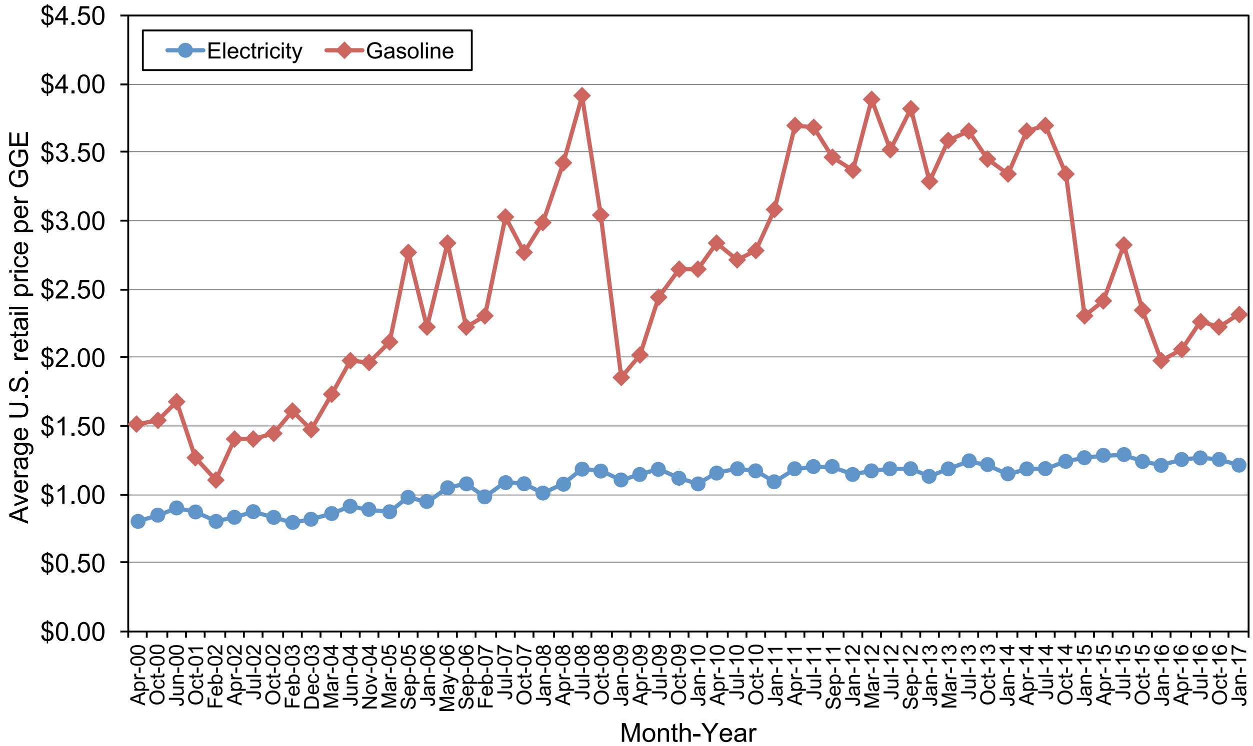


Figure 15. Recent trends in fuel pricing (in $/GGE) for gasoline and electricity (AFDC, 2017d).

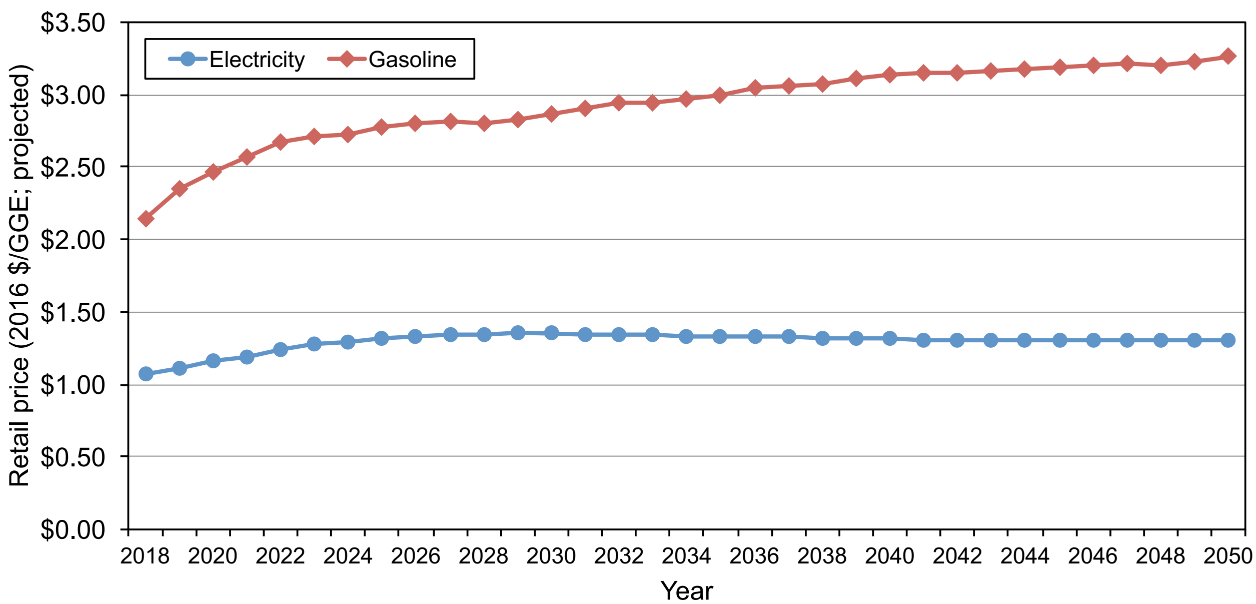


Figure 16. Projected fuel pricing (in 2016 $/GGE) for gasoline and electricity (EIA, 2017a).

Fuel production and renewable power sources

As discussed earlier in this report, the well-to-wheels GHG emissions and petroleum usage for BEVs and PHEVs are both considerably lower than for comparable ICE vehicles. However, analysis of emissions for these vehicle types assumes an average mix of various power sources for electricity generation.[13] Table 6 lists the average distribution of energy sources for electricity generation in the U.S. (LLNL/DOE, 2017), with renewable sources listed in bold. (Although nuclear power does not result in any GHG emissions, the uranium used in such power plants is considered nonrenewable [EIA, 2016]. There is also some debate regarding the extent to which biomass is truly carbon-neutral, and thus renewable [Cho, 2016].)

Considering that 86% of electricity in the U.S. comes from nonrenewable sources, and 65% comes from GHG emitting fuels, the cleaner average nature of BEVs and PHEVs can be improved considerably by increasing the use of renewable fuels (and/or nuclear) to generate electricity across the U.S. As a result of the variability across the country regarding the specific sources of electricity generation, the overall cleanliness of PEVs relative to ICEs can differ considerably based on where (state, county, etc.) the vehicle is driven and charged (CityLab, 2015; Scientific American, 2012). A report by the European Environmental Agency (EEA, 2016) estimates that current BEV GHG emissions could be reduced by a factor of 10 if completely renewable power sources were used.

A practical option to increase the use of renewable fuels for generating electricity specifically for vehicle charging involves integrating solar-powered stations to supply electricity directly to the ESVEs within a specific charging station or location (Bloomberg, 2017; CleanTechnica, 2016; HybridCars.com, 2014).

[13] The resultant emissions from this average mix of power sources also determine the mpge of vehicles that operate on electric power. The calculation of mpge is based on the equivalent mpg required for a gasoline-powered ICE to emit the same level of GHGs, based on the average amount of GHGs emitted to generate each unit of electric energy (e.g., kWh).

Table 6
Average distribution of energy sources for electricity generation in the U.S. (LLNL/DOE, 2017). Renewable energy sources are listed in **bold**.

Energy source	Percent
Coal	37.6%
Natural gas	26.3%
Nuclear	21.9%
Hydro	**6.3%**
Wind	**4.8%**
Biomass	**1.4%**
Petroleum	0.7%
Solar	**0.7%**
Geothermal	**0.4%**
TOTAL	*100.0%*

Smart or intelligent charging

A survey conducted last year revealed that many "smart" or "intelligent" charging functions in development are desired or expected by vehicle users when charging a PEV (Schoettle and Sivak, 2016). In general, scenarios that enable consumers (or the PEV itself) to exercise greater control and management over vehicle charging were given a higher preference level than those that offer greater convenience. A partial list of smart-charging functions includes plug-and-charge (automatic payment authorization), eVehicle roaming (prenegotiated billing agreement that is applicable most places the vehicle is publically charged), optimized load management (balancing of charging cost versus real-time demand), and vehicle-to-grid applications (ability to use vehicle to supply power back to the grid in exchange for compensation—also called reverse charging).

However, the currently competing protocols[14] to fully enable such smart charging—ISO 15118 and SEP 2.0—are also still in development, and do not always equally satisfy the expectations of PEV users. Table 7 (from Schoettle and Sivak, 2016) shows a comparison of charging scenarios in terms of support by current protocols (i.e., ISO 15118 and SEP 2.0) and consumer expectations (based on ranking of relative importance). Two of the top four most

[14] For additional details and discussion of these smart charging protocols, see Schoettle and Sivak (2016).

important scenarios to consumers are not currently supported by the SEP 2.0 protocol, and the remaining two scenarios are only partially supported. However, all of the top four scenarios are currently supported by the ISO 15118 protocol. Furthermore, the remaining two applicable charging scenarios in Table 7, although ranked as least important, are (or will be) at least partially supported by both protocols.

Table 7
Comparison of charging scenarios, support for such scenarios by current protocols, and consumer preferences (relative importance based on rank), sorted by rank (from Schoettle and Sivak, 2016).

Charging scenario	Supported by protocol? ISO 15118	Supported by protocol? SEP 2.0	Relative importance to consumers (rank)
Optimized load management	✔	✔ (partial)	#1
Plug-and-charge	✔	✖	#2
eVehicle roaming	✔	✖	#3
Optimized load management to maximize renewable energy usage	✔	✔ (partial)	#4
Optimized load management for home area networks	✔ (partial)	✔	#5
Vehicle-to-grid (V2G) energy source	✔*	✔	#6
Inductive (wireless) charging	n/a	n/a	#7

✔ = Fully supported ✔ (partial) = Partially supported ✖ = Not supported

✔* = Fully supported in a future revision

V2G (vehicle-to-grid) technology

Vehicle-to-grid (or V2G) functionality, likely a key component of future smart-charging systems, allows the exchange of power bidirectionally between the vehicle and the electrical grid, typically with an agreement that the vehicle owner may be compensated for supplying such energy, depending on the specific circumstances. A recent analysis concluded that a single vehicle using V2G technology could generate around $1,000 per year for the owner (Shinzaki, Sadano, Maruyama, and Kempton, 2015). In addition to the obvious monetary benefit to vehicle owners, IEEE estimates that if 1 million PEVs were connected, roughly 10,000 megawatts would be available ("about 20 average sized power plants") for V2G power exchanges (IEEE, 2012).

Summary of key aspects of fuel sources and related refueling infrastructure

Table 8 summarizes several key aspects of the underlying fuel sources for PEVs and the related refueling infrastructure. Gasoline and is presented for comparison to the alternative fuel sources.

Table 8
Relevant aspects of the fuel sources and charging infrastructure for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV).

Aspect	Current ICE	Battery electric (BEV)	Plug-in hybrid electric (PHEV)
Fuel type	Gasoline	Electricity	Gasoline + electricity
Refueling infrastructure	Yes	Electric grid readily available; charging station required for Level 2 or higher	Can use both BEV and ICE refueling infrastructures
Total number of existing and planned public refueling stations [15, 16, *]	112,458	15,949 (stations) 34,993 (connections)	
Home and/or workplace refueling	No	Yes	
Fuel price [17, 18]	$2.38 / gal	$1.21 / GGE $0.128 / kWh	Fuel properties of both gasoline and electricity apply for PHEVs
Gasoline-gallon equivalent (GGE) [19]	1 gal	33.7 kWh	
Flammable fuel	Yes	No	
High voltage	No	Yes	
Gravimetric energy density (MJ/kg) [20]	44	0.5	
Volumetric energy density (MJ/L) [20]	32	1.1	

[*] For BEV and PHEV recharging, stations are the physical sites that contain one or more connections (i.e., individual connectors or EVSEs); these counts do not include private (fleet or business) or residential chargers.

[15] U.S. Census Bureau (2015).
[16] AFDC (2017a).
[17] National average prices for gasoline and electricity, April 1 – April 17, 2017 (AFDC, 2017d).
[18] AFDC (2014).
[19] EIA (2017c).
[20] OECD/IEA (2016).

Public opinion regarding PEVs

Public opinion is generally positive regarding acceptance of PEVs. For example, individuals have expressed an interest in PEV technologies over traditional ICE vehicles as gasoline prices climb (Schoettle and Sivak, 2015). Another recent study documented the fact that many vehicle owners would be interested in upgrading to more electrified vehicles, with many conventional ICE owners willing to consider purchasing a hybrid (including PHEV) and many hybrid owners willing to consider purchasing a BEV (Sivak and Schoettle, 2014). A survey of light-truck owners—a group traditionally opposed to PEVs—found that around 10% would consider an all-electric light truck, and around 15% would consider an all-electric light truck of the same make/model as their current light truck (Schoettle and Sivak, 2017). (Similar views about interest in PEV ownership were also expressed by passenger-car owners in that survey.)

Government support

Support from the U.S. government for both alternative fuel types and vehicle types is relatively strong.[21] In 2015, funding support for battery research and development was approximately $80 million (DOE, 2016b). Several goals of this research for electric vehicle batteries include the following targets for 2020: reduce cost by a factor of four, reduce size by factor of two, reduce weight by a factor of two (or more), all in an attempt "to more than double the battery pack energy density (from 100 Wh/kg to 250 Wh/kg)" (DOE, 2016b).

In addition to research funding, various government agencies at both the national and state level have enacted legislation specific to PEVs, often with the goal of encouraging or incentivizing vehicle owners (including government, commercial, and individuals) to consider purchasing PEVs. Such laws generally specify tax breaks, reduced cost of vehicle registration, rebates or grants for equipment installation, and other similar cost reductions to encourage the purchase of PEVs. One of the more significant incentives to encourage the purchase of a PEV is a federal tax credit of up to $7,500 (EPA, 2017b).[22] Table 9 shows the number of individual laws and incentives in place for the U.S. (National) and for each state.

[21] The government support as discussed in this report was established and/or provided under the previous federal government administration, and is less certain with the current administration. For example, future CAFE standards established with the previous administration will be re-reviewed and possibly modified or eliminated (EPA/NHTSA, 2017).

[22] Another significant, long-running incentive program that allowed for a tax credit of up to $1,000 for installing charging equipment expired at the end of 2016 (IRS, 2016).

Table 9
Number of PEV-related (BEV and PHEV) laws and incentives currently in place (as of May 22, 2017) (AFDC, 2017c).

State	PEV-related laws/incentives	State	PEV-related laws/incentives
National [23]	***26***	South Carolina	7
California	56	Wisconsin	7
Washington	21	Missouri	6
Colorado	18	Delaware	5
Illinois	16	Iowa	5
Arizona	15	Idaho	5
Maryland	15	Vermont	5
Connecticut	14	Alabama	4
Oregon	14	Maine	4
Massachusetts	13	New Mexico	4
Virginia	13	Pennsylvania	4
North Carolina	12	Washington, D.C.	4
Rhode Island	12	West Virginia	4
Utah	12	Wyoming	4
New York	11	Arkansas	2
Minnesota	10	Kentucky	2
Florida	9	Louisiana	2
Georgia	9	Nebraska	2
Hawaii	9	New Hampshire	2
Indiana	9	Tennessee	2
Nevada	8	Alaska	1
Ohio	8	Mississippi	1
Texas	8	Montana	1
Michigan	7	Kansas	0
New jersey	7	North Dakota	0
Oklahoma	7	South Dakota	0

[23] ***National*** includes all EV-related U.S. laws and incentives enacted on a national level, independent from individual state laws and incentives.

Key Findings

Vehicle availability and sales

- The number of individual PEV models available for purchase has increased rapidly recently, nearly doubling from model year 2016 to 2017.
- Sales of PEVs have also increased significantly in recent years, increasing by more than 700% in the U.S. since 2011. China and Europe have seen even larger increases in PEV sales in recent years.
- The prices of PEVs are slowly dropping and approaching prices that are similar to comparable ICE vehicles.

Fuel economy and emissions

- The fuel economy of both types of PEVs is substantially better than comparable gasoline-powered vehicles; PHEVs and BEVs average more than 3.5 times and 4.5 times better fuel economy, respectively, than ICE vehicles.
- Even PHEVs with the lowest electric-only ranges emit lower levels of GHGs and consume less petroleum (well-to-wheels) than comparable ICE vehicles.
- BEVs emit lower levels of GHGs and consume much less petroleum on average than comparable ICE vehicles or PHEVs. Additionally, BEVs would have the potential to be even cleaner if a higher percentage of energy sources used to generate electricity in the U.S. were renewable.

Batteries and charging

- Charging times have dropped slightly in recent years but are still much longer than refueling a gasoline-powered vehicle; however, PHEVs can operate on gasoline only so they do not require charging the same way a BEV does.
- Energy density of batteries is increasing while the cost ($/kWh) continues to decrease. Both trends enable increasingly less-expensive, longer-range, and faster-charging PEVs.

Driving range and range anxiety

- Maximum driving range, a significant factor in limiting BEV acceptance (based on so-called range anxiety for drivers), has improved in recent model years, with some of the longest-range BEVs capable of distances similar to some PHEV and ICE vehicles.
- The maximum driving range of PHEVs (which combines the gasoline and electric ranges) is already comparable to the range of most ICE vehicles.
- Some PHEVs are now capable of electric-only driving ranges that are longer than some of the lowest-range BEVs.
- Advances in battery performance and driving range may soon enable BEVs (and PHEVs operating on electricity) to replace conventional ICE vehicles for most U.S. drivers' daily trips.

Refueling infrastructure

- The infrastructure to enable PEV charging is readily available through the current electrical grid throughout the U.S. in both commercial and residential settings
- Charging is often available or can be installed at home or work (unlike ICE refueling).
- The number of public charging stations has grown very rapidly in recent years, with approximately 16 thousand currently available in the U.S. (supplying approximately 35 thousand individual connections).
- As one might expect, states with larger populations tend to have more public charging stations; correspondingly, areas of higher population density tend to have more stations than lower-density rural areas.
- The average mix of fuel sources for generating electricity in the U.S. is approximately 65% fossil fuels (coal, natural gas, and petroleum), while only around 14% is generated from renewable resources (the remainder of electricity in the U.S. comes from non-renewable nuclear power); BEVs (and PHEVs operating on electricity) can be even cleaner if electrical utilities could make greater use of renewable resources.

Fuel pricing

- Compared to gasoline, electricity prices have been remarkably low and stable for at least the past decade.
- Electricity prices are projected to remain relatively low and stable in comparison to gasoline prices over the next several decades.
- "Smart" charging can enable various advanced charging-related functions such as optimized balancing of charging prices versus demand. It can also allow for vehicle-to-grid (V2G) capabilities so that vehicle users are potentially able to supply (i.e., sell) electricity back to the grid as needed, based on the local demand for electricity at any given time.

Public opinion and government support

- Public interest in PEVs (as demonstrated by sales trends) has increased considerably in recent years.
- Users of most vehicle types would be more willing to consider a PEV if it were offered in their current vehicle type (car, pickup truck, etc.), with interest increasing if a PEV were offered in the specific make and model of their current vehicle.
- Government support has been relatively strong in recent years, especially for advanced battery R&D and in the form of financial incentives such as tax rebates. The federal government currently offers a $7500 (maximum) tax credit for the purchase of a PEV; all but three states offer some form of financial incentive for owning a PEV.

Summary

This report examined the current status and recent progress regarding various technical issues and issues related to public acceptance that have traditionally hindered the more widespread acceptance and adoption of plug-in electric vehicles (PEVs), which include both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). As a reference for comparison, information for current gasoline-powered internal combustion engines was also presented where appropriate.

The main issues explored in this report include:

- vehicle availability, including sales trends and costs
- fuel economy, GHG emissions, and petroleum usage
- batteries, charging time, driving range, and range anxiety
- charging infrastructure availability and smart charging
- public opinion and government support

Overall, recent advances and improvements in several of these areas have led to PEVs becoming increasingly more competitive with traditional gasoline-powered internal-combustion engine (ICE) vehicles. Furthermore, future costs of the vehicles and fuel, coupled with rising public interest and increasing numbers of charging locations, are expected to make such vehicles even more capable of replacing ICE vehicles for the majority of U.S. drivers in the relatively near future.

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