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National Economic Value Assessment of Plug-In Electric Vehicles

Volume I

December 2016

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While reviewer comments have significantly improved the study methodology and the articulation of results, some comments and suggestions could not be fully addressed or resolved given the limited scope of this study and availability of empirical or other sound data. Any shortcomings of the present study are the responsibility of the authors.

Abstract

The adoption of plug-in electric vehicles (PEVs) can reduce household fuel expenditures by substituting electricity for gasoline while reducing greenhouse gas emissions and petroleum imports. A scenario approach is employed to provide insights into the long-term economic value of increased PEV market growth across the United States. The analytic methods estimate fundamental costs and benefits associated with an economic allocation of PEVs across households based upon household driving patterns, projected vehicle cost and performance attributes, and simulations of a future electricity grid. To explore the full technological potential of PEVs and resulting demands on the electricity grid, very high PEV market growth projections from previous studies are relied upon to develop multiple future scenarios. The main Aggressive scenario expands the fleet to 73 million PEVs by 2035, approximating the level of market growth required to achieve deep greenhouse gas emission reductions in the light-duty vehicle sector. Variations on the Aggressive scenario include the Niche and Breakthrough scenarios with lower levels of PEV market growth (12 and 24 million PEVs by 2035, respectively), High Cost and Low Cost scenarios with higher and lower cost projections for all future light-duty vehicles, and High Oil and Low Oil scenarios with higher and lower gasoline prices by 2035. While the methodology does not assess the likelihood of different market growth scenarios, the Aggressive and Low Cost scenarios are the focus of the study, representing futures in which PEVs are widely adopted within mainstream households, reach optimistic cost reductions by achieving full economies of scale, and impose large demands on the electricity grid.

The methodology employed allows for an examination of the economic value of PEVs across nine census divisions of the continental United States. Private costs include the incremental cost of PEVs over conventional and hybrid electric vehicles, the cost of home charging equipment, and the cost of electricity used by PEVs. Private benefits are fuel savings as electricity is substituted for gasoline. The sum of these private costs and benefits is presented as the net private economic value of PEVs. Public costs are defined as including the cost of workplace and commercial charging equipment, as well as costs or benefits external to the market resulting from changes in greenhouse gas emissions and petroleum imports. Most cost input assumptions are taken from external studies, including relative future vehicle costs (standardized U.S. Department of Energy projections), charging equipment costs, gasoline prices and carbon intensity, and externality values for greenhouse gas emissions and petroleum imports. Electricity prices and carbon intensities, before and after strong PEV market growth, are determined within the study. A novel analytic contribution is the economic allocation of PEVs at the household level, which determines the miles driven per year per vehicle as different types of PEVs displace conventional gasoline vehicles. The sum of both private and public costs and benefits is presented as the total social economic value of increased PEV adoption. These economic values are determined by accounting for regional variations in miles driven per vehicle by household, variations in PEV performance due to climate, regional gasoline and electricity prices, and the future carbon intensity of electricity for different regions.

Results suggest positive total social economic value associated with increased PEV deployment, driven primarily by the private benefits of fuel savings. The net positive total social benefits for the Niche and Breakthrough scenarios are \$4.7 and \$9.3 billion per year by 2035, respectively. By comparison, the Aggressive and Low Cost scenarios have total social benefits estimated at \$26.5 and \$34.2 billion per year, respectively. Total private and social benefits vary significantly

by region, mostly due to variations in the relative cost of gasoline and electricity, as well as variations in total miles driven per year by PEVs. Macroeconomic analysis suggests that the Aggressive scenario, when compared to the Baseline scenario, generates approximately 52,000 additional jobs per year (average from 2015 to 2040) and a $6.6 billion increase in average annual gross domestic product from 2015 to 2040.

List of Abbreviations and Acronyms

A-VMT	annual vehicle miles traveled
AEO	Annual Energy Outlook
BAU	business-as-usual
BEV	battery electric vehicle
BLAST-V	Battery Lifetime Analysis and Simulation Tool for Vehicles
Btu	British thermal unit
CAFE	Corporate Average Fuel Economy
CI	carbon intensity
CMU	Carnegie Mellon University
CV	conventional vehicle
DCFC	direct current fast charger
DOE	U.S. Department of Energy
D-VMT	daily vehicle miles traveled
e-VMT	electric vehicle miles traveled
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EVSE	electric vehicle supply equipment
FUF	fleet utility factor
GDP	gross domestic product
GHG	greenhouse gas
HOV	high occupancy vehicle
IMPLAN	IMpact analysis for PLANing
kWh	kilowatt hour
L1	Level one (charger)
L2	Level two (charger)
LDV	light-duty vehicle
MMBtu	million British thermal units
MUD	multi-unit dwelling
MW	megawatt
MWh	megawatt hour
NHTS	National Household Travel Survey
NRC	National Research Council
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
ReEDS	Regional Energy Deployment System (model)
SERA	Scenario Evaluation and Regionalization Analysis (model)
U.S. DRIVE	United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
VMT	vehicle miles traveled

Executive Summary for Policymakers

The recent increase in the market adoption of plug-in electric vehicles (PEVs) is an opportunity to enhance the U.S. economy while reducing greenhouse gas (GHG) emissions and petroleum imports. Due to the relatively high efficiency of PEVs, the fuel savings achieved by substituting electricity for gasoline can help to compensate for any additional cost of PEVs compared to conventional or hybrid electric gasoline vehicles. These fuel savings can generate significant economic value to private households, while reductions in GHG emissions and petroleum imports can lead to significant public benefits. This national economic value assessment (NEVA) study examines this economic opportunity by developing multiple long-term scenarios in which PEVs achieve very high market share, the electricity grid continues to be decarbonized due to increased renewable generation capacity, and both PEVs and competing gasoline vehicle technologies experience strong technology progress in terms of reduced upfront costs and improved fuel economy.

Unique contributions of the NEVA study include novel modeling approaches to estimating PEV utilization within mainstream households, impacts on the electricity grid due to large PEV electricity demands, and regional variations in economic value across nine census divisions. Findings suggest that increased PEV market share generates net positive economic value at the census division level for private households. Major factors that contribute to variation across regions are variations in vehicle miles traveled (VMT) per year per vehicle and regional variations in electricity and gasoline prices. With the assumption that conventional, petroleum-based gasoline carbon intensities are stable into the future, results suggest that increased PEV market share also generates positive social benefits due to reductions in GHG emissions and petroleum imports.

PEVs include both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). PHEVs have both gasoline engines and batteries that can be recharged by connecting to an electrical outlet. BEVs have only batteries that are recharged by connecting to an electrical outlet. PEVs with larger batteries, and therefore longer electric drive capability, tend to have higher upfront costs than conventional vehicles (CVs) or hybrid electric vehicles (HEVs), both of which run exclusively on gasoline. The lower price per mile of electricity compared to gasoline tends to compensate for higher upfront costs, depending upon vehicle usage patterns, fuel economies, PEV type, and fuel prices. Future short-range BEVs—with a real-world range of 70 miles, for example—can have retail prices comparable to or lower than future gasoline CVs.

The main Aggressive scenario developed for this study assumes that 14 percent of all miles traveled by light-duty vehicles (LDVs) are electric-miles—hereafter referred to as e-miles or eVMT—from PEVs by 2035. This requires approximately 73 million PEVs to be deployed by 2035, which is 27 percent of the projected total LDV fleet in that year. These PEVs consist of 55 million PHEVs and 18 million BEVs, all with varying levels of electric range. This scenario is not developed as a prediction of future PEV market share but instead serves as a means of exploring the implications of strong PEV market expansion into mainstream consumer households and high demands on the electricity grid. Two scenarios with lower but still substantial degrees of PEV market adoption are also developed: the Niche scenario with 9 million PHEVs and 3 million BEVs, and the Breakthrough scenario with 18 million PHEVs and

6 million BEVs. Multiple additional scenarios explore variations around other key assumptions used to develop the Aggressive scenario.

The economic value of displacing CVs and HEVs with PEVs is estimated by taking into account projections of a range of future costs and benefits. Costs include any additional cost of PEVs over CVs and HEVs to consumers when purchased, as well as the cost of home, workplace, and commercial charging equipment. Fuel savings are the major private benefit and are determined as the difference between household gasoline costs without PEVs and household gasoline and electricity costs with PEVs. Social or public benefits include the value of GHG emission and petroleum import reductions, which are calculated using estimates of future externality prices.

The remaining sections of this executive summary review key aspects of the NEVA study. Section ES.1 reviews the problem statement and study scope, section ES.2 is a brief overview of the methodology, and section ES.3 reviews high-level valuation results and key scenario insights. This report is Volume I of the NEVA study, and it contains all of the major modeling assumptions and final results. A subsequent Volume II report will examine a broader range of sensitivities around modeling input assumptions and resulting influences on results.

ES.1 Scenario Approach and Research Objectives

Energy scenario modeling provides a means of exploring uncertain potential futures without the constraints and limitations of predictive forecasting models. Scenario methodologies can vary significantly, but generally provide value through the generation of new information or insights, integration of smaller parts into larger and internally consistent wholes, and formal means of ensuring consistency within or between scenarios (Börjeson et al. 2006). Scenarios can prove useful when used to support strategic and innovative thinking about major shifts or deviations from status quo or business as usual projections (Wack 1985; Laitner et al. 2003; Paltsev 2016). The main research question addressed in this scenario study is the following:

> *To what degree might PEVs benefit the U.S. economy over the long term, after market acceleration policies have subsided and PEVs have been adopted on a large scale, nationwide, and within mainstream consumer households?*

This question is of particular interest in the context of aggressive projections of PEV technology progress and high market share success. Though the scenario methodology employed here does not determine the likelihood of different levels of PEV market growth, exploring very aggressive market growth trends is useful as a means of improving our understanding of the following issues:

1. The capacity for PEVs to meet the driving needs of mainstream consumer households
2. Potential impacts on the grid resulting from large PEV electricity demands
3. The long-term value of continued technical progress with electric-drive and other advanced LDV technologies in terms of cost reductions and higher fuel economies
4. Future GHG emissions for PEVs relative to gasoline as regional electricity grids continue to decarbonize

5. Private and social benefits associated with a relatively stable PEV-success future, achieved after market transformation efforts required to sustain strong market growth have subsided
6. The degree to which PEVs may be able to contribute to future GHG emission reduction targets, such as an 80% reduction by 2050.

With respect to the first issue, PEVs can be an economic and suitable vehicle choice for some early adopter households today, especially in states with strong incentives in place and relatively high gasoline prices, such as California. In addition, the limited all-electric range of today's BEVs may be acceptable for particular early adopter consumer segments, such as households with a high frequency of short-distance trips and few long-distance trips. As battery and vehicle costs decline over time and with higher levels of production, BEVs may become suitable for the driving needs of a larger portion of mainstream consumer households across multiple states and regions. The second issue listed above concerns increased demands on the electricity grid. PEVs place only modest pressure on generation, transmission, and distribution systems today, with approximately 500,000 in cumulative PEV sales as of August 2016 (CAPEVC 2016), but significant pressure may result from PEVs being adopted on the scale of tens of millions of vehicles.

With regard to the third issue listed above, aggressive projections of future technological progress for LDV drivetrain technologies are of interest to better understand the full long-term technical potential of a given set of technologies. While batteries and electric drive components are improving today, so are the engines for conventional internal combustion engine vehicles (ICEVs, or simply CVs) as well as the batteries and electric drive components for gasoline HEVs. These improvements for CVs and HEVs are also applicable to future PHEVs. Similarly, continued improvements in aerodynamic drag and vehicle light-weighting are expected to improve the performance and fuel economy of both PEVs and gasoline CVs and HEVs. By considering scenarios with high technology success over the long term, and relying on an integrated representation of the cost and performance of a wide range of LDV drivetrains, the present study is able to compare future advanced PEVs to future advanced gasoline vehicles.[1] The NEVA methodology does not generate new projections of relative LDV cost and performance attributes. Instead, standard U.S. Department of Energy projections are relied upon as external input assumptions to the NEVA analytic framework (see discussion of Figure ES-1 below).

The fourth and fifth issues concern the evolution of the electricity grid and policy support mechanisms required in the near term to accelerate PEV market adoption. One critique of PEVs in use today is that the relatively high carbon intensity of electricity in some regions does not necessarily result in GHG emission reductions compared to gasoline vehicles. This is more of a

[1] The present study focuses on the economic value of PEVs relative to improved future gasoline vehicles. While other advanced LDV technologies also show promise over the long term, these options are not addressed in the present study for the sake of simplicity. For a discussion of scenarios with a broader range of advanced vehicles and fuels, see NRC 2013. For more information on all LDV technologies and fuels supported by the U.S. Department of Energy, including advanced hybrid technologies, advanced biofuels, and hydrogen fuel cell vehicles, visit http://energy.gov/eere/transportation.

concern in Western and Midwestern states than on the East and West Coasts (Anair and Mahmassani 2012). An examination of the long-term market potential of PEVs is therefore of interest when combined with a simulation of an evolving electricity grid. On the issue of near-term market growth, it is likely that strong policy support mechanisms will continue to be needed to expand markets and maintain growth (Greene, Park, and Liu 2013). A long-term, high-market-share scenario can therefore provide insight into what might be the "end game" value to society of PEV technologies in general, as well as long-term private benefits to consumers, after purchase incentive programs and other market transformation support mechanisms have largely subsided.

With respect to the sixth and last issue listed above, this study focuses on a main Aggressive scenario in which approximately 14 percent of all LDV miles driven are e-miles by 2035, which requires approximately 73 million PEVs on the road by 2035. In meeting this scenario design input assumption, the Aggressive scenario is comparable to the PEV market growth trajectory from a 2013 study from the National Academy of Sciences (NRC 2013) that focused on LDV sector dynamics required to achieve deep reductions in LDV GHG emissions by 2050.

The scenario approach developed to address these six issues is a means of estimating the national economic value of PEVs in meeting a predetermined market growth trend. More specifically, in the Aggressive scenario the 14% of LDV miles as eVMT by 2035 is not only met at a national level, but also within each of the nine census divisions. The scenarios are therefore a formalized approach to estimating the relative economic value of PEVs by backcasting from fixed future market outcomes, rather than by applying predictive or exploratory methods to determine the likely or optimal evolution of regional PEV markets within a heterogeneous policy landscape.[2] A more complete and integrated economic evaluation would account for state and regional PEV-specific policy factors, as well as any policies, behavioral trends, or market dynamics beyond the LDV sector, such as the influence of carbon policies on electricity demand in other sectors, changes in urban form and generational travel preferences, or the demand for biomass resources to either generate electricity or produce transportation fuels such as hydrogen or advanced biofuels. Combining this multi-sector and regional scope with market prediction or cost optimization methods could result in a more robust cost benefit assessment. A major challenge to developing this type of robust assessment framework for PEVs is the limited capability of existing models to estimate how consumers might purchase advanced LDVs in the future (Stephens et al. 2016).

ES.1.1 Study Scope and Limitations

The primary added value of the NEVA study is a straightforward presentation of technology costs and fuel utilization as PEV market growth displaces incumbent CVs. The study includes unique analytic methods to assess regional variations in technology performance, interactions with the grid, and household travel patterns. Given the focus on regional variability, this framework can also be applied to detailed assessments at the state or local level. While other factors not accounted for in this study will influence the future economic value and market

[2] Following the classification proposed by Börjeson et al. (2006), the present approach is a type of normative, transforming scenario study, addressing the general question "*How can a specific target be met?*" and relying upon a backcasting estimation approach rather than prediction or optimization methods.

growth of PEVs, this relatively simple assessment of first-order factors provides insights into the underlying trends that determine the fundamental costs and benefits associated with expanding PEV markets. These trends and factors include the following:

- Projections of the potential for PEV costs to decline and performance to improve when produced in high volumes, as well as improvements in the cost and performance of future CVs displaced by PEVs.
- The displacement of CVs by PEVs, which is estimated through an economic allocation of PEVs across mainstream households based upon relative vehicle prices, fuel savings, household driving patterns, and the limited range of BEVs. This economic allocation algorithm is an internally consistent means of determining the miles driven and fuel prices incurred by different PEV types when they displace CVs in particular households, and is therefore a major factor contributing to the estimation of net costs and benefits.
- Potential impacts on the electricity grid from PEV charging, including changes in electricity price and carbon intensity.
- Long-term trends associated with the GHG intensity of electricity and gasoline.
- Monetization of the social value of reductions in GHG emissions and petroleum imports.

This analysis does not depend upon any explicit modeling of market competition between PEVs and other advanced LDVs, or the influence of particular policy mechanisms such as the Corporate Average Fuel Economy (CAFE) standard or the Zero Emission Vehicle Mandate. Therefore, the study is not a formal cost-benefit assessment of specific policies required to expand PEV markets. In addition, limitations on study scope prohibited an economic evaluation of the air quality implications of PEV market adoption, which has been identified as an important near-term issue and examined elsewhere (Michalek et al. 2011; EPRI 2015; Holland et al. 2015). An additional limitation of the study is that it does not account for market feedback mechanisms influencing prices, such as changes in gasoline prices in response to changes in gasoline demand, or feedback from international markets for LDVs, such as cost reductions due to increased learning with electric-drive components. In general, the scenarios are highly dependent upon projections of long-term technology trends, do not attempt to simulate transitional dynamics or market dynamics, and do not build upon current policy or market conditions as a basis for projecting into the future. A final limitation is the focus on plug-in passenger vehicles and exclusion of analysis specific to light-duty trucks.

ES.2 Methodology

The economic value estimation methodology combines detailed analyses of multiple LDV technology types with regional data on household travel patterns, climate, gasoline prices, and simulations of grid electricity prices. Figure ES-1 summarizes the NEVA analytic framework, which consists of four main sources of external data, shown as inputs on the left side of the figure, being used within four interconnected models: (1) Vehicle Simulation, (2) Grid Simulation, (3) Cost, Benefit Accounting, and (4) Macroeconomic modeling. Acronyms for the specific model names shown in parenthesis are identified in the notes below Figure ES-1. Vehicle attributes such as cost and performance are external to the study, and are used as inputs to the Vehicle Simulation model along with travel data such as total annual miles driven and the frequency of long-distance trips. Vehicle Simulation results are then used in the Cost, Benefit Accounting model to determine the allocation of PEVs to different households based upon the perceived value of different PEVs, with the total number of PEVs required being sufficient to meet the total eVMT scenario design requirement discussed above. Additional data external to the study used in the PEV allocation calculations are electric vehicle supply equipment (EVSE) costs and gasoline costs. Electricity prices, used to determine net fuel savings as PEVs displace CVs, are determined internally through an iterative exchange of regional data between the Cost, Benefit Accounting model and the Grid Simulation model. The Grid Simulation analysis determines required changes in electricity transmission and generation infrastructure in response to increased regional electricity demand and PEV charging patterns. Resulting changes in electricity prices and carbon intensities are then incorporated into the overall economic value calculations to determine total private and social costs both nationally and regionally, shown as Results in Figure ES-1. Changes in total costs for vehicles and fuels are also used as inputs to a Macroeconomic model to generate additional results such as estimates of jobs and changes in gross domestic product (GDP). Through these four interconnected models the NEVA framework integrates multiple data types into a consistent representation of regional PEV and EVSE costs and benefits. Additional details of the methodology, data, and models are discussed in the sections below.

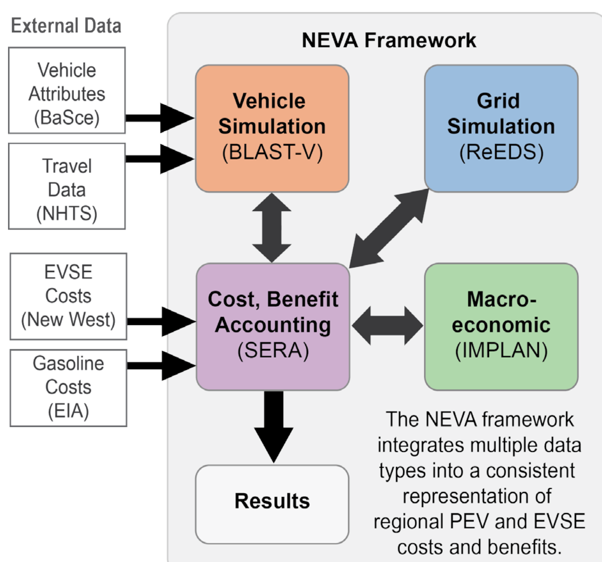


Figure ES-1. Overview of the national economic valuation assessment (NEVA) framework

Notes: Acronyms for sources of external data: BaSce: Baseline and scenario; NHTS: National household travel survey; EIA: Energy Information Administration. Acronyms for framework models: BLAST-V: Battery lifetime analysis and simulation tool for vehicles; ReEDS: Regional energy deployment system; SERA: Scenario evaluation and regionalization analysis; IMPLAN: IMpact analysis for PLANning.

ES.2.1 Private and Public Costs and Benefits

The economic valuation results are reported in terms of the annual costs and benefits associated with increased PEV market share in 2035. These costs and benefits include the following:

- **Private vehicle costs:** the incremental retail price to consumers of PEVs compared to CV and HEV alternatives, plus the capital cost of home EVSE. Vehicle fuel economy and costs are based on high technology progress projections, with sensitivities around low and high costs (Moawad et al. 2016). These BaSce vehicle costs (Baseline Scenario, see Figure ES-2) have been developed in conjunction with U.S. DRIVE (United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability), and are considered fixed inputs to the present study; after applying a retail markup factor, no additional calculations made within the assessment framework alter the relative costs between PEVs and other advanced LDVs. The result is an approximate representation of the Vehicle Technologies Office's goal to produce PEVs that are "as affordable and convenient as today's gasoline powered vehicles by 2022" (DOE 2014, p. 2). For comparison, empirical trends in battery costs reported by Nykvist and Nilsson (2015) suggest that near-term battery cost reductions could result in PEVs becoming competitive more quickly than indicated by the BaSce vehicle costs (see discussion of Figure ES-2).

- **Private EVSE costs:** home EVSE costs, which are taken from the lower range of costs seen in recent installations, assuming some progress in reducing costs for future systems and applying nominal low and high cost sensitivities (EERE 2015).
- **Private benefits:** the net value of household fuel savings as electricity is substituted for gasoline. This benefit is based upon projections for gasoline prices, with low and high trends taken from the Energy Information Administration's 2015 Annual Energy Outlook (AEO 2015). Electricity prices are generated from the National Renewable Energy Laboratory (NREL) Regional Energy Deployment System (ReEDS) model after accounting for increased electricity demand by PEVs. The difference in fuel and electricity costs to households is based upon these gasoline and electricity price trends and the relative fuel economies of CVs, HEVs, and PEVs after accounting for regional climate effects. Total household VMT is the same before and after introducing PEVs, with second or third CVs or HEVs in a household fulfilling any long-distance trips that BEVs are not able to fulfill.
- **Public costs:** the capital cost of workplace and commercial EVSE stations, with workplace EVSE being owned privately but typically being available as a common asset to serve PEVs owned by employees. These are taken from the low range of the same source for current home EVSE costs (EERE 2015), with the exception of direct current fast charge (DCFC) station costs. An average, nominal DCFC cost is assumed based upon an estimate for a current 100 kW system (NRC 2015), acknowledging that future costs are likely to decline over time but that power levels may also increase up to 350 kW or more, which would tend to add costs for those stations.
- **Public benefits:** external costs associated with GHG emission and petroleum import reductions as well as any macroeconomic benefits in terms of increased jobs or GDP. The cost per metric ton of carbon dioxide equivalent (CO_2e) GHG emissions is taken from the U.S. Environmental Protection Agency's (EPA's) Interagency Working Group report on the Social Cost of Carbon (IAWG 2015), and the external cost of petroleum imports is based upon the Oil Security Premium estimate used in the EPA's assessment of CAFE benefits (Leiby 2012).

It is anticipated that a strong value proposition combined with additional policy support mechanisms, such as direct subsidies or purchase rebates, will be required to shift toward high PEV market shares and away from conventional gasoline vehicles. Similar support mechanisms would likely be required for any major alternative fuel or advanced vehicle transition, as discussed in the 2013 *Transitions to Alternative Fuels* study by the National Academy of Sciences (NRC 2015) and other recent analyses of anticipated market transformation efforts (Greene, Park, and Liu 2013; Ogden, Fulton, and Sperling 2016). The present analysis does not examine costs associated with the transition to high market share growth but instead focuses on a long-term future in which more stable market conditions have been established. There are four distinct analytic models used to develop estimates of the economic value of increased PEV market share by 2035. Each is reviewed in the sections below.

ES.2.2 Vehicle Simulation: Vehicles, Driving, and Charging (BLAST-V)

Information about energy consumption and travel patterns for both PHEVs and BEVs is calculated using the Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V) model, relying upon a breakdown of regional travel data within the National Household Travel Survey (NHTS) database. BLAST-V uses trip-level data along with climate, vehicle, and driver data to determine the temporal and spatial distribution of trips. Inclusion of these data enables BLAST-V to account for the effects of local climate, driver aggression, vehicle cabin thermal management, battery system thermal management, battery wear, and charger power and availability (Neubauer and Wood 2014). Outputs from the model are used to calculate geographic variations in vehicle energy usage, which in turn is used in calculations of vehicle market share in the vehicle sales, stock, and economic accounting model discussed in the following section.

In addition to determining which types of PEVs are driven how far each year in different households, costs to consumers for vehicles and charging infrastructure are key external data inputs used in the economic value assessment. Figure ES-2 indicates trends over time in the manufacturer's suggested retail price (MSRP) of all vehicles represented in the analysis, including four types of PHEVs and four types of BEVs, each distinguished by the nominal number of all-electric miles resulting from a full charge. The left-hand panel indicates vehicle prices and the right-hand panel indicates prices as a ratio of CV prices. As indicated, the price of PHEVs declines gradually over time, while the price of BEVs declines rapidly until about 2030. The price of CVs increases slightly until 2030, and the price of all PHEVs other than the PHEV10 are very similar. The price of the BEV70 drops below the CV price trend around 2025, while the price of long-range BEVs—with 210 and 280 miles of all-electric range—remains approximately 25% to 35% higher than that of CVs by 2035, as shown in the right-hand panel. The prices for the PHEV10 and BEV140 are comparable to the HEV by 2035. This comparison indicates the degree to which these external data represent an approximation of the Vehicle Technologies Office's cost goal. Moreover, within the economic allocation of PEVs across households, the limited range of the BEVs is assumed to reduce the perceived value of those vehicles, especially in single-vehicle households looking to replace an existing conventional vehicle, or in households making frequent long-distance trips (see section 2.2).

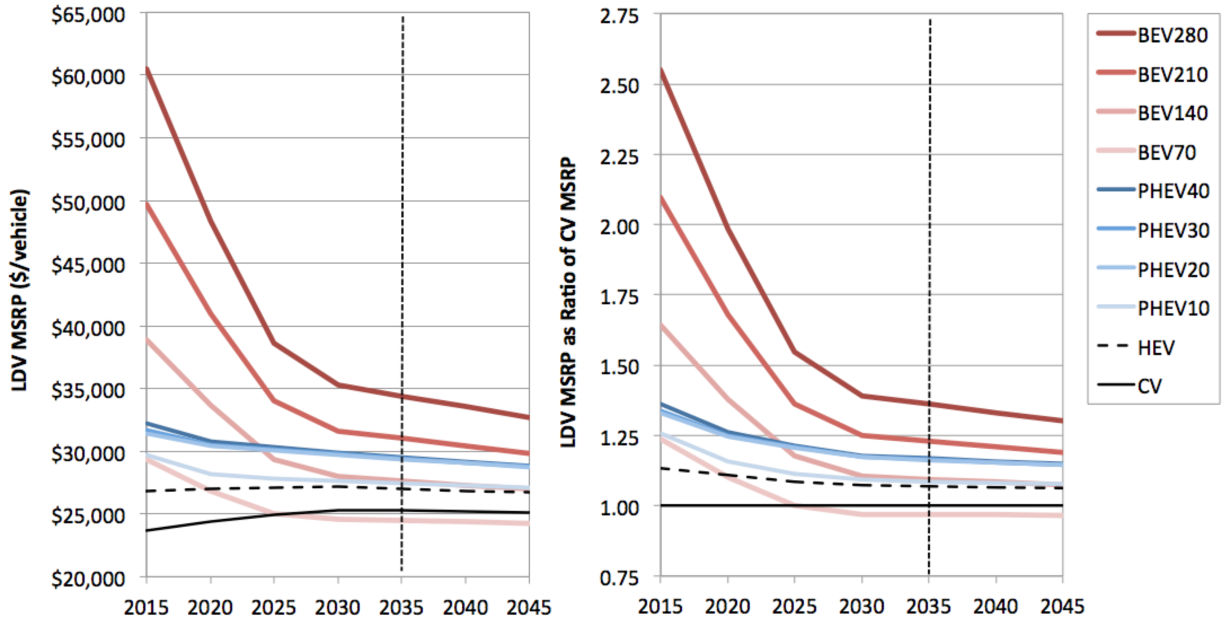


Figure ES-2. Time series representation of the high-med light-duty vehicle BaSce cost trend results from Moawad et al. (2016), after applying a 1.5 retail markup factor to estimate the manufacturer's suggested retail price (MSRP), shown in units of dollars per vehicle (left) and as a ratio of CV retail prices (right)

The MSRP trends shown in Figure ES-2 are the "medium" price trends for LDVs used in the main Aggressive scenario, taken from the set of "high uncertainty" or high technology progress results from BaSce (Moawad et al. 2016). A variation on these medium price trends is the "low" LDV price trend used as inputs to the Low Cost scenario. This low cost trend is indicated by the red line with square symbols in Figure ES-3 for the BEV210, along with medium price trend for the same BEV210 (blue line with triangles) and the medium CV price trend (solid black line). Both trends for the projected BEV210 can be compared to the recently announced base price of $35,000 for the Tesla Model 3, which is reported to have an all-electric range of 215 miles (GCC 2016a). As indicated, this Tesla Model 3 near-term retail price is about two years ahead of the low price trend. Given this announced price for a near-term vehicle, as well as other promising technology improvement trends (see Faguy 2015), the Aggressive and Low Cost scenarios (which incorporate the medium and low cost trends, respectively, from Moawad et al. (2016)) are paired together through much of the report as bookends on a relevant range of future possible PEV economic value results. If long-term PEV prices ultimately fall below the low price trends used in the Low Cost scenario, the resulting net social benefits would tend to be larger than those estimated for the Low Cost scenario.

The cost assumptions for EVSE stations are summarized by the points and numbered values in Figure ES-4, which also indicates cost ranges reported in the literature for recently installed stations. The lower range values (indicated by diamond symbols in the figure) are selected as representative of future average costs for home, workplace, and commercial EVSE. The $108,500 estimate for DCFC stations is a relatively high estimate for current stations, but is used as a proxy for DCFC stations that may be installed in the future at higher power levels of 350 kW or more.

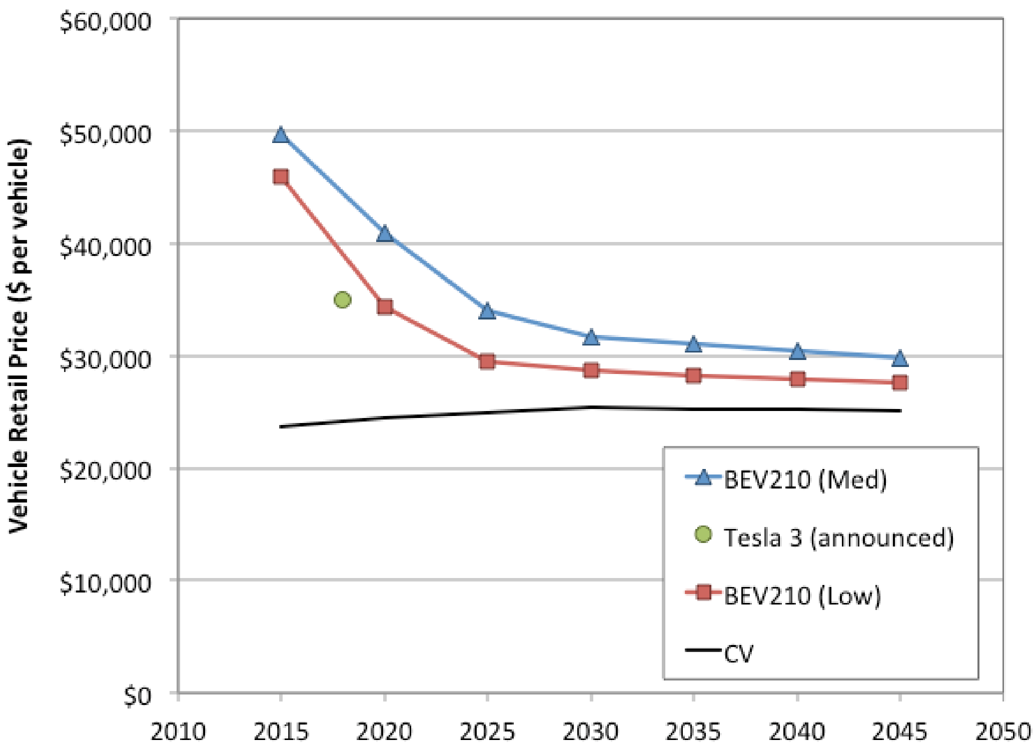


Figure ES-3. Comparison of projected medium and low BEV210 price trends to medium CV and Tesla 3 announced prices

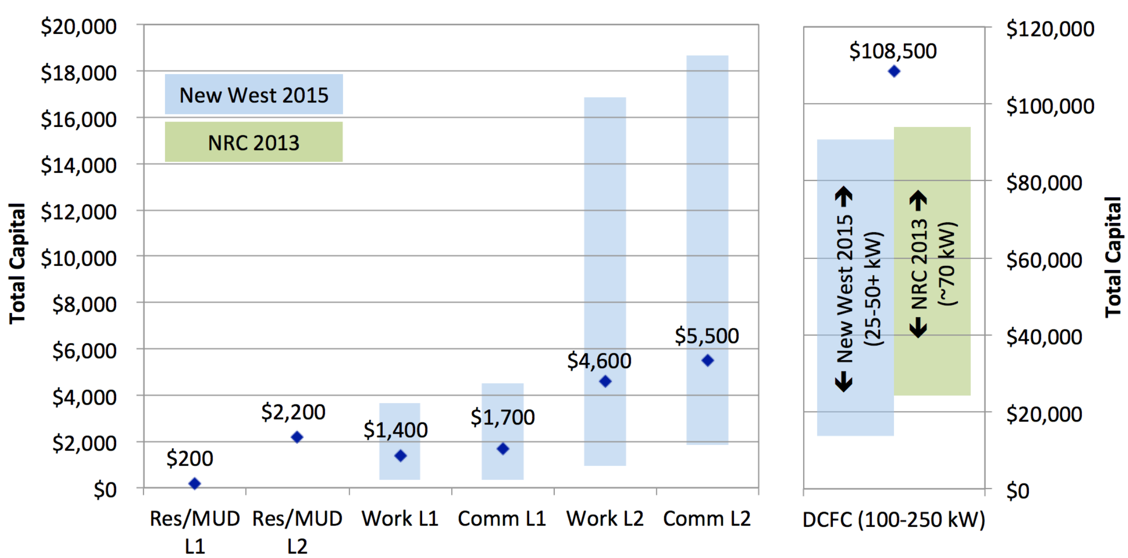


Figure ES-4. Average values used as inputs for the total capital and installation cost of EVSE by type and location in 2035

Notes: Costs include capital equipment costs and installation costs. Numerical values in the figure are taken from lower ranges reported by EERE (2015) for Level 1 (L1) and Level 2 (L2) stations and the NRC (2013) report for high-power DCFC stations.

ES.2.3 Cost, Benefit Accounting: Vehicle Fleet, EVSE, and Economic Accounting (SERA)

The model used to track vehicle adoption rates, fuel demand, fuel supply, and the total social cost and benefit economic valuation results is the Scenario Evaluation and Regionalization Analysis model (SERA) (Bush et al. 2013). The SERA scenario disaggregation tool reconciles national PEV market shares for new vehicle sales through 2035 with a number of trends associated with the prevalence of different PEV types on a regional level. SERA's geographically detailed vehicle stock model then translates PEV market shares into region- and urban area-specific vehicle stocks over time as market shares increase and vehicle cost and performance attributes improve. The vehicle stock is computed using the default vehicle-survival functions of the SERA model (Bush et al. 2013), which is consistent with the vehicle-survival function in the Argonne VISION model (Zhou and Vyas 2014): over a 20-year period vehicles are driven less and retired from the vehicle fleet at an increasing rate as they age. The vehicle-stock computations are regionalized to the ZIP code level, as reported in the NHTS database discussed in the previous section. Baseline fuel costs are taken from AEO 2015, electricity prices are generated using the NREL ReEDS model (discussed below), vehicle cost and performance trends are taken from the BLAST-V analysis discussed in section 2.2 (Moawad et al. 2016), and external costs are from standard references in the literature, including the social cost of carbon (IAWG 2015) and an energy security premium estimate (Leiby 2012).

The accounting methods used to determine the economic value of all LDVs as well as changes due to increased PEV market share are based upon the geographically articulated stock model and resulting gasoline and electricity usage trends. Baseline electricity prices and carbon intensities are recalculated with the ReEDS model by simulating electricity generation and transmission changes in response to total PEV electricity demand and charging profiles. Fuel costs and incremental vehicle costs incurred over time are reconciled as a single set of costs and benefits in the analysis target year 2035. Incremental vehicle costs in 2035 are accounted for across the entire LDV fleet with respect to a social discount time period of 11.68 years, using a 2.3% annual discount rate and a standard vehicle retirement rate. Total social economic value results for PEVs therefore reflect actual fuel savings for the entire LDV fleet in 2035, and approximately one-twelfth of the incremental cost of all PEVs sold less than 11.68 years previously (see section 2.3).

ES.2.4 Grid Simulation: Electricity Generation Costs and Emissions (ReEDS)

The Regional Energy Deployment System model (ReEDS) is an electricity system capacity expansion model that develops scenarios of future investment and operation of generation and transmission capacity to meet U.S. electricity demand (Sullivan et al. 2015). The model performs system-wide least-cost optimization in 2-year solve periods from 2010 out to 2050 to provide estimates of the type and location of fossil, nuclear, renewable, and storage resource deployment; the transmission expansion requirements; and the generator dispatch and fuel needed to satisfy regional demand requirements and to maintain grid system adequacy. The model also considers technology, resource, and policy constraints including state renewable portfolio standards. In this analysis, for the Baseline scenario the model projects a renewable energy penetration of 38% in 2035. With increased PEV market share, the model projects the additional generation capacity to mostly come from renewables in 2035, due to competitive generation economics, as seen from Figure ES-5. The renewable energy penetration increases to 39.4% in the Aggressive scenario in

2035 compared to 38% in the corresponding Baseline scenario. The additional scenarios indicated in the figure are discussed in more detail in sections 2.4 and 3.4.

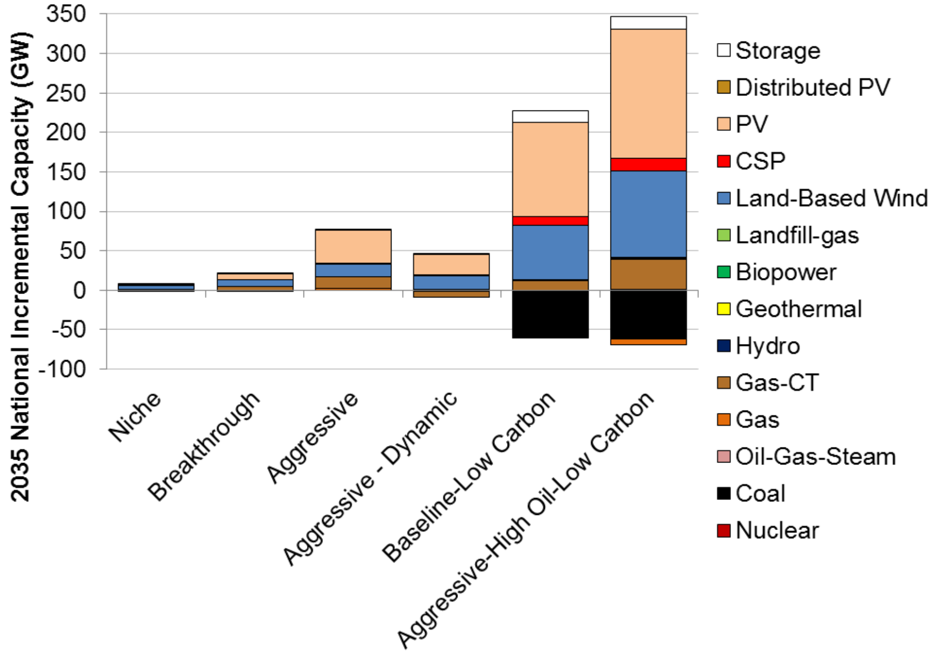


Figure ES-5. Year 2035: Incremental installed electricity generation capacity compared to the Baseline scenario

ES.2.5 Macroeconomic: Jobs and Economic Impact Modeling (IMPLAN)

Jobs and economic impacts are estimated using the IMpact analysis for PLANing (IMPLAN) input-output (I-O) model. Each scenario contains a set of expenditures on services and commodities such as vehicles, electricity, petroleum products, and chargers. Economic impacts consist of two components: changes in domestic economic activity as a result of these expenditures and changes in household spending as a result of changes in net disposable household income.

Net disposable household income changes because of increased spending on vehicles in each scenario compared to the Baseline scenario, which occurs due to the cost of home EVSE and the incremental price difference between PEVs and the CVs and HEVs they replace. Meanwhile, consumption of petroleum decreases and expenditures on electricity increase, resulting in net fuel savings for households. Domestic economic activity resulting from these expenditures occurs as demand for domestically produced electricity increases, demand for domestically produced petroleum decreases, and demand for domestically produced charging stations increases.

ES.2.6 Scenario Development

The initial input assumption to the scenario development process is that 14% of all LDV miles traveled are e-miles by 2035, which is consistent with the adoption rate assumed for a deep GHG emission reduction scenario from a 2013 NRC study on the transition to alternative fuels (NRC 2013). Given this e-mile percentage assumption, which is applied to each census division, a range of PEV types are allocated to households according to their perceived value to consumers, which is dependent upon a variety of regional factors. The results are the total e-miles by PHEVs and BEVs on the left-hand panel of Figure ES-6, with the corresponding total vehicles on the road shown in the right-hand panel. As shown, there are 73 million PEVs on the road by 2035 in this main Aggressive scenario, with PHEVs taking a larger market share than BEVs, which is consistent with the relative retail prices indicated in Figure ES-2.

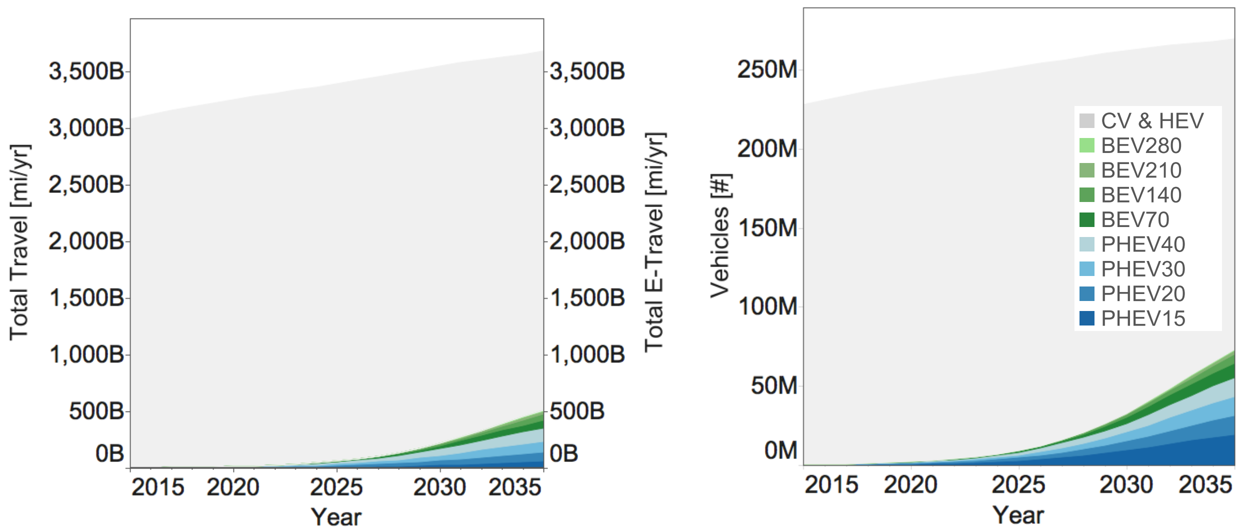


Figure ES-6. Total e-miles traveled (left) and PEVs on the road (right) in the Aggressive scenario

Figure ES-7 provides an overview of all scenarios developed to better understand variations in input assumptions to the main Aggressive scenario, which is shown in bold. The Baseline scenario, shown in the bottom left, is the primary reference for determining differences in economic value as a result of increased PEV market growth in the other scenarios. It is similar to the Reference scenario from the Energy Information Administration's 2015 Annual Energy Outlook report (EIA 2015).[3] Starting from the Baseline scenario, Figure ES-7 indicates Niche and Breakthrough scenarios building in PEV market growth toward the Aggressive scenario. These two scenarios have lower total market shares of PEVs than the Aggressive scenario does, and they are developed in order to identify any scaling effects related to the size of the future PEV fleet. Above the Aggressive scenario are two variations that account for changes in the future price of global oil, and therefore the price of domestic gasoline. Each relies upon projections for High Oil and Low Oil gasoline prices from EIA (2015), and they are compared to the main Aggressive scenario, which assumes the Reference Oil price (green box). Similarly, two variations on LDV and EVSE capital cost trends, the High Cost and Low Cost scenarios, are shown in the lower portion of the figure and are compared to the High Technology Progress with Medium Cost assumptions (green box) for the Aggressive scenario. The input assumptions for the Aggressive scenario are therefore shown as green boxes with two sets of high and low

[3] The AEO 2015 Reference scenario does include some PEV adoption, with approximately 1.8 million PHEVs and 0.7 million BEVs on the road by 2035. For the sake of simplicity, and because the market shares are small relative to other scenarios examined in this study, we account for these 2.6 million PEVs as additional market growth within the non-Baseline scenarios. They therefore contribute to the economic value calculations for PEVs in each scenario.

variations on both the price of gasoline and cost trends for future vehicles and EVSE infrastructure.

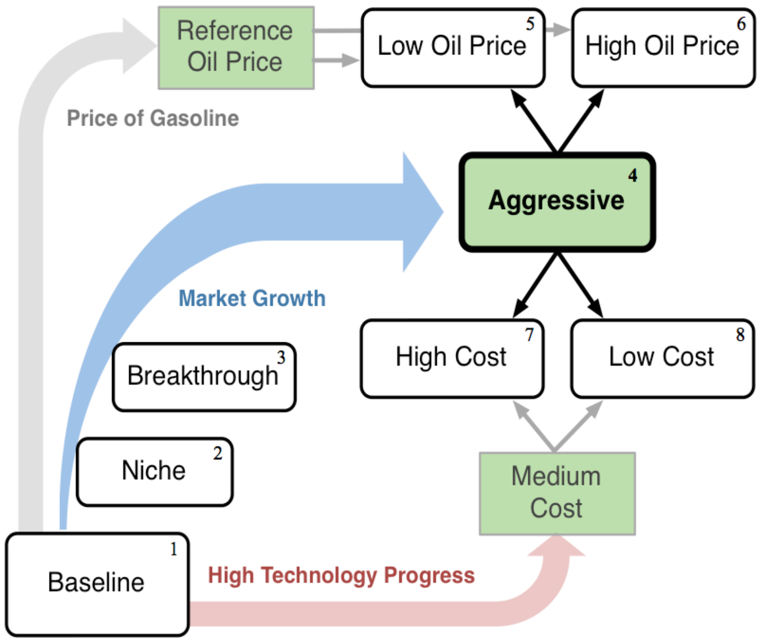


Figure ES-7. Scenarios and major input assumption variations

ES.3 Summary of Results

The total social economic value of increased PEV adoption in 2035 is indicated with respect to the Baseline scenario for each of the other seven main scenarios shown in Figure ES-8. The top panel indicates absolute negative costs and positive benefits as stacked bars, with net valuation results (the sum of all costs and benefits) indicated by vertical black lines and shown numerically in units of billions of dollars per year next to each scenario name. The bar colors indicate the economic value components shown in the legend. Negative costs, including home and public EVSE costs, electricity costs, and incremental PEV costs, are shown to the left of zero on the horizontal axis. Positive benefits, including fuel savings, and reductions in GHG emissions and petroleum consumption, are shown to the right of zero. By definition, Baseline scenario results are zero, serving as the reference for changes in economic value in each scenario.

The Aggressive scenario is associated with an estimated $26.5 billion per year in net positive economic value. High Cost and Low Cost scenarios have approximately 20% lower and higher net benefits, respectively, while Niche and Breakthrough scenarios are scaled to lower total PEV adoption levels. High gasoline prices in the High Oil scenario significantly increase fuel savings, resulting in $83.7 billion per year in net benefits, a three-fold increase over net benefits in the Aggressive scenario. Net benefits in the Low Oil scenario are about one quarter of those in the Aggressive scenario. It should be noted that both the High Cost and Low Oil scenarios involve changes in market prices for vehicles and gasoline that would tend to dampen PEV sales in general, and may therefore be considered less consistent with the high PEV adoption rates assumed as inputs to the main Aggressive scenario.

The per vehicle per year results in the lower panel of Figure ES-8 may be considered an indicator of the effectiveness of achieving positive benefits per PEV introduced. Per vehicle results decline only slightly with increasing market shares across the Niche, Breakthrough, and Aggressive scenarios, suggesting only slight declines in marginal returns on average at the household level in moving to very high PEV market shares. The other scenario results are more or less proportional to variations in the aggregate results in the top panel, though total PEVs on the road by 2035 do vary by scenario (see section 4.8). Results for the High Oil case ($910 per PEV per year) and the Low Oil case ($107 per PEV per year) bracket the net positive result of $362 per PEV per year in the Aggressive scenario, as well as results for the High and Low Cost variations on the Aggressive scenario.

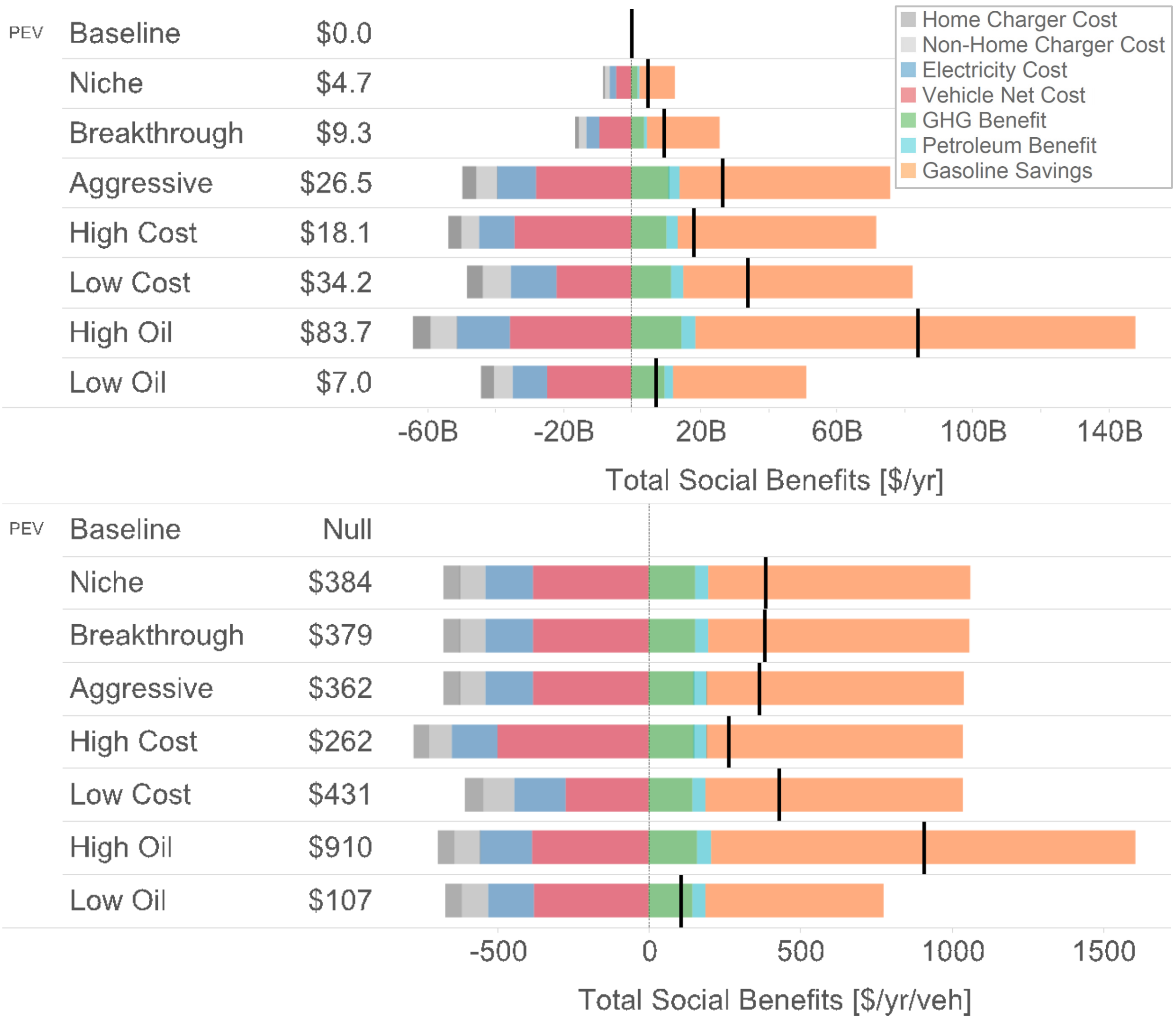


Figure ES-8. Breakdown of total costs and benefits in each scenario for 2035

ES.3.1 Regional Variations in Net Benefits

Benefits by region vary with the size of the total LDV market in each census division and the relative costs and benefits associated with adopting PEVs into each division. Each census division achieves the same total eVMT percentage as the national average, as discussed in section ES.1, while relative benefits depend upon household travel patterns, climate influences on LDV performance, regional gasoline and electricity prices, and the carbon intensity of the electricity utilized. A map of states and census divisions is provided in Figure ES-9. Absolute total social valuation results for the two main scenarios of interest, the Aggressive and Low Cost scenarios, are summarized by region in Figure ES-10. Regions with the largest total net benefits are indicated first, starting with the South Atlantic, and are shown increasing cumulatively towards the national totals at the bottom of the graph. Aggressive scenario results are shown as orange bars and Low Cost scenario results are shown as blue bars. The cumulative results sum to the national total for each scenario, suggesting a range of benefits between $26.5 and $34.3 billion per year (see section ES.2.2 for a discussion of relative vehicle costs in the Aggressive and Low Cost scenarios).

This sequence of benefits from largest to smallest by division only accounts for absolute results, and does not address the relative value of adopting PEVs within each division. Total net social benefit per PEV results are shown as a range between Aggressive (orange) and Low Cost (blue) scenarios by census division in Figure ES-11. The largest benefits (ranging from $434 to $509 per PEV per year) are seen in the West North Central and East South Central divisions, while the smallest benefits (ranging from $262 to $368 per PEV per year) are seen in the New England and Middle Atlantic divisions. The range of $362 to $431 per PEV per year for the national average falls more or less in the middle of these higher and lower division ranges. While all divisions see a net positive benefit for these two scenarios, results suggest a variation between roughly $250 and $500 per PEV per year, or about 200%, across all census divisions.

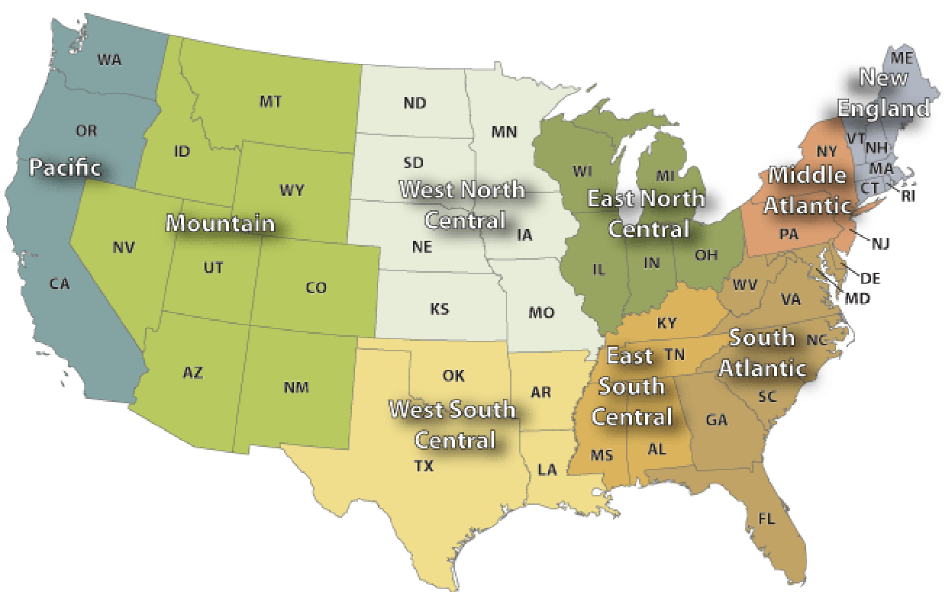


Figure ES-9. U.S. states and census divisions

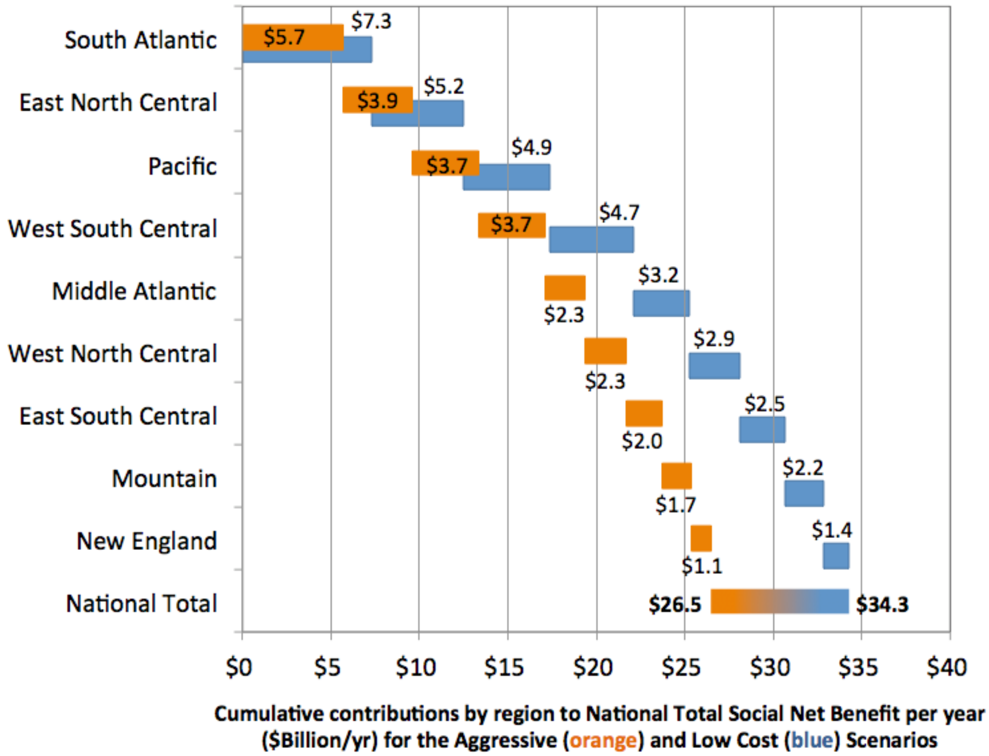
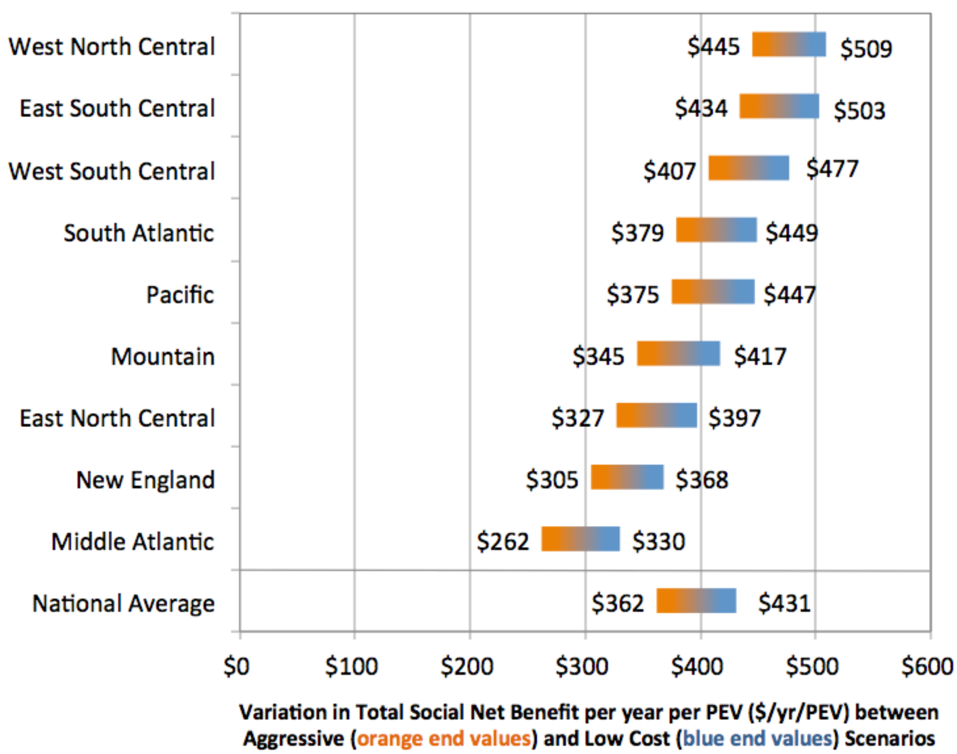


Figure ES-10. Respective contributions to total social net benefit by region for the Aggressive and Low Cost scenarios



ES-11. Range of total social net benefit per PEV by region for the Aggressive and Low Cost scenarios

ES.3.2 Employment and Economic Activity Results

The introduction of PEVs and EVSE infrastructure has impacts on a variety of other sectors within the economy. Using results from the Cost, Benefit Accounting model, these impacts are assessed in the Macroeconomic portion of the NEVA framework using the IMPLAN model (see Figure ES-1). Summary results are presented in Table ES-1, which shows the average annual impacts for the range from 2015 to 2040. Overall, the introduction of PEVs has positive impacts for nearly all economic indicators in each scenario. The Aggressive and Low Cost scenarios are associated with an average (2015–2040) of approximately 51,500 to 108,400 additional jobs per year and an increase in GDP of \$6.6 billion to \$9.9 billion per year, respectively. Additional details of the macroeconomic modeling approach are discussed in section 2.5, and additional results are presented in sections 3.5 and 4.6.

Table ES-1. Average Annual Impacts for Each Scenario

Economic Metrics (2013 dollars)	Jobs (number of jobs/yr)	Income (\$million/yr)	GDP (\$million/yr)	Output (\$million/yr)
Niche	110,000	3,855	5,571	(619)
Breakthrough	99,000	3,707	5,804	1,723
Aggressive	52,000	3,016	6,592	11,003
High Cost	(30,000)	176	2,528	11,994
Low Cost	109,000	5,104	9,913	11,201
High Oil	147,000	6,990	12,505	20,196
Low Oil	1,000	1,046	3,732	8,444

ES.3.3 Scenario Highlights and Insights

Key scenario highlights and insights, which build upon and are consistent with the quantitative results reviewed above, include the following:

- **Increased PEV market growth is correlated with net positive private household benefits.** In most future scenarios, private household fuel savings tend to outweigh any additional cost of PEVs relative to conventional and hybrid vehicles, as well as the cost of home charging infrastructure. Results from the Aggressive scenario suggest a net positive private benefit of \$18.6 billion per year by 2035, corresponding to an average benefit of \$255 per PEV per year. The Niche and Breakthrough scenarios have net positive private benefits of \$3.3 and \$6.6 billion per year by 2035, and corresponding average benefits of \$273 and \$269 per PEV per year, respectively.
- **Increased PEV market growth tends to result in net positive total social benefits.** The total social economic value of increased PEV market share is the sum of both private and social costs and benefits. Social or "public" costs and benefits are defined as including the additional cost of workplace and commercial charging infrastructure, as well as economic valuations of reductions in GHG emissions and petroleum imports. With declining carbon intensities for grid electricity as renewable generation increases in

the future, and compared to gasoline with a constant carbon intensity used in CVs and HEVs, increased PEV adoption in the Aggressive scenario results in net GHG reductions in all U.S. census divisions by 2035. When accounting for the cost of public charging infrastructure and the benefits of GHG and petroleum import reductions, the total social benefit of increased PEV adoption is estimated at $4.7, $9.3, $26.5, and $34.2 billion per year for the Niche, Breakthrough, Aggressive, and Low Cost scenarios, respectively. The economic value of PEVs varies significantly by region, with the highest benefits per PEV being achieved in the Midwest and Southern regions, followed by Pacific, Mountain, and Northeastern regions.

- **PEV market growth increases economic activity, while net job and GDP growth is highly dependent upon gasoline prices, PEV costs, and fuel economies.** Household fuel savings, reductions in petroleum imports, and increased domestic electricity consumption tend to stimulate GDP and create U.S. jobs. However, these trends tend to be counterbalanced in the modeling by reduced household disposable income resulting from purchasing home charging infrastructure and more expensive PEVs. Positive job growth results range from approximately 52,000 to 109,000 net jobs per year (average from 2015 to 2040) for the Aggressive and Low Cost scenarios, respectively, compared to the Baseline scenario. All scenarios see positive net GDP, with a low of $2.5 billion per year in the High Cost scenario, and a range of $6.6–$9.9 billion per year in the Aggressive and Low Cost scenarios, respectively.
- **Private benefits of fuel savings are highly dependent upon the future price of gasoline.** A long-term trend of low gasoline prices would tend to both suppress PEV sales and diminish fuel savings, which is inconsistent with the high market growth rates assumed in the scenarios. In contrast, higher future gasoline prices will tend to reinforce PEV market adoption and increase household fuel savings. In the Aggressive High Oil scenario, where gasoline prices increase to $5.50-$5.90 per gallon by 2035, compared to $3.40-$3.75 per gallon in the Aggressive scenario, private benefits increase to $72.7 billion per year, corresponding to average private benefits of $791 per PEV per year.
- **BEVs economically satisfy the driving needs of a relatively small market.** In comparison to PHEVs, the allocation algorithm represents BEVs as less attractive to consumers due to either their high upfront costs compared to alternatives or their limited range, or both. While increased public charging will likely make BEVs more attractive, it is uncertain to what degree this may provide a market advantage over the purchase of other LDV options. The economically efficient allocation approach used in this study, which only captures a portion of all consumer preferences and vehicle attributes, results in PHEVs dominating future PEV markets. For example, in the Aggressive scenario PHEVs are 76% of all PEV on the road by 2035. Future trends that may influence BEV market shares and have not been accounted for in this analysis include electricity rate structures designed for BEVs, consumer preferences for green vehicles and the electric-drive experience, changes in urban form and integrated transportation systems, changes in vehicle ownership and car-sharing, and the introduction of connected and automated vehicles.
- **PEV electricity demands are small in comparison to total installed electric capacity and resulting generation, and the majority of incremental capacity and generation**

are projected to come from renewable sources by 2035. The electricity demands from 73 million PEVs deployed by 2035 increases the installed capacity by less than 5% and the required electric generation by less than 4%. Grid capacity expansion simulations, subject to future technology costs and policies, tend to project increasing installation of renewable generation by 2035 in response to any increase in marginal demand, whether from PEVs or other sources. For the main Aggressive scenario and the High Oil scenario in 2035, compared to their respective baseline scenarios, these simulations suggest electricity price increases of 1.2% and 2.2%, carbon intensity reductions of 3.4% and 5.6%, and renewable penetration increases of 1.7% and 2.6%, respectively.

- **Changing the charging times for PEVs to better complement the grid can reduce the incremental system cost, but may also result in modestly increased GHG emissions, depending on the regional grid mixture.** Avoiding vehicle charging during peak electric demand periods enables existing generation to support much of the incremental PEV demand, thereby reducing the need for additional capacity. At the same time, reducing additional capacity reduces the incremental system cost. In the present analysis, PEV market growth increases the system cost by 2.9% for the main Aggressive scenario compared to the Baseline scenario. Smart charging is estimated to reduce the increase in system costs for the Aggressive scenario from 2.9% to 2.7%. However, the modeling approach used may not capture the full potential of controlled or "smart" charging. More detailed simulations are needed to better understand the potential influence on PEVs of both smart charging and tailored future rate structures.
- **The cost of providing sufficient public charging infrastructure to support PEV markets is approximately half the value of the social benefits of GHG and petroleum reductions.** While PEV market responsiveness to greater or lesser levels of public charging availability is still uncertain, the present study assumes a base level of relatively high public charging availability to support strong PEV market growth in the Aggressive scenario. The workplace and public charging infrastructure estimated as necessary to support PEV market growth in the Aggressive scenario suggests a cost of $6.2 billion per year by 2035. In comparison, the social benefits of GHG and petroleum reductions by 2035 in the same scenario are $10.9 and $3.2 billion per year, respectively.

The remainder of the report provides additional details and explanations of the study topic, methodology, and results. Section 1 provides a brief introduction to the topic and relevant background information, including descriptions of previous related studies, a discussion of technology and policy factors influencing PEV market growth, and a brief review of existing policies supporting PEV markets today. Section 2 covers the analytic methodology, with a brief overview of the entire methodology as well as detailed discussions of each of the four models used in the analysis. Section 3 discusses intermediary results that are helpful in understanding the underlying factors that contribute to the economic valuation results. Section 4 reviews detailed economic valuation results for private, public, and total social costs and benefits, regional variations, results for jobs and economic activity, anticipated trends in criteria emissions, and sensitivities on key analysis inputs. Section 5 provides a summary of inputs and modeling limitations, conclusions in terms of scenario highlights and insights, and recommendations for future work.

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1 Introduction and Background

Growth in the market adoption of PEVs over the last four years has been unprecedented, with annual sales increasing from about 18,000 vehicles in 2011 to more than 110,000 vehicles per year in 2014 and 2015. This is approximately 0.7% of national LDV sales. From 2011 to August 2016, cumulative U.S. sales are approximately 500,000 PEVs (CAPEVC 2016). In addition to increases in total sales, and as indicated in Figure 1, the number of makes and models available to consumers has increased from 4 to 26 between 2011 and 2015. The most common makes and models are indicated in the legend, with the Chevy Volt, Nissan Leaf, Tesla Model S, and Toyota Prius Plug-in being the most common PEVs.[4] Falling gasoline prices, among other factors, resulted in reduced PEV sales in 2015, while PEV sales in the first and second quarter of 2016 exceeded quarterly sales in any previous year (Vlasic 2016; CAPEVC 2016). Announcements of additional future PEV makes and models are a strong signal of automotive commitment to PEVs, and a broad coalition of industry partners have recently committed to expanding nationwide networks of charging infrastructure (GCC 2016b; WHOPS 2016).

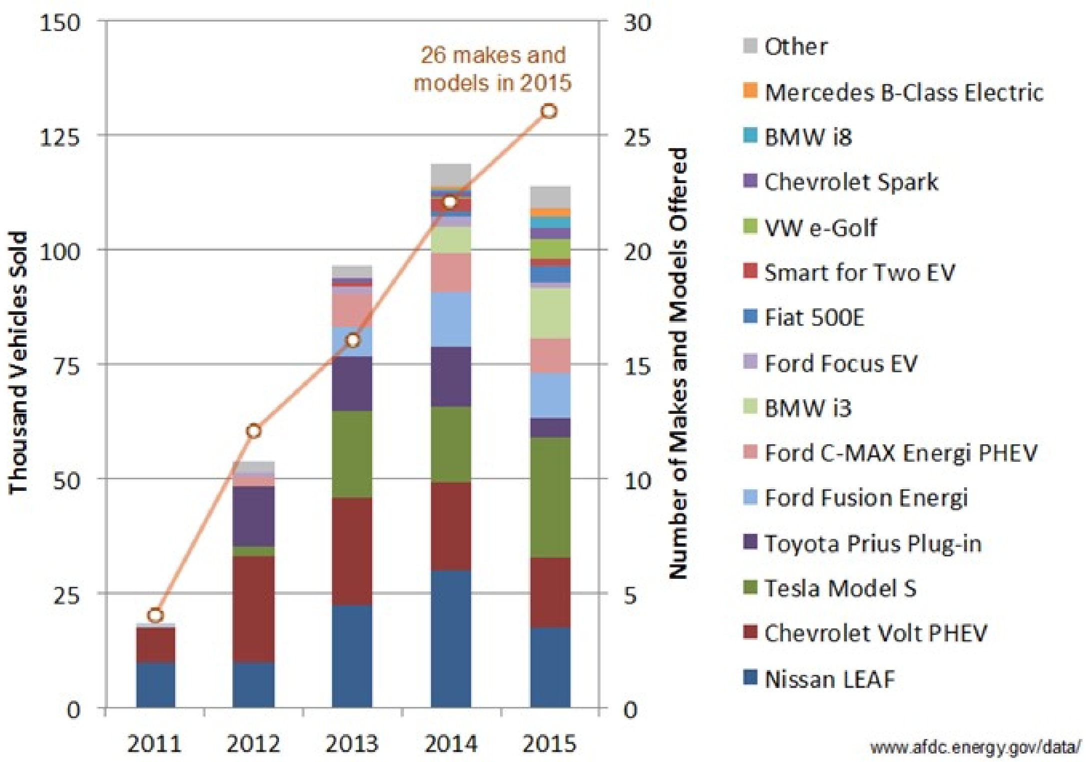

Figure 1. PEV sales per year by make and model (source: www.afdc.energy.gov/data)

In addition to these positive market trends, there have been significant advances in battery and electric-drive technologies as well as major increases in the availability of workplace and public charging infrastructure (Faguy 2015; AFDC 2016). During this same time period a variety of

[4] In addition to those indicated in the legend of Figure 1, years 2013–2015 had significant sales of the Toyota RAV4 EV, Cadillac ELR, Mitsubishi i-MiEV, Porsche Panamera and Cayenne E-Hybrids, Kia Soul EV, Honda Fit EV, Honda Accord, BMW X5, Tesla Model X, Mercedes S550 Plug in, and Volvo XC90.

state and federal policies have supported the commercialization of PEVs, though continued policy support will be required to maintain strong market growth. These support policies have typically been motivated by a desire to achieve one or more of the following goals (DOE 2013):

- Increase energy security by reducing U.S. dependence on imported oil
- Reduce fuel costs for households and businesses
- Protect the environment and public health by reducing criteria and greenhouse gas emissions
- Spur innovation in U.S. industry, create jobs, and generate economic growth.

While these recent market trends are promising, there are significant uncertainties associated with projecting future market growth for light-duty PEVs. Several studies have examined current trends, policy influences, and early adopter purchase preferences (Jin, Searle, and Lutsey 2014; Axsen and Kurani 2013). Market projections are highly uncertain due to the lack of consumer awareness and experience with PEVs among mainstream consumers as well as the complexity of policy drivers influencing LDV markets (Axsen and Kurani 2012; NRC 2015). A review of drivers and factors influencing PEV markets is provided in Section 1.3.

Rather than contributing to ongoing work to better understand the drivers and conditions for strong PEV market growth in the near term, the present analysis develops long-term future scenarios in which PEV market shares have increased dramatically by 2035. These future scenarios assume continued and aggressive progress in PEV technology development, including performance improvements and cost reductions in batteries, power electronics, and vehicle light weighting (Moawad et al. 2016). In general, the scenarios examined here assume that technology trends align with the technology development goals of the U.S. Department of Energy's (DOE's) Vehicle Technologies Office. While other studies examine these goals with respect to policy influences and market dynamics over the next several decades (NRC 2013; Greene, Park, and Liu 2013; Stephens et al. 2016; Ogden, Fulton, and Sperling 2016), the present study assumes that strong market growth occurs and focuses on an estimation of the long-term economic value of increased PEV adoption.[5] Therefore, as discussed in the executive summary, the approach is not a strict cost-benefit analysis of any particular set of policy mechanisms. Rather, the scenarios involve relatively simple comparisons of costs and benefits based upon fundamental relationships between PEV cost and performance trends, household driving behavior, and interactions between PEV charging and the regional evolution of the electricity grid out to 2035. The strong PEV market growth rate in the Aggressive scenario approximates that required to achieve an 80% reduction in LDV GHG emissions by 2035, as articulated and projected by the National Academy of Sciences report *Transition to Alternative Vehicles and Fuels* (NRC 2013).

This report is Volume I of the NEVA study, and it reviews all of the major modeling assumptions and final results. A subsequent Volume II report will examine a broader range of sensitivities around modeling input assumptions and the resulting influences on final results.

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[5] Scenario development can be a useful approach to explore future outcomes that are beyond the capabilities of predictive models (Wack 1985; Craig, Gadgil, and Koomey 2002).

The remainder of this chapter provides additional introductory and background information. Section 1.1 reviews the study problem statement and scope, section 1.2 reviews finding from previous studies, and section 1.3 is a brief overview of factors related to PEV market share growth. Section 1.4 reviews existing policies supporting PEV markets.

1.1 Problem Statement and Study Scope

There are many pressing policy issues and analysis questions related to the near-term commercialization of PEVs and other advanced alternative fuel vehicles. Some of these issues have persisted across multiple decades, reaching back to the first energy crisis in the mid-1970s, as reviewed by McNutt and Rodgers (2004) and more recently by Greene (2016). Several recent studies have focused on technology trends and policy mechanisms during the transition period in which advanced alternative fuel vehicles gain market dominance over conventional gasoline vehicles (NRC 2013; Greene, Park, and Liu 2013; Ogden, Fulton, and Sperling 2016). In contrast, the main research question addressed in this study is the following:

> *To what degree might PEVs benefit the U.S. economy over the long term, after market acceleration policies have subsided and PEVs have been adopted on a large scale, nationwide, and within mainstream consumer households?*

This question is of particular interest in the context of optimistic projections of technology progress and high market share success. Though the NEVA methodology does not estimate the probability of different levels of PEV market adoption, a future scenario with very high PEV market share is of interest to improve our understanding of several issues:

1. The capacity for PEVs to meet the driving needs of mainstream consumer households
2. Potential impacts on the grid resulting from large PEV electricity demands
3. The long-term value of continued technical progress with electric-drive and other advanced LDV technologies in terms of cost reductions and higher fuel economies
4. Future GHG emissions for PEVs relative to gasoline as regional electricity grids continue to decarbonize
5. Private and social benefits associated with a relatively stable PEV-success future achieved after market transformation efforts required to sustain strong market growth have subsided
6. The degree to which PEVs may be able to contribute to future GHG emission reduction targets, such as an 80% reduction by 2050.

Strong PEV market growth conditions are a prerequisite input assumption for the Aggressive scenario. The goal of developing the Aggressive scenario is to improve our understanding of key factors contributing to potential economic value of achieving strong PEV market growth over the next 20 years (see section ES.1). The Aggressive scenario therefore assumes market success occurs and focuses on the long-term economic allocation of electric drive vehicle technologies, charging infrastructure, and changes in electricity grid supply. To summarize this and other study scope topics, a series of relevant aspirational research questions related to PEV markets and economic value is presented in the left column of Table 1. Most of these research questions cannot be answered fully given existing empirical data on PEV technologies, market dynamics, and consumer behavior. The corresponding methods, assumptions, and contributions from the present study are listed in the right column of the table.

These aspirational research questions and corresponding study methods and assumptions should be kept in mind when considering the significance of the economic valuation results. Additional details on methods and assumptions are provided in section 2.

Table 1. Aspirational Research Questions and Corresponding Study Methods and Assumptions

Aspirational Research Questions	Study Methods and Assumptions
What is the maximum feasible rate of PEV adoption?	The study assumes 14% of all light-duty vehicle miles driven are e-miles by 2035 (NRC 2013). This requires approximately 73 million PEVs by 2035.
What policies would be required to achieve this maximum rate of adoption?	Policies promoting PEVs are not explicitly included in the economic valuation.
Can PEVs be widely adopted within the mainstream consumer market?	The approach assumes an economically efficient allocation of PEVs by type across all households based upon total miles driven, frequency of short- and long-distance trips, climate influence on fuel economy, regional gasoline and electricity prices, and the number of vehicles per household.
To what degree can public charging infrastructure increase the market adoption of PEVs?	Each scenario assumes a base level of relatively high public charging availability. However, the relationship to PEV market growth is not explicitly modeled.
What impact will PEV electricity demand have on the electric grid?	The additional electricity demand from PEVs is modeled explicitly. Grid simulation methods used in this study suggest an increase in electricity price, though more detailed simulation methods are needed to better understand demand impacts. Innovative means of moderating these impacts exist, but they are not fully addressed in this study.

1.2 Review of Previous Studies

This study explores potential economic benefits associated with widespread adoption of PEVs out to 2035. There are a growing number of studies looking at similar issues. Each study contributes differently to improve modeling methodology, geographic scale, or a variety of other factors. This section provides a review and comparisons with some of the most relevant reports, notably the 2001, 2007, and 2015 reports by the Electric Power Research Institute (EPRI) and the 2014 California Transportation Electrification Assessment (TEA) reports.

EPRI has released several reports that explore the benefits and impacts of introducing a large number of electric vehicles across the United States. In their 2001 report, EPRI explored the benefits of HEVs with no all-electric range and PHEVs with 20- and 60-mile all-electric range (EPRI 2001). They found that HEVs, including those that can plug in, offer great efficiency improvement, potential petroleum use reduction, and substantial greenhouse gas and criteria pollutant emissions reductions. Impacts on oxides of nitrogen and hydrocarbon emissions were explored. Similar to the current study, it was recognized that the use of HEVs will result in an incremental increase of cost ranging from $2,500 to $10,000 per vehicle, depending on the electric range. It was also seen that HEVs result in a reduction in the total cost of energy, which includes the use of gasoline and electricity.

EPRI also published a study in 2007 that investigates the GHG emissions and air quality impacts of aggressive market penetration of PHEVs (EPRI 2007a, 2007b). The study was separated into two parts; the first part focused on GHGs and the second on air quality and criteria pollutants. Similar to the present study, models are run to understand the dynamics of vehicle adoption and utility and grid resource mixture impacts, and then the GHG and pollutant emissions are calculated.

EPRI found that the well-to-wheels GHG emissions decrease more for vehicles with high electric range than for vehicles with lower electric range. For criteria pollutants, deployment of PHEVs is found to reduce exposures to ozone and particulate matter in many regions and can reduce the rates of deposition for acids, nutrients, and mercury. The benefits increase with an increase in the amount of all-electric vehicle miles traveled (VMT) or greater emissions constraints on electric power generation.

The 2015 report by EPRI focuses on exploring the environmental impacts of a variety of electric vehicles in future U.S. scenarios (i.e., light-duty and medium-duty transportation and industrial equipment). Estimates for greenhouse gas emissions, criteria pollutants, and resulting air quality are assessed for several scenarios in the year 2030. Interactions with the electricity grid are modeled using EPRI's Regional Energy and Economic Model Development and the US-REGEN model. All scenarios show that inclusion of electric vehicles results in the reduction of total GHG emissions and electrification of transportation can lead to improved air quality.

The California TEA reports were prepared by ICF International and Energy and Environmental Economics. There are two phases for this study resulting in two reports (CalETC 2014a and 2014b). Phase 1 was released in August 2014 and focuses on the role of electrified transportation to support California GHG and air quality goals. Similar to the current study, a variety of vehicle types and market sizes were selected. The TEA study includes PEVs for passenger cars and light trucks as well as forklifts, truck stop electrification, and transport refrigeration units, while the current study only focuses on PEVs. Though the geographical scale and scenarios are different, benefits were calculated in a very similar manner. The results with electric vehicles were compared to those with conventional vehicles to determine the incremental differences. Assumptions for VMT and energy consumption for the TEA study are drawn from Argonne National Laboratory's VISION model.

Phase 2 focuses on analyzing impacts on the electric utility costs (Energy and Environmental Economics 2014). The study finds that there are potentially significant net benefits for customers and the state of California. The TEA study explores distribution system upgrades, impacts from varying the charging strategy, and infrastructure costs. The current study does not explore distribution system impacts but does consider time-resolved charging when considering grid impacts, and it also explores the added cost of additional charging and infrastructure for the entire United States.

Some of the studies in the literature calculate the impact of electric vehicles on criteria pollutant emissions and a smaller subset also perform an economic assessment. Three examples include (1) the 2015 EPRI-NRDC vehicle electrification study (EPRI 2015), (2) a study by Carnegie Mellon University (CMU) looking at electric vehicle impacts in PJM, a regional transmission operator in the north eastern United States (Weis et al. 2015), and (3) the CalETC study, which focuses on the California grid (ICF 2014 and Energy and Environmental Economics 2014).

The EPRI-NRDC study explores the impacts of a national rollout of electric vehicles on both GHG emissions and criteria pollutants. They find that, in aggregate, vehicle electrification reduces all pollutants (NO_x, SO_2, VOC, and $PM_{2.5}$) across all sectors. This study did not look at the economic implications of reduced pollutants. The CMU study found that in a near-term, high coal grid (PJM), delayed vehicle charging reduces generation costs; however, criteria pollutant emissions costs increase, largely driven by increases in CO_2, SO_2, NO_x, and $PM_{2.5}$. The increasing emissions costs offset social petroleum displacement costs resulting in a net increase in costs. This is not necessarily true for future and high wind grid mixes in PJM. The study found that the emissions per electric vehicle decline moving from the current grid to the future grid. This resulted in overall lower life cycle damage costs for PHEVs. In contrast, the CalETC study, which examines the California grid, shows the change in criteria pollutant emissions creates a benefit even for the current grid and grows with time. The differences are likely due to the grid mixture in California, where the thermal fleet is largely natural gas combined cycle plants, while PJM has a significant coal fleet.

Previous studies generally show improvements with the addition of electric vehicles with respect to GHG emissions and criteria pollutants but also caution that the time that vehicles charge and the grid mixture in their area are important to consider. From an economic perspective, a few previous studies have explored the benefits and costs associated with alternative vehicles. The EPRI 2001 study explored the benefits of HEVs in comparison to conventional vehicles. CMU provided a comparison of life cycle benefits and costs for a variety of vehicles and different grid mixtures in PJM territory. Lastly, the CalETC study provided a benefit-to-cost ratio for electric vehicles in California considering both private and public components.

The present study builds upon previous studies by expanding the geographic scope to the national scale, while maintaining regional detail, and extending PEV market projections through 2035 when a cleaner grid has been developed in response to policy constraints and technology improvements. This study does not address the economic value of criteria emissions, which were addressed nationally in the 2015 EPRI study, but it does include external costs for GHG emissions and petroleum reductions. The result is an assessment of the overall private and public benefits associated with the expansion of the electric vehicle fleet for the entire United States.

1.3 Increasing PEV Market Share

Strong PEV market growth into the future will require a strong value proposition to consumers and continued market support mechanisms to overcome various barriers to adoption, such as lack of consumer awareness, lack of EVSE availability, and economics of scale in PEV component manufacturing (NRC 2015; Greene, Park, and Liu 2013). The market and policy environment for

PEVs is complex, and various studies have attempted to simulate one or more of the key complexities (Struben and Sterman 2008; Eppstein et al. 2011; Shepherd, Bonsall, and Harrison 2012). In contrast to these previous efforts, this study does not develop new estimates of future PEV market shares. Instead, an Aggressive scenario with high PEV market share growth is derived from a National Academy of Sciences study of the "maximum feasible market expansion" of PEVs (NRC 2013). While much has been learned about PEV market adoption since completion of the 2013 NRC study, many uncertainties remain and recent market trends in PEV market growth are still not statistically significant enough to develop robust forecasts of future market trends.

As background on the motivation and design of the present study, some of the key factors leading to either increased or decreased PEV market growth are reviewed in Figure 2. The left side of the figure indicates two main dynamics related to gasoline market prices. First, increased gasoline prices are expected to make PEVs more attractive to consumers, while lower future gasoline prices will tend to erode the fuel savings expected to result from purchasing a PEV. Second, a longer-term feedback loop is the possibility that domestic (and global) success of PEV markets could result in decreased demand for gasoline, resulting in a reduction in gasoline prices, which in turn may lead to decreased PEV market growth. Though this is a long-term potentiality, it has been highlighted in previous studies as a significant issue for policymakers working to develop an enduring framework to support the widespread commercialization of PEVs and other alternative fuel vehicles (Small and Dender 2007).

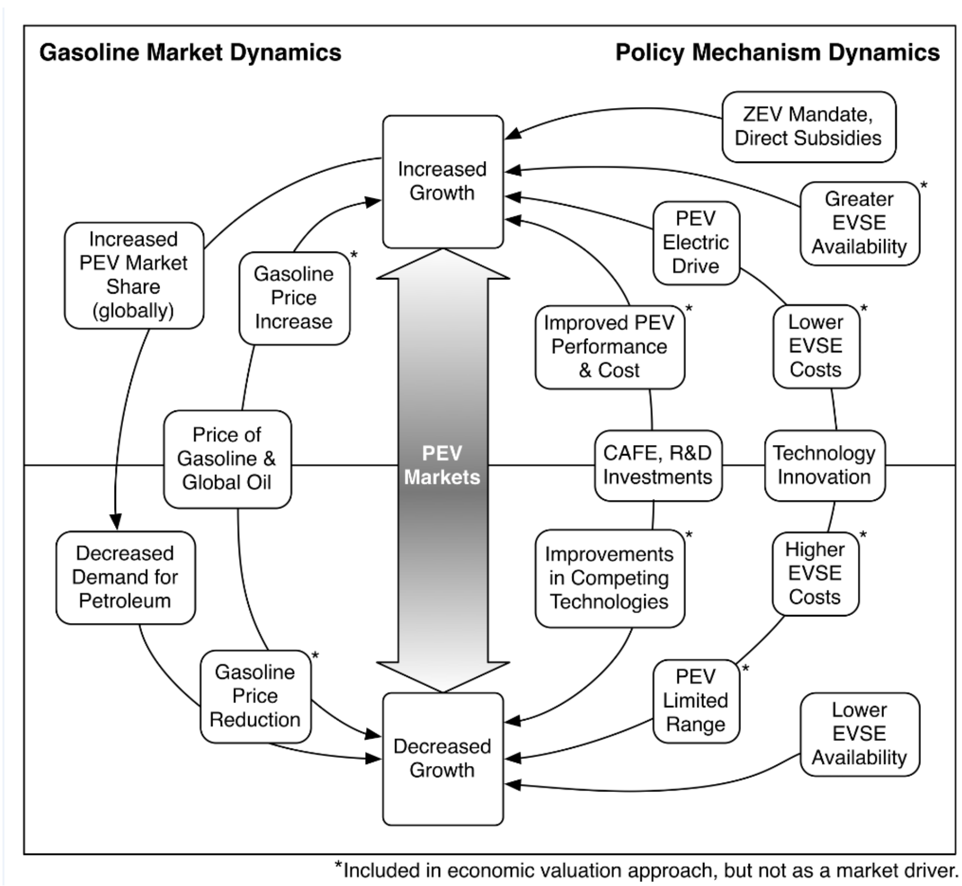


Figure 2. PEV market growth drivers and dynamics (source: NREL)

The right-hand side of Figure 2 indicates a number of dynamics resulting from various policy mechanisms, most already being established, but some that could be reinforced or weakened over the next 5–10 years based upon policymaker decisions. These mechanisms can be separated into the following four categories. Of these four, categories 2 and 3 are addressed explicitly in the present study:

1. **Established policies.** The CAFE standard is in place and requires manufacturers to produce more efficient LDVs. This mechanism may result in increased PEV performance and cost, resulting in improved PEV competitiveness, but it may also result in improved technologies competing in the LDV sector. Moreover, the current structure of CAFE may have little net impact on PEV markets or benefits (Jenn, Azeveo, and Michalek 2016). A second established policy is continued investments in the research and development pipeline to generate improved vehicle technologies. Again, these activities may benefit PEVs, resulting in increased market share, and they could also benefit competing technologies to the degree that PEV sales are inhibited.
2. **Technology innovation.** Auto manufacturers and EVSE suppliers will generate innovative technology and business case solutions as PEV markets grow. Two key issues are reductions in EVSE costs to consumers and increased all-electric range for PEVs, both of which can lead to increased PEV market growth. Increased all-electric range can increase consumer fuel savings and reduce range anxiety for BEVs. By comparison, higher EVSE cost trends and shorter all-electric range for PEVs will tend to dampen PEV market growth.
3. **EVSE availability.** One option for compensating for the limited range of BEVs is to increase the availability of public EVSE networks, although direct causal relationships between PEV purchase behavior and EVSE availability are not well understood. It is not clear, for example, how much more consumers are willing to pay to enable more extensive EVSE networks. However, it is very likely that some level of increased EVSE availability will result in increased PEV sales.
4. **Focused PEV incentives.** Several states have adopted financial incentives, such as rebates, focused on PEVs. Other states have adopted the ZEV Mandate, requiring automakers to comply with predetermined levels of ZEV credits. These types of PEV-specific policies can lead to increased PEV market share.

It is anticipated that additional PEV makes and models will continue to be introduced over the next 5–10 years, and that costs for batteries and other electric-drive components will decline with increased production volumes. As PEV markets evolve over time, consumer responsiveness to gasoline prices and PEV retail prices will become more applicable to the general population as more diverse consumers (e.g. other than early adopters) make the decision to purchase a PEV. The degree to which increased consumer awareness in general influences purchase decisions, and is therefore a market driver in and of itself, is another key consideration.

As PEV market growth occurs, additional data can be collected to better understand the degree to which mainstream consumers might value the electric-drive experience of PEVs and the degree to which limited range of BEVs can be compensated for by increased availability of public charging. Gaining an improved empirical basis for understanding how consumers value these factors will increase the reliability of PEV market forecasting models.[6] The degree to which increased consumer awareness influences purchase decisions, and is therefore a market driver in and of itself, is another key consideration.

While predictive models will improve over time, the present study attempts to place into context some of the market factors shown in Figure 2 by exploring general trends anticipated over the long term. During the early years of PEV market growth, tradeoffs between these various factors may be very dynamic. However, if relatively more stable conditions are established to accelerate PEV market growth, there will be particular costs associated with those conditions. A major focus of the present study is the development of a national estimate of the costs associated with achieving stable PEV market growth conditions between today and 2035. This scenario development process is considered less challenging, analytically, than attempting to simulate the cause-and-effect dynamics spanning the transitional market growth period between today and 2035.

For a brief review of existing policies in place today to support PEVs see section 1.4.

1.4 Review of Existing Policies Supporting PEVs

National-, state-, and local-level decision makers across the country are using policy measures and incentives to encourage the electrification of the transportation sector and to adjust existing processes to account for the increased adoption of electric vehicles by consumers. The sheer number and variety of policies and incentives, and their nuances across different states, makes for a policy environment that is both challenging to summarize and complex to analyze. Over the past few years, at least three reports have provided a thorough review of the policy landscape and provided insight to the effectiveness of the measures at increasing customer adoption.

The International Council on Clean Transportation provides a review and quantification of the incentives that states across the United States are using to encourage PEV deployment (Jin, Searle, and Lutsey 2014). They value both direct incentives (e.g., monetary incentives like rebates, financing, and free charging) and indirect incentives (e.g., benefits like high occupancy vehicle [HOV] lane access and emissions testing exemptions) to understand the total value of incentives within each state, for BEVs and PHEVs individually. Colorado and Georgia are found to provide the highest level of total consumer benefit for BEVs, while California and Hawaii lead for PHEVs. Colorado, California, Louisiana, Illinois, Hawaii, Pennsylvania, and South Carolina have total incentive values above the U.S. average for both vehicle types. Other states are more technology specific, providing higher incentives for BEVs (Georgia, New Jersey, Arizona) or PHEVs (Washington, Maryland).

The total values assigned to the benefits are used to explore the connection between incentives and vehicle sales. Not all incentives are found to be equally effective in deploying vehicles; policies designed to promote BEVs are deemed to be more effective than those for PHEVs.

[6] Consumer choice models supported by the DOE today generate widely varying results in attempts to predict PEV market shares. See Stephens et al. (2016).

Finally, the relative cost-effectiveness of providing direct subsidies, HOV lane exemptions, public charging, and incentives for home chargers is determined through a regression analysis. Public charging yields the highest cost-benefit ratio for BEVs. HOV exemptions are the most cost-effective incentive for PHEVs (and rank second best for BEVs).

In a follow-on analysis, the International Council on Clean Transportation (Lutsey et al. 2015) investigates the link between incentives and PEV deployment for 25 U.S. metropolitan areas. Results indicate that policy indeed accelerates EV development in several cities, particularly those in states that have adopted the California Zero Emission Vehicle (ZEV) program. In particular, statistical correlations were found between the share of PEVs in a city and the number of public chargers, the value of monetary incentives, and the number of vehicle models available for purchase.

In addition to California's cities, Atlanta, Seattle, and Portland are among leading metropolitan areas, touting impressive vehicle sales figures driven by effective policy. The authors conclude that cities are an important focus point for collaboration between governments, the auto industry, electric utilities, and advocacy groups that is driving the EV market forward.

Another recent report from the Luskin Center at the University of California, Los Angeles (DeShazo et al. 2015) provides a summary of the state-level incentives that reduce the purchase price of PEVs, incentivize the installation of charging infrastructure, and enhance EV driver experiences. Individual customers may receive state rebates of $1,500–$4,000 toward the purchase of an EV. Tax credits are in the range of $600–$7,500 and sometimes depend on vehicle type.

Figure 3 indicates the variety and distribution of state-level policies impacting PEV owners across the country. The policies are categorized according to type, although it should be noted that there are significant differences in the details of the policies within each category. While many of the policies reduce costs or increase convenience to EV drivers, there are also policies that aim to even the playing field between owners of traditional and electric vehicles. The most common examples are an additional registration fee for alternative fuel vehicles and a tax on alternative fuels. Detailed information about individual policies is accessible from the DOE Alternative Fuels Data Center, accessible online at www.afdc.energy.gov.

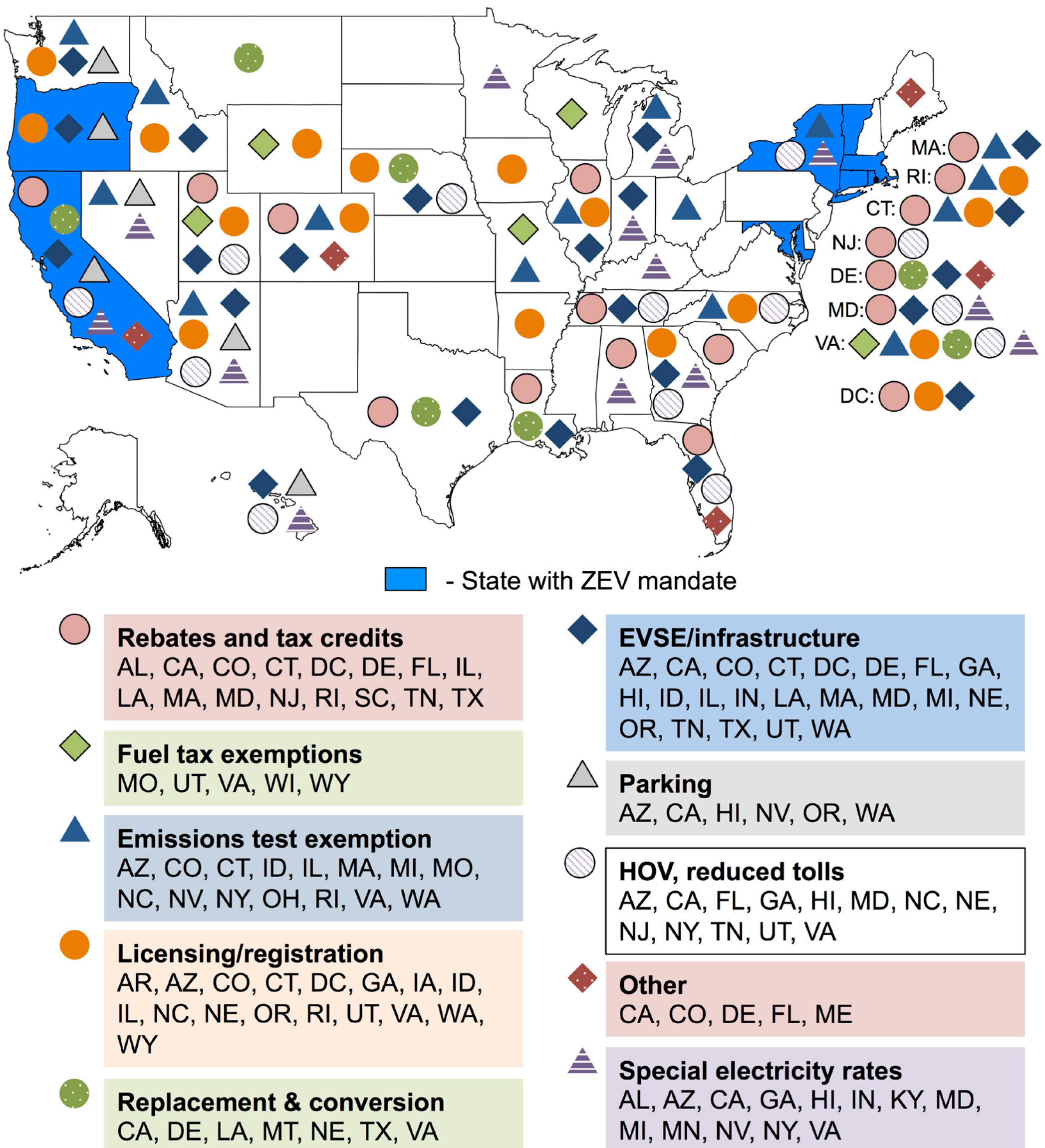


Figure 3. Policies and incentives supporting plug-in electric vehicles

2 Methodology

This section of the report includes five subsections. Section 2.1 gives an overview of the entire study methodology, briefly explaining the major models used, how calculations flow from one analytic model to another, and how scenario variations are developed to address the problem statement and study scope described in the previous section. The subsequent four sections describe the assumptions, input data, and application of the following topics and analytic models (model acronyms and names shown in parentheses):

- Section 2.2. Vehicles, driving, and charging
(BLAST-V: Battery Lifetime Analysis and Simulation Tool for Vehicles)
- Section 2.3. Vehicle fleet, EVSE, and economic accounting
(SERA: Scenario Evaluation and Regionalization Analysis)
- Section 2.4. Electricity generation costs and emissions
(ReEDS: Regional Energy Deployment System)
- Section 2.5. Jobs and economic impact modeling
(IMPLAN: Impact Analysis for Planning).

These sections provide more detailed descriptions of the overall methodology reviewed in Section 3.1. Figure 4, described below, provides a concise summary of the analytic framework and interactions among the four models and can be used as a guide to the content within and connections between the analytic approaches described in Sections 3.2 through 3.5.

2.1 Methodology Overview

The methodology allows for a detailed examination of the long-term economic value of PEVs deployed regionally and nationally. The value assessment involves a consistent accounting of the following private and public costs and benefits:

- **Private costs**
    - The incremental retail price to consumers of PEVs compared to CVs and HEVs
    - The capital cost of home EVSE
- **Private benefits**
    - The net value of household gasoline savings as electricity is substituted for gasoline
- **Public costs**
    - The capital cost of workplace and commercial EVSE stations
- **Public benefits**
    - External costs associated with GHG emission and petroleum import reductions
    - Any macroeconomic benefits in terms of increased jobs or GDP.

The approach involves an internally consistent stock model to account for vehicle technology cost trends over time, fuel economy trends over time, vehicle vintages and retirements, and fuel utilization calculations based upon annual VMT by vehicle type, region, and LDV vintage (e.g., model year) fuel economies. The calculations are resolved at multiple geographic scales, with final results reported both nationally and by census division. The approach does not account for market dynamics, costs and benefits for particular stakeholder groups, or an explicit representation of specific policy drivers. It is therefore a bottom-up, techno-economic cost estimation approach rather than a formal market-based cost-benefit analysis methodology as discussed and applied elsewhere (c.f. Massiani 2015; Michalek et al. 2011). The approach does not include a vehicle adoption model and therefore does not address the transition period as PEV markets are developed over time, but instead examines a future scenario in which PEVs have already achieved significant market success by 2035. For studies employing similar bottom-up approaches that do address the transition period and influence of policy drivers, see the National Academies study on *Transitions to Alternative Vehicles and Fuels* (NRC 2013), the Baker Institute study on electric drive vehicles in California (Greene, Park, and Liu 2013), or the recent University of California, Davis study of alternative fuel transitions (Ogden, Fulton, and Sperling 2016).

Figure 4 provides a high-level overview of the methodology with respect to the four main analytic models employed. This figure can be used as a guide to sections 2.2 through 2.5 and is also reviewed briefly here to explain high-level interactions and data exchange between models. The variables indicated in the figure correspond to the equations, explanations, and definitions provided in Box A. These are a simplified version of the actual calculations used in the study and are presented for explanatory purposes only. For more extensive and detailed explanations of the calculations used within each model, see the descriptions provided in sections 3.2 through 3.5, as well as the documentation and reports referenced for each model.

The approach begins by incorporating a quantitative characterization of vehicle cost and performance attributes from Moawad et al. (2016), as well as driving and charging behavior based upon National Household Travel Survey (NHTS) data. These are shown along with other assumptions and calculations in the blue box labeled *Vehicles, driving and charging*. These calculations are determined using the BLAST-V model, which simulates the performance and resulting utilities for all LDV platform options in different U.S. regions and for different NHTS households. The utilities reflect the degree to which different PEVs meet household driving needs and take into account both the frequency of long-distance trips and adjustments to real-world fuel economy due to regional variations in climate. The resulting utilities for each vehicle type are then passed to the *Vehicle fleet, EVSE, and economic accounting* model, SERA, which incorporates vehicle and EVSE cost and performance characteristics to determine private costs and relative vehicle market shares by region ($C_{Hm\text{-}EVSE}$ and $C_{W/C\text{-}EVSE}$). Preliminary regional electricity prices are used at this point in the calculations to determine the PEV market shares required to meet the e-mile scenario target (14% of all VMT as e-miles by 2035). This e-mile constraint ($VMTe$ and $VMTg$) is only applied to determine PEV market shares (N_{PEVs}) in the main Aggressive scenario. All other scenarios have total e-mile results and PEV market shares that vary based upon which input assumptions or sensitivities are being explored.

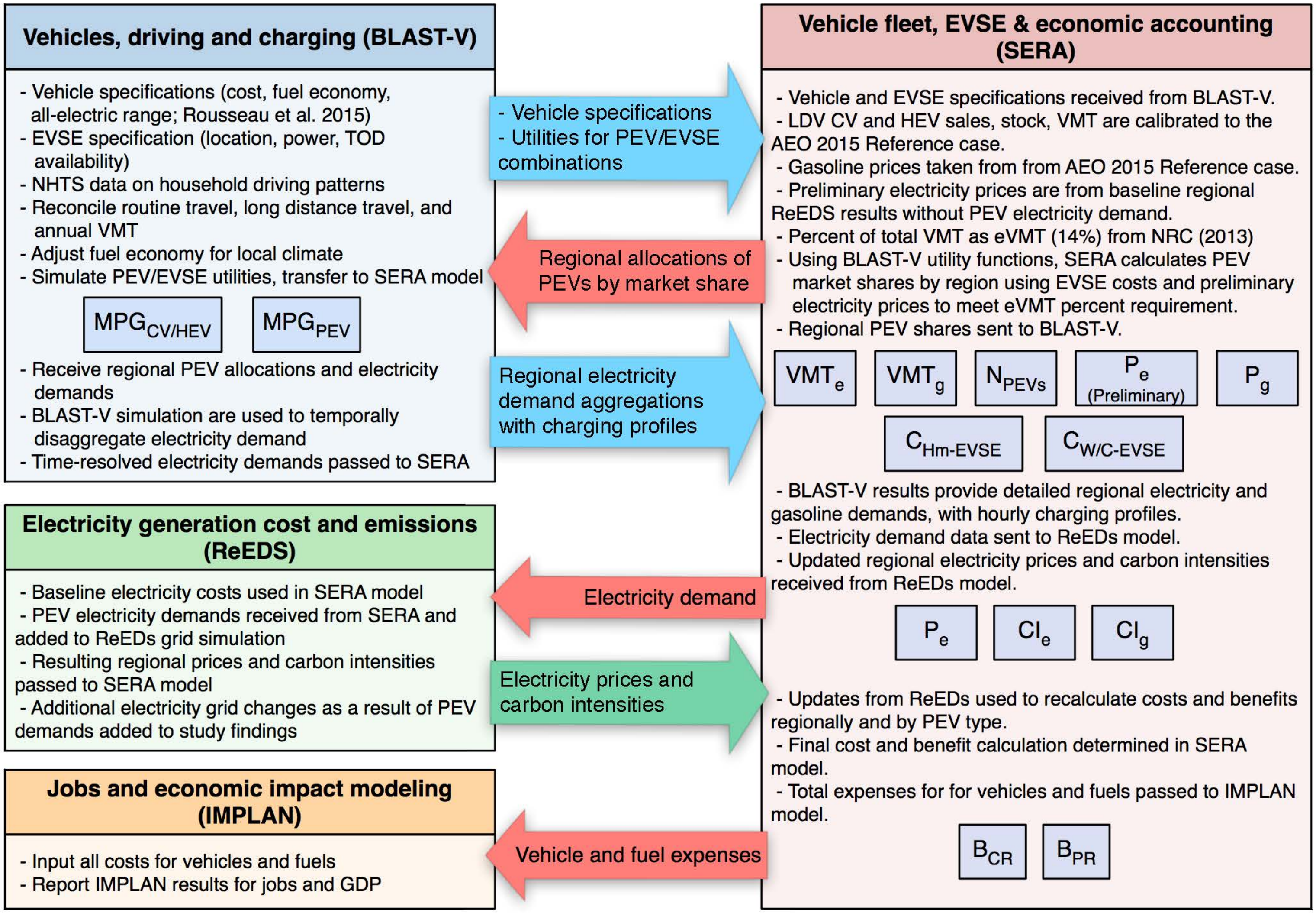


Figure 4. Methodology overview

Box A: High-Level Economic Valuation Equations

The end result of all economic value calculations is the total social benefit (B_{TS}), which is the net change in total costs and benefits associated with increased PEV market share in any given PEV scenario compared to the corresponding Baseline scenario. This result is shown in Equation A1 as consisting of the sum of private costs (C_P) and three "public" or common costs shared across all households in a region: (1) the cost of workplace and commercial EVSE ($C_{W/C\text{-}EVSE}$), (2) the benefit of carbon or GHG emission reductions (B_{CR}), and (3) the benefit of petroleum import reductions (B_{PR}). These results can be expressed in terms of dollars per year or in terms of dollars per year per PEV. These values are calculated in the SERA model as a summation of all vehicles deployed within and fuel and electricity consumed by the LDV fleet over time up to the year 2035. To set capital costs for vehicles and EVSE on a similar basis as fuel savings, they are spread out over a nominal lifetime of 11.68 years (see section 2.1.3). Each of these four components of total social benefits is reviewed in turn below.

Equation A1

Total Social Benefits		Private Costs		Cost of Workplace & Commercial EVSE		Benefit of Carbon Reductions		Benefit of Petroleum Reductions
B_{TS}	=	C_P	+	$C_{W/C\text{-}EVSE}$	+	B_{CR}	+	B_{PR}

Private costs (C_P) include the three components shown in Equation A2. The first is the incremental vehicle cost, which is the difference between PEV retail cost (C_{PEV}) and the retail cost of the conventional and gasoline hybrid electric vehicles being displaced by PEVs ($C_{CV/HEV}$). The second component is the capital cost of home EVSE ($C_{Hm\text{-}EVSE}$). The third component is fuel savings associated with substituting electricity for gasoline when PEVs are adopted into households. Fuel savings are calculated as the difference between gasoline costs incurred before the introduction of PEVs and the sum of gasoline and electricity costs after the introduction of PEVs. As shown, fuel savings are determined as miles driven multiplied by fuel price and divided by fuel economy. In the equation below this is shown as a simple difference; the actual calculations in the SERA model account for changes in VMT, fuel prices, and fuel economies with respect to improving fuel economies of new LDVs, and the geography and temporal variations in fuel prices, VMT per vehicle, vehicle aging and retirements, and influences of climate on fuel economy and e-mile range.

Equation A2

Private Costs		Incremental Vehicle Cost	Home EVSE Cost	Incremental Fuel Savings: Gasoline Cost	Electricity Cost
C_P	=	$C_{PEV} - C_{CV/HEV}$	$+\ C_{Hm\text{-}EVSE}$	$-\left[\dfrac{VMT_g * P_{gsln}}{MPG_{CV/HEV}}\right.$	$\left.-\ \dfrac{VMT_e * P_{elec}}{MPG_{PEV}}\right]$

Cost of workplace and commercial EVSE ($C_{W/C\text{-}EVSE}$) is estimated as a total cost (capital and installation) per level 1 or level 2 EVSE station installed either at a workplace or commercial location. Because some workplace EVSE may also be available to the general public, and because PEVs using workplace chargers may change over time, both EVSE types are included as "public" EVSE available to the general PEV fleet. Details on the cost per station and number of workplace and commercial stations per PEV by type are described in section 3.3.2.

Benefit of carbon reduction (*B_{CR}*) is determined by multiplying the number of e-miles driven by two factors: (1) the difference in the per-mile carbon intensity of the gasoline vehicles compared to the PEVs displacing those vehicles, and (2) the social cost of carbon (C_{SCC}). Total e-miles driven is the total number of PEVs (N_{PEV}) multiplied by the e-miles driven per PEV (VMT_e). Per-mile GHG emissions are determined as the carbon intensity of gasoline or electricity (CI_{Glsn} and CI_{Elec}) divided by the fuel economy of the LDVs using those fuels (MPG_{CV} and MPG_{PEV}). The social cost of carbon varies over time with units of dollars per ton of carbon dioxide (see section 2.3.3).

Equation A3

Benefit of Carbon Reductions		Number of PEVs		e-miles driven		Difference in GHGs per mile (gasoline vs electricity)		Social Cost of Carbon
B_{CR}	=	N_{PEV}	×	VMT_e	×	$(CI_{Gsln}/MPG_{CV} - CI_{Elec}/MPG_{PEV})$	×	C_{SCC}

Benefit of petroleum reduction (*B_{PR}*) is determined by multiplying the reduction in gasoline consumed as a result of introducing PEVs by a fixed value representing the social value of reducing U.S. petroleum imports. The calculation of reduced gasoline consumption is identical to that used to determine fuel savings, consisting of total miles driven by gasoline vehicles divided by vehicle fuel economy, in each PEV scenario and corresponding Baseline scenario. A more detailed discussion of this social benefit is provided in section 2.3.3.

<u>Key for variables</u>

B_{CR} = Benefits of carbon reductions ($/year)

B_{PR} = Benefits of petroleum reductions ($/year)

$C_{Hm\text{-}EVSE}$ = Cost of home electric vehicle supply equipment ($/unit)

$C_{W/C\text{-}EVSE}$ = Cost of work or commercial electric vehicle supply equipment ($/unit)

CI_{Gsln} = Gasoline carbon intensity (g CO_2eq/MJ)

C_{SCC} = Social cost of carbon ($/tonne CO_2e)

$MPG_{CV/HEV}$ = Fuel economy of conventional or hybrid electric vehicles (miles per gallon)

MPG_{PEV} = Fuel economy of plug-in electric vehicles (miles per gallon gasoline equivalent)

N_{PEVs} = Number of plug-in electric vehicles

P_{elec} = Price of electricity (cents/kWh)

P_{gsln} = Price of gasoline ($/gallon)

VMT_e = Electric vehicle miles traveled (miles per year)

VMT_g = Gasoline vehicle miles traveled (miles per year)

After determining PEV market shares, driving simulations are developed in BLAST-V for the resulting regional distributions of PEV fleets to determine variations in charging profiles, fuel economies ($MPG_{CV/HEV}$ and MPG_{PEV}), and resulting electricity demand. This step takes into account a broad range of combinations of PEVs and charger types. The resulting electricity demands are passed to the SERA model to resolve geographic disaggregation and then to the *Electricity generation cost and emissions* (ReEDS) model to estimate marginal generation costs and GHG emissions for electricity. Resulting electricity prices from ReEDS, resolved at the geographic scale of census divisions, are then used to recalculate public and private costs using updated price and electricity GHG values in the SERA model (B_{CR} and B_{PR}). These final results are passed to the jobs and economic impact model (IMPLAN) to generate additional macro-scale results.

2.1.1 Vehicle and EVSE Station Input Assumptions

This section provides a brief overview of input assumptions for vehicles and EVSE stations. The cost and performance of future LDVs are taken from the optimistic technology progress results of a recent assessment in which batteries and other vehicle components attain DOE research and development goals over time (Moawad et al. 2016). Retail costs to consumers for new LDVs in 2035 are shown in the second column of Table 2 for each vehicle type. The real-world fuel economies for operation on gasoline and electricity are also indicated, as well as the nominal all-electric range in e-miles for BEVs. The last two columns indicate nominal annual miles driven for typical vehicles and the split between gasoline miles compared to electric miles for PHEVs. The gasoline miles indicated for BEVs represent miles incurred on long-distance trips that a BEV could not fulfill and are therefore driven by a CV or HEV within the same household. In the full set of calculations determining social benefits, the vehicle costs change over time (see Figure ES-1), fuel economies vary slightly by climate, and annual VMT vary regionally based on household travel data (see section 2.2). The resulting VMT and fuel economy values are combined with regional gasoline and electricity prices to determine gasoline fuel savings.

Characteristics of the EVSE stations deployed to support PEVs are indicated in Table 3 and are listed by location and type. As would be the case with actual LDVs offered in the marketplace by 2035, types of EVSE supporting PEVs would be different from those used today and would likely include significant diversity in terms of functionality, power levels, and costs. The characteristics indicated here are used as average values in the economic value calculations. Characteristics such as capacity could vary significantly; the values indicated are nominal values based upon typical systems offered today. The capital and installation costs indicated are taken from the lower ranges of EVSE costs seen today because it is anticipated that costs will decline over time with increased manufacturing volumes, streamlined permitting, and experience with siting and installation. While future workplace or commercial EVSE may be acquired by businesses that attain revenue by means other than the sale of kWh to PEVs, as is the case with gasoline convenience stores today, the economic value analysis assumes that the full capital costs indicated are eventually born by PEV owners. The last two columns in the table indicate the number of EVSE required per 1,000 PEVs deployed. Additional details on EVSE modeling assumptions are provided in Section 2.3.2.

As discussed in the following section, the relative market shares for each PEV type in future scenarios are determined based upon the perceived cost of each vehicle to average consumers in each region. This consumer perceived cost is determined based upon the vehicle and EVSE costs discussed above and accounting for temporal and regional factors influencing average annual VMT, fuel economies, and fuel prices. It is assumed, for this simplified assessment, that consumers place value on the first 7.5 years of fuel costs. This payback period is longer than expected from typical consumers (c.f. Elgowainy et al. 2013); it is justified here on the assumption that in order to achieve very high PEV market shares by 2035, some consumer behavior decisions tools (or policies) have been established to increase consumer awareness of the benefits of future fuel savings. For a discussion of consumer perceptions of green product attributes, see Ottman, Stafford, and Hartman (2006). While total e-miles are fixed in the Aggressive scenario, reducing this payback time to a lower value would tend to increase the market share of less expensive PEVs that have lower fuel economies. A comparable sensitivity has been conducted for the demand elasticity parameter, as discussed in section 4.8. A second important assumption is the imposition of a perceived consumer cost penalty for the limited range of BEVs, based upon the all-electric range of the BEV. This penalty is based upon statistical analysis of historical vehicle purchases and is consistent with some stated preference survey results (Brooker et al. 2015; Helveston et al. 2015).

A graphical example of how these perceived consumer costs compare across LDV types in shown in Figure 5. The upfront retail purchase price of the vehicle (blue bar) dominates, and relative fuel costs for gasoline (grey bar) or electricity (green bar) decline for PHEVs with larger batteries and BEVs with longer all-electric ranges. Home EVSE costs are an additional consumer cost (orange bar). The range penalties for BEVs are shown as the final (and most uncertain) cost as a blurred red bar, declining for BEVs with longer all-electric range, and reduced from the original penalty estimates by 40% due to wide availability of public charging infrastructure in the Aggressive scenario. Treatment of the BEV range penalty is discussed in section 2.3.

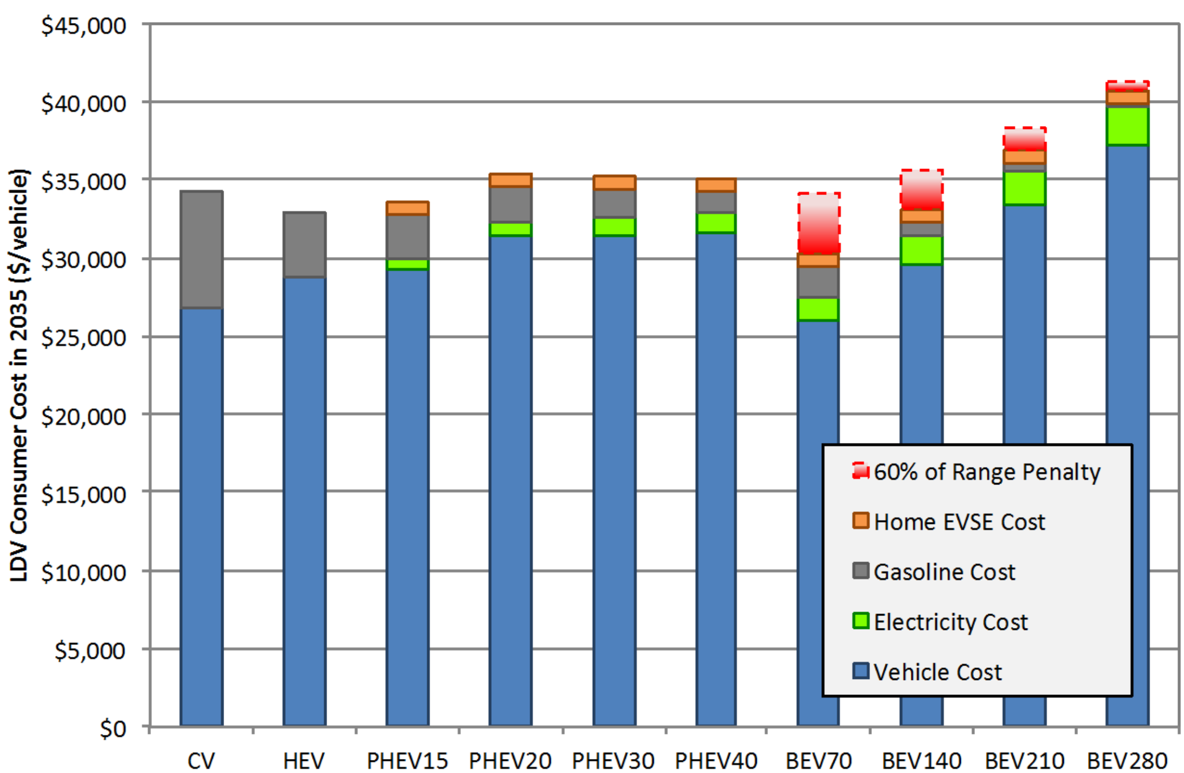


Figure 5. Costs to consumers per year by PEV type in 2035 using nominal miles traveled per year

Table 2. Attributes for LDVs Sold in 2035 in the Aggressive Scenario

LDV Type and Electric Miles	Attributes of New LDVs Sold in 2035					
	Vehicle Retail Price	Fuel Economy		Range (miles)	Nominal Miles/Year	
		Gasoline (mpg)	Electricity (Wh/mile)		Gasoline	Electricity
CV	$26,800	47.6	-	350	13,600	-
HEV	$28,800	87.8	-	350	13,600	-
PHEV15	$29,300	89.7	186	350	9,100	4,500
PHEV20	$31,400	90.1	173	350	7,600	6,000
PHEV30	$31,500	90.8	174	350	6,500	7,100
PHEV40	$31,600	92.3	174	350	5,100	8,500
BEV70	$26,000	-	178	70	*(3,600)*	10,000
BEV140	$29,600	-	182	140	*(1,500)*	12,100
BEV210	$33,500	-	195	210	*(800)*	12,800
BEV280	$37,300		208	280	*(500)*	13,100

NOTES:

- Vehicle costs are in 2013 dollars and include a 1.5 retail price markup factor over the manufactured costs reported for the high progress and mid cost case from Moawad et al. (2016).
- National Highway Traffic Safety Administration CAFE values are calculated from unadjusted 2-cycle testing. EPA window sticker values are calculated from adjusted 5-cycle testing. All range and fuel economy values in this report are meant to reflect EPA window stickers (most reflective of real world averages). For reference see #10 in https://www3.epa.gov/fueleconomy/documents/420f14015.pdf.
- Nominal miles/year values are for example only, set equal to average new LDV miles in NHTS 2009.
- Gasoline miles shown for BEVs would be the displaced miles driven by CVs or HEVs within the same household for long-distance trips not satisfied by BEVs due to limited range.

Table 3. Assumed EVSE Costs and Performance Attributes for Nominal EVSE

EVSE Location and Type		Cost ($/unit)			Nominal Capacity (kW)	EVSE Units/1,000 PEVs	
		Capital	Installation	Total		PHEVs	BEVs
Home	Level 1	$50	150	$200	1.4	481	487
	Level 2	$900	$1,300	$2,200	3.3	283	286
MUD	Level 1	$50	150	$200	1.4	74	72
	Level 2	$900	$1,300	$2,200	6	44	42
Work	Level 1	$700	700	$1,400	1.4	167	166
	Level 2	$2,400	$2,200	$4,600	6	167	166
Public	Level 1	$700	1000	$1,700	1.4	0.5	0.4
	Level 2	$2,400	$3,100	$5,500	6	2.4	10.1
	DCFC	$55,500	$53,000	$108,500	100–350	0	0.469

NOTES: MUD: Multi-unit dwellings. DCFC: Direct current fast charge. Costs are in 2013 dollars.

2.1.2 Scenario Development

This section reviews the self-consistent methodology of accounting for LDV sales and fuel use, relying on the vehicle and EVSE attributes reviewed above, to estimate the social benefits associated with future scenarios of PEV market growth. The study focuses on a single main Aggressive scenario. In addition, multiple additional scenarios are developed to explore the influence on total social benefits of variations across different input assumptions.

Total PEVs deployed in the Aggressive scenario is determined based upon an assumption that 14% of all LDV miles driven are e-miles by 2035. This assumption results in very high PEV market shares, with about 73 million PEVs on the road in 2035, which is about 27% of the LDV fleet. This e-mile input assumption is based upon a *PEV Emphasis* scenario developed in a National Academy of Sciences study on the technical potential for various LDV technologies to achieve an 80% reduction in GHG emissions by 2050 (NRC 2013). This e-mile threshold requirement is combined with the consumer perceived cost of ownership results discussed above, and shown in Figure 5, to determine the market shares of different types of PEVs over time. The results from simulating the evolution of the LDV fleet over time based upon these market shares are shown in Figure 6, with total e-miles driven by PEV type in the left-hand panel and total PEVs on the road by type in the right-hand panel. Grey portions of the figures indicate total gasoline miles and CVs or HEVs, green wedges indicate BEVs, and blue wedges indicate PHEVs. As indicated, BEVs provide approximately 4% of total e-miles by 2035, and BEVs are approximately 9% of total PEVs on the road by 2035.

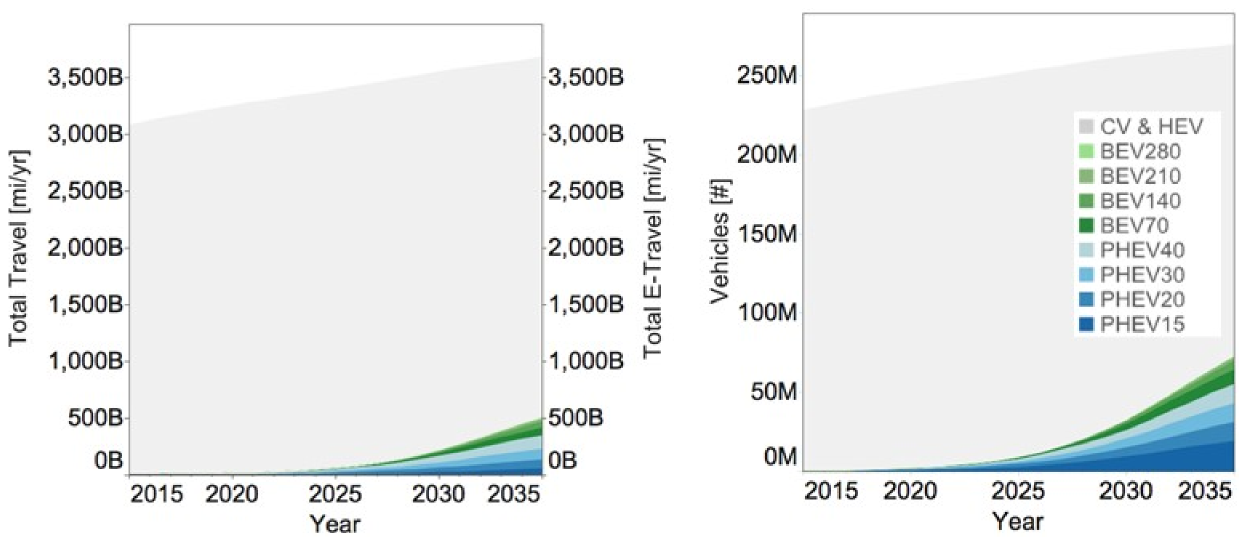


Figure 6. National breakdown of vehicle miles and stock by type for the main Aggressive scenario

The Aggressive scenario is not intended to serve as a prediction of future PEV market shares. The methodology employed does not estimate any explicit likelihood or probability associated with different levels of PEV market growth. The PEV shares shown in Figure 6 are not realized as a result of any particular set of policy initiatives or market conditions. Instead, the Aggressive scenario has been developed as a useful thought experiment to explore potential relationships between future technology progress trends, fuel prices, and market constraints. Given the goal of estimating potential economic benefits, these trends are aligned in a manner that is consistent with a high PEV market share future. The result is not a likely or probable market future, but rather an optimistic portrayal of a high PEV market growth future developed to better understand the potential economic value of PEVs given a variety of technology trends and market constraints. In other words, the Aggressive scenario has been developed to explore the full potential for PEVs to provide economic benefits when adopted at scale by mainstream consumers, when supplied with electricity from an evolving electricity grid, and when compared to similarly optimistic technology trends for incumbent conventional and hybrid electric gasoline vehicles.

A key part of the realism that has been imposed in the economic valuation methodology is the structure of assumed LDV costs and fuel economies. All LDVs are assumed to achieve high technology progress with respect to cost and performance, as indicated in Table 2. The scenarios assume an allocation of a broad range of PEV types rather than the success of a single "best case" PEV compared to the incumbent CV. The allocation algorithm used to determine relative PEV shares is based upon a utility function in which households with particular driving patterns choose combinations of PEVs and EVSE charging options that provide the greatest economic benefit (see section 2.3.1). The algorithm is a simplified consumer choice algorithm and does not take into account the full range of consumer preferences or vehicle attributes that might influence consumer purchase decisions. For example, the relatively low market shares for BEVs could shift as a result of increased mainstream consumer preferences for the all-electric drive experience or the perceived "greenness" of BEVs compared to PHEVs. The approach does, however, take into account the basic costs of PEV ownership (retail vehicle prices and fuel costs) and the limited range of BEVs with respect to regional variations in household driving patterns, gasoline and electricity prices, and climate. The algorithm employed, a nested logit model, is described in more detail in Section 2.3.1.

Note that the relative market shares indicated in Figure 6 are distinct from PEV sales trends seen over the past several years (shown by make and model in Figure 1). This variation is due to PEV market shares being directly derived from the consumer perceived costs summarized in Figure 5. Given the long-term focus of the economic valuation, there is no attempt to reconcile present-day PEV market shares with these projected market shares. That being said, the very large growth in PEV market share would require both strong policy incentives and high technology progress between 2016 and 2035. Deviations from present-day trends are not unlikely during such a dynamic market transformation.

A secondary result of the PEV allocation algorithm is the number and type of different EVSE stations supporting PEVs. In general these results follow from the utility function results generated based upon household driving patterns, with, for example, the allocation of Level 1 vs. Level 2 home or work chargers depending upon the type of vehicle adopted and total annual VMT and number of long-distance trips. The number of commercial EVSE stations is based upon assumptions about the percentage of total kWh provided to PHEVs and BEVs, and the average kWh supplied per EVSE unit, relying upon previous estimates developed by Melaina and Helwig (2014). These input assumptions are reviewed in section 2.3.2 and EVSE allocation results are reviewed in section 3.3.

The intermediary results indicated in Figure 6 are from the Aggressive scenario and are the basis of the vehicle and EVSE costs contributing to the total social benefits associated with that scenario. The shares of CVs and HEVs in the Baseline scenario are taken from the AEO 2015

Reference Case, as are prices for gasoline and total VMT in the LDV sector. The main adjustment to AEO Reference Case results is that LDV fuel economies and prices are assumed to progress according the same trends used in the Aggressive scenario, based upon Moawad et al. (2016). The increased market share of PEVs then remains as the major distinction between the Aggressive scenario and the Baseline scenario. The difference in total social benefits between these two scenarios is the net social benefit attributed to increased PEV market share in the Aggressive scenario.

In order to provide additional insight into the various input assumptions used in the Aggressive scenario, six additional PEV scenarios are developed as variations on the Baseline scenario. As summarized in Figure 7, three general trends define how the Baseline scenario is modified to develop scenarios: (1) market growth, (2) price of gasoline, and (3) technology progress. The Niche and Breakthrough scenarios examine lower levels of total PEV market growth by 2035 in order to examine scaling effects associated with the allocation of PEVs across households in each census division. An important study design assumption is that the percent of e-miles displaced by PEVs is assumed constant across all census divisions. In this regard the study is an exploration of the degree to which PEVs provide economic value by region rather than an estimation of an economic allocation of PEVs across different regions.

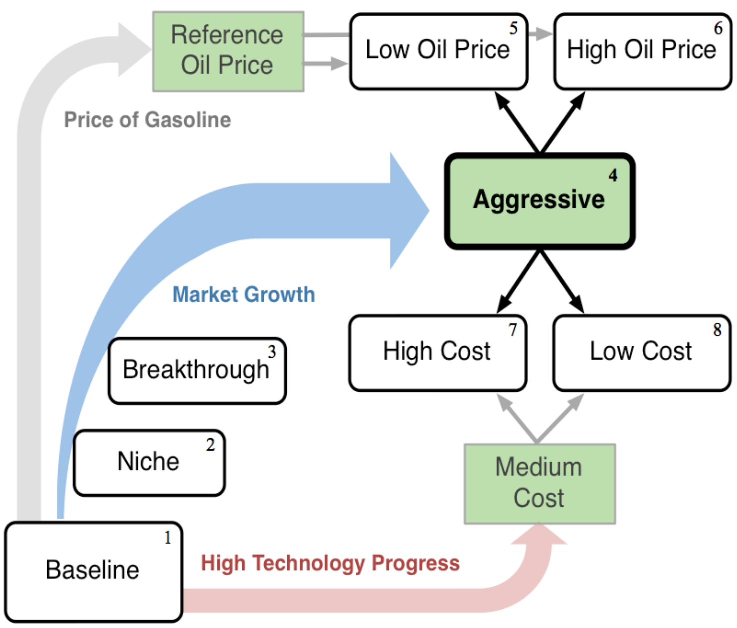


Figure 7. Scenarios and major trends

The High Oil Price and Low Oil Price scenarios are named based upon the corresponding High Oil and Low Oil cases in AEO 2015, which project high and low gasoline prices over time relative to the Reference case. These scenario variations explore the degree to which PEVs provide economic value when the gasoline displaced by electricity has a higher or lower price. Note that no demand elasticities or rebound effects are accounted for in developing these scenarios (Small and Dender 2007). Relative PEV shares are estimated as changing in response to changes in gasoline and electricity prices. These estimates are based upon exogenously defined gasoline prices, while electricity prices are recalculated, through grid simulations, in response to increased electricity demand from PEVs.

The set of scenarios selected provides significant insights into the benefit and cost of implementing electric vehicles under a specific set of assumptions. For this report, the number of sensitivity analyses is limited to vehicle stock, fuel and vehicle cost, all performed independently. Additional variations and inclusion of additional factors could be considered for future work. Tighter integration of the involved models and inclusion of a vehicle choice model could enable a more interconnected modeling framework, with which to perform a broader and more interrelated uncertainty analysis.

The High Cost and Low Cost scenarios are variations on the Aggressive scenario with respect to the retail price of LDVs and the cost of EVSE stations. Vehicle fuel economies are held constant while retail prices vary according to the high and low cost ranges from Moawad et al. (2016). Because these scenarios do not result in changes in fuel prices or consumption, changes in net private and social benefits are only due to changes in EVSE costs and the incremental cost of PEVs compared to the CVs and HEVs they replace.

The net economic benefits of each non-baseline scenario are, by definition, the benefits resulting from all PEVs introduced by 2035. The Baseline scenario is therefore indicated as having zero PEVs.[7] The High Oil and Low Oil Baseline scenarios also have no PEVs, and are generated to determine the net benefits of introducing PEVs when CVs and HEVs are consuming gasoline with higher or lower prices (see section 2.3). All scenarios assume high technology progress with respect to fuel economy improvements, while the High Cost and Low Cost scenarios assume cost variations around LDVs with those projected fuel economies (Moawad et al. 2016). Finally, all scenarios rely on the business as usual grid, except for the High Oil scenario and corresponding High Oil Baseline scenario, which use a low carbon grid from the ReEDS model.

2.1.3 A Simple Bottom-Up Cost Accounting Approach

A more complete and integrated cost-benefit analysis approach could shed light on interesting relationships between different stakeholders and the potential value of different potential market support mechanisms. Additional value could also be attained through the use of a formal discrete choice model, an integrated economic model, and a more nuanced electricity market simulation model. These additions could include a more consistent treatment of household economics, including loans for new or used vehicles, loans for home EVSE equipment, and potential revenue or benefit to workplace establishments as a result of financing workplace charging. Admittedly, there are cost-effectiveness, actor behavior, policy, and other issues relevant to PEV market adoption that cannot be addressed through the relatively simple approach used here. For example, the distribution of both vehicle and EVSE capital costs over an approximately 12-year period is an oversimplification of many disparate trends related to the appropriate discounting of public costs and benefits vs. private costs, the role of tax rebates and other policy mechanisms relied upon during early PEV market growth, and the inevitable conflict between declining gasoline sales and road taxes with the introduction of alternative fuels. Similarly, VMT changes resulting from consumers' choices of vehicles are not modeled.

[7] The AEO Reference scenario actual projects 2.6 million PEVs by 2035, but these are accounted for as PEVs deployed in the non-baseline scenarios for the sake of determining the economic value of increasing PEV market share. In other words, the Baseline scenario used in this study matches future trends for CVs and HEVs from the AEO 2015 Reference scenario, but does not include the PEV market growth.

2.2 Vehicles, Driving and Charging (BLAST-V)

Information about energy consumption and travel limitations for both PHEVs and BEVs is calculated using the Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V) model, relying upon a breakdown of regional travel data within the NHTS database. BLAST-V uses trip level data along with climate, vehicle, and driver data to determine the temporal and spatial distribution of trips. Inclusion of this data enables BLAST-V to account for the effects of local climate, driver aggression, vehicle cabin thermal management, battery system thermal management, battery wear, and charger power and availability (Neubauer and Wood 2014). Outputs from the model are used to calculate geographic variations in vehicle energy usage, which in turn is used in calculations of vehicle market share in the vehicle sales, stock, and economic accounting model (section 2.3).

The fraction of VMT driven by PEVs on electricity, or eVMT, is a strong function of electric range, travel patterns, and charging behavior. PEV eVMT estimations in this analysis serve two primary roles:

1. As inputs for calculation of public and private fuel costs associated with PEV adoption
2. As criteria for determining which households are allocated different types of PEVs.

Role 1 is relatively straightforward and is discussed in section 2.3, while role 2 is closely linked to driving and charging assumptions and is therefore explained in this section. As eVMT directly impacts private costs, consumers' preferences in vehicle adoption are likely related to their own individual travel patterns. In this analysis, total eVMT is determined exogenously, but the allocation of PEVs that drive these eVMT is determined based upon regional market factors influencing private ownership costs. PEV adoption is primarily by consumers with favorable travel patterns that enable the most compelling ownership costs relative to CVs or HEVs.

To estimate PEV allocations based upon consumer perceived vehicle cost, the U.S. fleet of personal light-duty vehicles is modeled using the U.S. Federal Highway Administration's 2009 National Household Travel Survey (NHTS 2009). Longitudinal estimates of individual daily-VMT (D-VMT) distributions are derived from a combination of NHTS data and from the Puget Sound Regional Council's (PSRC) 2006 Traffic Choices Study (TCS), which includes multiple months of GPS-tracked travel for hundreds of vehicles in the Seattle area. Lin et al. (2012) used a similar approach to resolve yearly and daily VMT. Longitudinal distributions of D-VMT for NHTS vehicles are then used to calculate individual utility factors for all PEV models in this study assuming one full charge per day at the vehicle's home location. Finally, all calculations are duplicated assuming various levels of access to home and workplace charging (in addition to the single home charge per day scenario). All calculations include corrections for local ambient temperature impact on electric range. The subsections below describe this approach and the input data in more detail. Intermediary utility results are discussed in section 3.1.

2.2.1 PEV Characterization

Both the main Aggressive scenario and variations are constructed with four types of BEVs with varying ranges (70, 140, 210, and 280 miles) and four types of PHEVs with varying electric ranges (15, 20, 30, and 40 miles).[8] These nominal all-electric ranges are generated with adjustments to approximate real-world range and are the result of an approximately 30% reduction to range values from the EPA 2-cycle test. The EPA 2-cycle test results are from simulated energy efficiencies using Argonne National Laboratory's Autonomie model (Moawad et al. 2016), with the two cycles being the EPA's Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET). The 30% adjustment factor is applied to the raw simulation results to account for on-road, non-dynamometer effects such as real-world driving speed/aggression, ambient temperature effects, and cabin heating/cooling loads (among others) (EPA 2006). More precise adjusted values are shown along with vehicle types and EPA 2-cycle simulated miles in Table 4.

Table 4. Relationship between Vehicle Type, Unadjusted Range, and Adjusted Range

Vehicle Type	Combined Unadjusted Range on Simulated EPA UDDS/HWFET (miles)	Combined Adjusted Range on Simulated EPA UDDS/HWFET (miles)
PHEV15	20	14
PHEV20	30	21
PHEV30	40	28
PHEV40	60	42
BEV70	100	70
BEV140	200	140
BEV210	300	210
BEV280	400	280

All LDV cost and performance attributes follow the high technology progress results from the recent Autonomie report on future LDVs (Moawad et al. 2016). Vehicle efficiencies are associated with the high technology progress (the high technology uncertainty case) and cost ranges are the associated low, medium, and high cases. Interpolations are made to determine attributes for intervening years and all costs are converted to 2013 dollars. As an example, fuel efficiency and range attributes for new LDVs in 2035 are indicated in Table 5.

[8] E-mile ranges include adjustments to approximate real-world range (i.e., approximately 30% reduction relative to EPA 2-cycle testing).

Table 5. Gasoline Efficiency, Electricity Consumption, and Total Electric and Gasoline Range Attributes for New LDVs in 2035

Vehicle Type	Gasoline Efficiency (miles per gallon)	Electricity Consumption (Watt-hour/mile)	Total Electric and Gasoline Range (miles)
CV	47.6	-	350
HEV	87.8	-	350
PHEV15	89.7	186	350
PHEV20	90.1	173	350
PHEV30	90.8	174	350
PHEV40	92.3	174	350
BEV70	-	178	70
BEV140	-	182	140
BEV210	-	195	210
BEV280	-	208	280

Several factors are taken into consideration in determining the cost of PEVs to consumers. Vehicle manufacturing costs are multiplied by 1.5 to determine retail prices (Elgowainy et al. 2013), and annual miles are multiplied by gasoline and electricity prices (which vary regionally and over time) to determine fuel prices. Other factors accounted for are regional variations in consumer driving patterns, influence of climate on fuel economy, and a perceived consumer price penalty for the limited range of BEVs.

As suggested in Table 6, PEV manufacturing costs are higher when compared to CV and HEV costs in 2035. Without considering the additional private savings from fuel and public savings from emissions reductions, PEVs are not sufficiently competitive to justify strong PEV market growth trends. Achieving strong PEV market growth trends would therefore require both strong market demand pull by consumers and significant purchase incentives and other supportive policies (Greene, Park, and Liu 2013). The scenarios are therefore best described as hypothetical market outcomes resulting from a combination of successful technology development, strong consumer demand, and enduring policy support mechanisms. In this respect, the scenario approach employed is not a strict cost-benefit analysis but rather a first-cut approximation of fundamental costs and benefits associated with achieving high levels of PEV market growth.[9]

Vehicle cost and performance data are classified by the year in which they are assumed, the uncertainty with technology status, and the success of technological advances. Table 6 shows the selected values for each vehicle type considered in this report.

[9] For a discussion and example of a formal cost-benefit analysis of policies supporting PEV market growth, see Massiani 2015. Also see Michalek et al. 2011.

Table 6. Capital Cost Projections for 2035 (2013$)

Cost Projection	Low			Med			High		
Uncertainty Projection	Low	Med	High	Low	Med	High	Low	Med	High
Vehicle Types									
CV	16,839	16,706	16,839	17,296	17,183	17,286	17,383	17,290	17,373
HEV	19,356	19,027	18,800	19,592	19,303	19,103	19,356	19,115	18,949
PHEV10	19,742	19,346	19,095	19,976	19,622	19,398	19,897	19,574	19,370
PHEV15	20,430	19,581	19,121	20,839	20,009	19,557	20,657	19,904	19,527
PHEV20	23,191	22,221	21,614	23,075	22,204	21,660	22,724	21,926	21,428
PHEV30	23,325	22,326	21,686	23,195	22,299	21,726	22,834	22,013	21,488
PHEV40	23,592	22,536	21,831	23,435	22,488	21,856	23,054	22,187	21,608
BEV70	20,853	19,652	18,766	20,379	19,419	18,713	19,251	18,543	18,012
BEV140	28,558	26,102	24,260	26,485	24,531	23,066	23,687	22,256	21,149
BEV210	37,055	33,072	30,096	33,218	30,053	27,689	28,574	26,264	24,454

2.2.2 NHTS Data

The U.S. fleet of personal light-duty vehicles is modeled using the 2009 NHTS dataset. The NHTS data contains a total of 309,163 vehicle samples, which translate to a weighted total of 211,501,318 (NHTS data includes weights for each household to control for over-/under-sampling with respect to geography and demographics of respondents). The weighted distribution of NHTS vehicles by vehicle age is indicated in Figure 8.

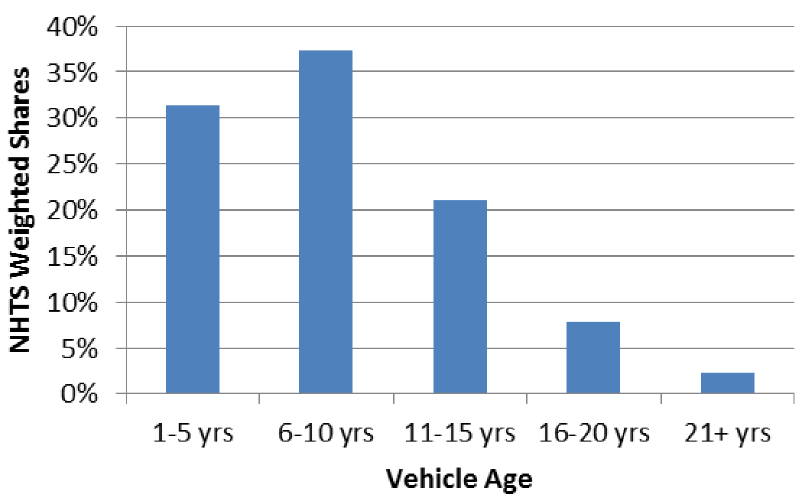


Figure 8. Weighted distribution of NHTS vehicle ages

The NHTS vehicle database can be used to reveal a strong correlation between vehicle age and average annual-VMT (A-VMT) (see Figure 9). A linear fit to the average A-VMT by vehicle age reveals that average A-VMT decays at a rate of 324 miles/year. Over the course of a vehicle lifetime, this decay rate introduces a significant difference in the way U.S. consumers operate newer versus older vehicles. Given the focus of this analysis on consumer adoption, NHTS vehicles are down-sampled to include only those 5 years old or less. This down-sampled set consists of 100,785 vehicle samples (65,123,441 weighted samples).

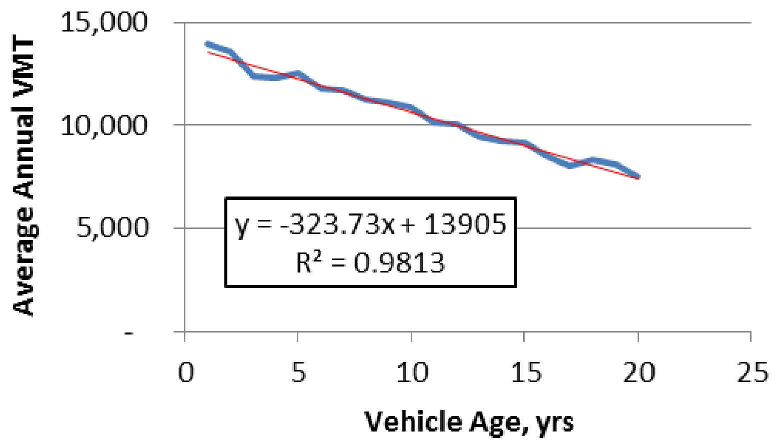


Figure 9. NHTS average A-VMT by vehicle age

Figure 10 shows the distribution of individual A-VMT from the subset of vehicles 5 years old or less. These data highlight the significant variation in operation between new vehicles in the U.S. market. This variation will influence the degree to which individual consumers will find PEVs economically attractive due to varying ratios between capital and operating expenses.

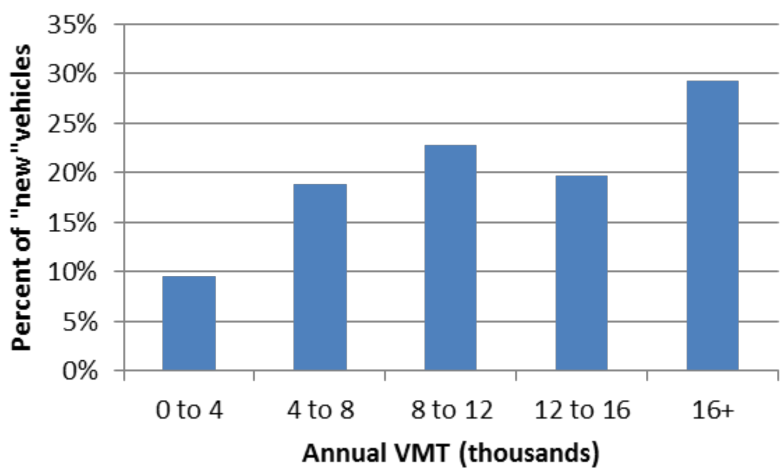


Figure 10. NHTS sample of vehicles 5 years old or less by annual VMT

Another important distribution for estimating PEV eVMT is the distance between home and work for vehicles used as the primary commuting mode for household workers. For the NHTS subset of new vehicles, the primary activity of the primary driver is identified. For those respondents who report a primary activity of working, primary commuting mode is also identified. NHTS data reveal that 57% of new vehicles are primarily operated by working individuals. Of those 57%, NHTS data show that 81% of drivers use a personal automobile as their primary commute mode to/from work. Taken together, this results in between 46% and 68% of new vehicles being used for commuting purposes on a regular basis (the lower bound represents the most conservative assumptions regarding treatment of "NA" responses in the NHTS dataset).

From the subset of new vehicles being used for commuting purposes on a regular basis, reported one-way distance from home to work is identified, with a cumulative distribution shown in Figure 11. Median one-way home-work distance is calculated as 10 miles; 25th and 75th percentiles are at 5 and 20 miles respectively.

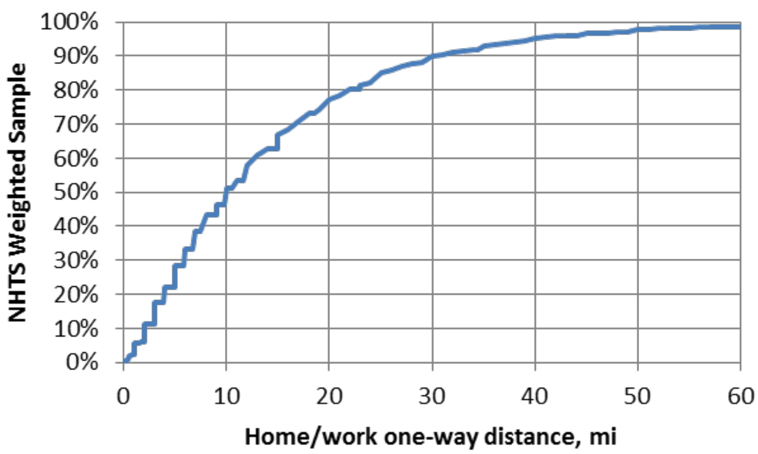


Figure 11. NHTS cumulative distribution of one-way home-work distance for new vehicles being operated as commuter vehicles

2.2.3 Individual D-VMT Distributions

As this analysis is concerned with investigation of individual PEV economics, individual travel patterns must be estimated in order to calculate eVMT. While cross-sectional distributions of NHTS D-VMT are frequently used to estimate PHEV fleet utility factors (SAE J2841 2010), estimation of a distribution of individual utility factors from single-day NHTS survey data is problematic. Given that the 2009 NHTS only sampled a single travel day from each participant, day-to-day variations in VMT—critical for estimation of individual PEV economics—are absent (Neubauer et al. 2012).

To address this shortcoming, longitudinal travel data from the PSRC TCS are used to estimate day-to-day variations in D-VMT for the NHTS dataset. This analysis employs separate methods for estimation of individual utility factors for PHEVs and BEVs. PHEV utility factor estimation is conducted by modeling individual distributions of D-VMT as gamma distributions, while BEV utility factors are generated through estimation of long-distance travel frequencies.

2.2.4 Representing Individual D-VMT Distributions Using Gamma Functions

Researchers at Oak Ridge National Laboratory have recognized the complications arising from estimation of individual PHEV economics from single-day travel datasets such as the NHTS. One solution is to represent individual distributions of D-VMT using gamma distributions. This method has been shown effective relative to the sample of longitudinal travel data from the PSRC TCS (Lin et al. 2012).

Gamma distributions of D-VMT require two scalar inputs to define shape and scale of the distribution. Gamma shape and scale are specified in this analysis by estimating the mean and mode of D-VMT for each vehicle in the NHTS subset of vehicles 5 years old or less. Given an estimate of A-VMT from the NHTS dataset, A-VMT could be divided by 365.25 days/year to calculate the mean of D-VMT. However, this implicitly assumes that the vehicle in question is driven some distance greater than zero every day of the year. In reality, many vehicles are left dormant several days per year. Annual drive days are estimated by processing the PSRC TCS for average annual drive days by A-VMT. D-VMT mode by A-VMT is also calculated from the PSRC TCS and shown in Figure 12.

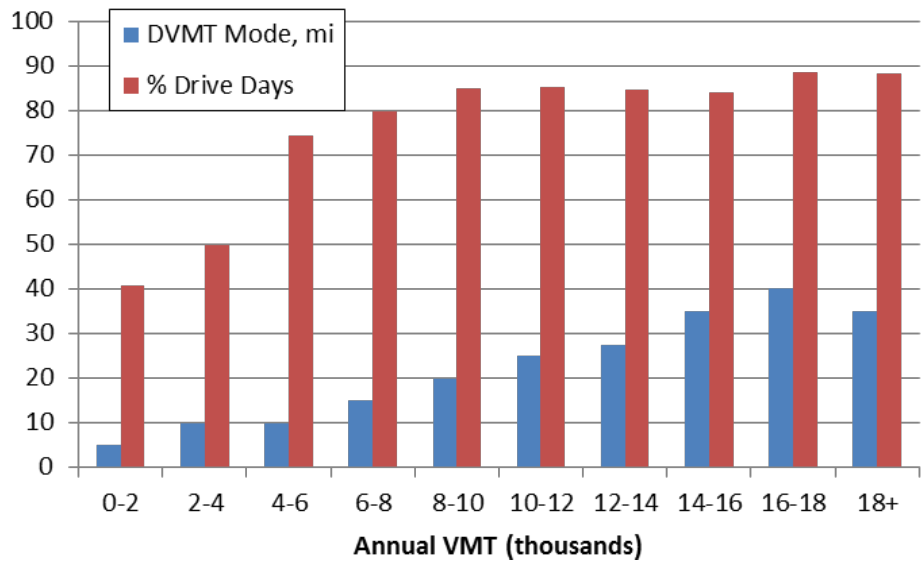


Figure 12. PSRC TCS average annual percent drive days and D-VMT mode by A-VMT

The sample of PSRC TCS data reveals that annual drive days and D-VMT mode both generally increase in vehicles with high A-VMT. On average, vehicles with A-VMT greater than 8,000 miles/year are driven between 80% and 90% of total days, or about six days per week.

Individual gamma distributions of D-VMT are defined by using NHTS-reported A-VMT to estimate D-VMT mode and percent drive days. D-VMT mean is calculated by dividing A-VMT by estimated annual drive days. Example gamma distributions of individual D-VMT are shown in Figure 13 for vehicles with A-VMT from 1,000 to 19,000 miles/year.

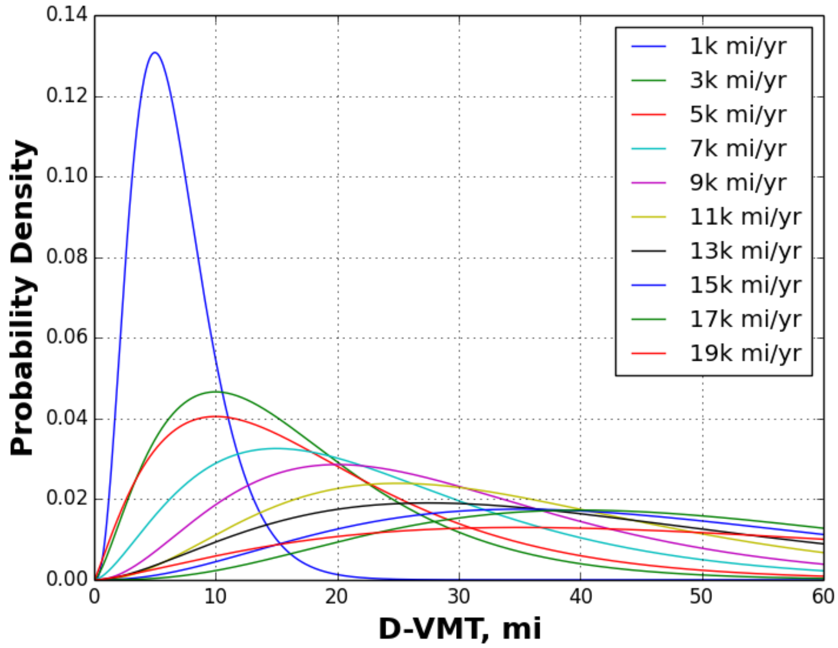


Figure 13. Example individual distributions of D-VMT

Estimation of shape and scale parameters for individual distributions of D-VMT is modified slightly for NHTS vehicles reported to be used on a regular basis for work commuting. D-VMT mode for commuter vehicles is estimated as the reported round-trip home to work distance.

2.2.5 Frequency of Long-Distance Travel with respect to A-VMT

While every mile driven in a BEV can be considered eVMT, baseline VMT in this analysis is derived from CV VMT. Therefore VMT accomplished in a CV that is unattainable in a BEV (due to range constraints) will count against BEV eVMT. This approach requires estimation of long-distance travel frequency (and associated VMT on long-distance travel days) for newer vehicles (1–5 years old) in the NHTS dataset.

Long-distance travel frequency is estimated by processing the PSRC TCS dataset to calculate distributions of days/year where D-VMT exceeds the single charge range of the four BEV types under study (70, 140, 210, and 280 miles). Results from the PSRC TCS dataset by A-VMT are shown in Figure 14. The following are some example data points from this plot (selected to help the reader confirm interpretation):

- 25% of vehicles driven between 4,000 and 8,000 miles/year recorded more than 12 days/year over 70 miles (top of blue box in the 4k–8k mile bin).
- 50% of vehicles driven over 16,000 miles/year recorded more than 4 days/year over 210 miles (middle of green box in the 16k+ mile bin).
- 100% of vehicles driven between 12,000 and 16,000 miles/year recorded at least 10 days/year over 70 miles (bottom whisker of blue box in the 12k–16k mile bin).

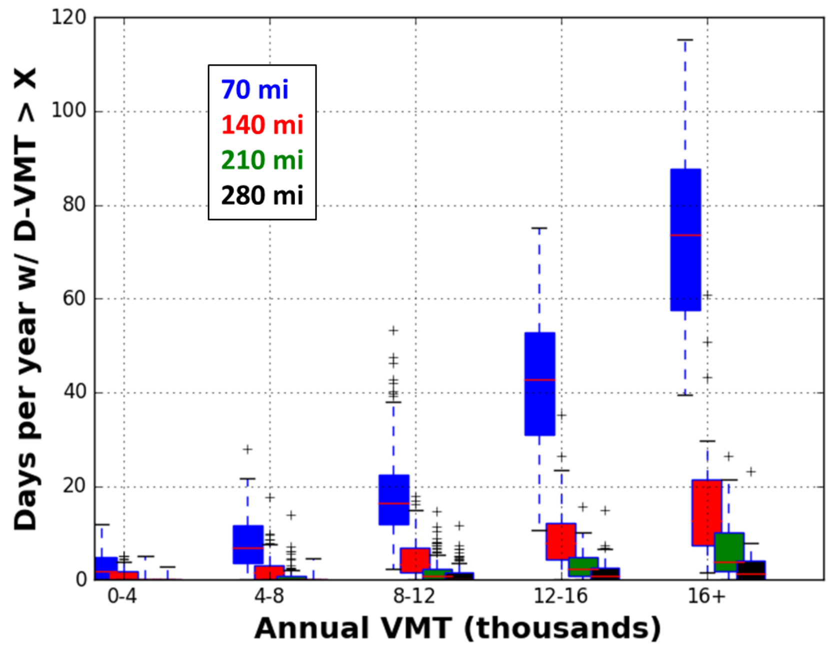


Figure 14. PSRC TCS long-distance travel frequency distributions by A-VMT

Several trends emerge from this plot. First, the frequency of days/year over X miles decreases as X increases from 70 to 280 miles (because every day over 280 miles also counts as a day over 70 miles, this result is implicit in the methodology). Second, median days/year over X miles increases with A-VMT for all X values (vehicles with high A-VMT exhibit a higher frequency of long-distance travel). Third, significant vehicle-to-vehicle variation is observed in all bins (while long-distance travel frequency trends with A-VMT, exact prediction requires more information).

For all NHTS vehicles, long-distance travel frequency information is appended at random from a PSRC TCS vehicle with comparable A-VMT. This information includes estimates of days/year over 70, 140, 210, and 280 miles and corresponding VMT. BEV individual utility factors are generated by calculating potential BEV eVMT as NHTS-reported A-VMT less the VMT associated with travel days over the rated electric range of the BEV.

2.2.6 Ambient Temperature Impacts on Electric Range

Local ambient temperature conditions are used to adjust estimated electric range for the simulated fleet of NHTS vehicles. Because the initial 30% range adjustment already accounts for average U.S. ambient conditions, the net local ambient temperature adjustment for all U.S. vehicles is zero (to avoid double-counting).

NHTS-reported home location ZIP codes are used to identify the nearest weather station from NREL's National Solar Radiation Data Base of Typical Meteorological Years (NREL 2015). Average ambient temperature is calculated for every day of the year at every TMY3 station. Daily average ambient temperature is then input to determine relative vehicle efficiency.

Figure 15 shows two polynomial curve fits of relative vehicle efficiency versus average ambient temperature, one for PEVs and one for conventional powertrains. These curves are used to account for decreased efficiency at extreme ambient conditions. Such effects include cabin air conditioning at hot ambient temperatures and cabin heating, increased lubricant viscosity, and reduced battery roundtrip efficiency at cold ambient temperatures. The relative efficiency curve for electric drive vehicles was developed by researchers at Carnegie Mellon University using telematics data collected from real-world operation of Nissan Leafs (provided by FleetCarma) (Yuksel and Michalek 2015). Conventional vehicle relative efficiency is based on real-world simulations of a 2011 Ford Fusion by researchers at NREL with models calibrated to on-road and dynamometer data collected by Argonne National Laboratory's Advanced Powertrain Research Facility (Wood et al. 2015). The relative efficiency curve for conventional vehicles is included for use in the vehicle sales, stock, and economic accounting model.

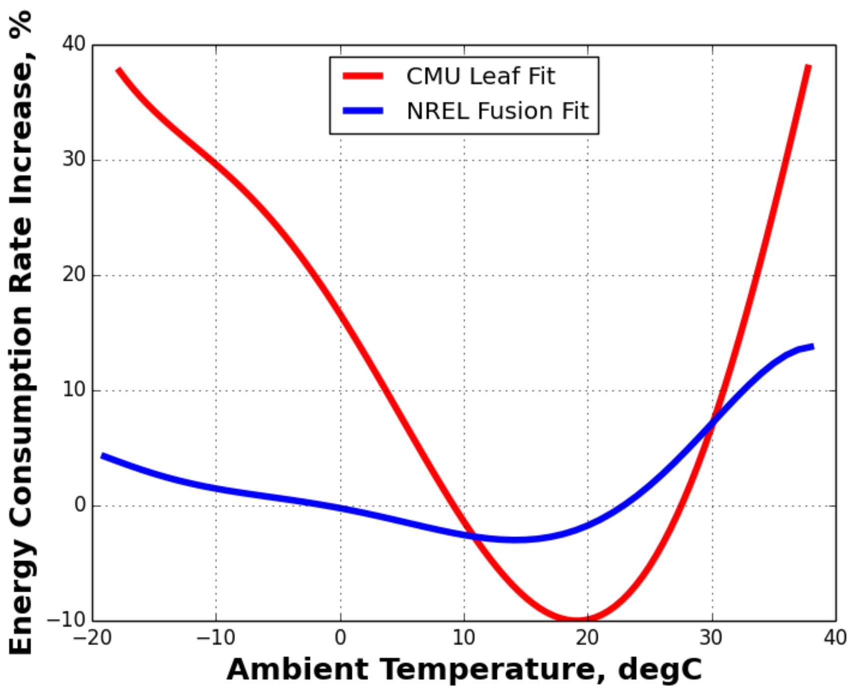


Figure 15. Relative energy consumption rate increase as a function of ambient temperature. Carnegie Mellon University fit to battery electric Nissan Leaf data (red) and NREL fit to conventional spark-ignited gasoline Ford Fusion simulations (blue).

2.2.7 Incremental eVMT Benefits Associated with Increased Charging Access and Power

To this point in the analysis, eVMT estimates have been derived assuming once-per-day charging at the home location such that every travel day begins with a fully charged battery and neglects intra-day charging. While this assumption is consistent with SAE J2841, recent analysis of EV Project data has revealed such assumptions are inconsistent with real-world consumer operation (Smart, Bradley, and Salisbury 2015). The incorporation of multiple charge events per day for some vehicles, based upon NHTS results, is discussed below.

In order to acknowledge the impact of various charging scenarios on eVMT (and weigh cost-benefit tradeoffs), incremental eVMT is simulated under a range of charging scenarios. As shown in Table 7, charging power at the home location is subdivided into individuals residing in single unit dwellings (SUD) and multiple unit dwellings (MUD), assuming that shared use of charging stations in MUDs requires power levels at the higher end of the Level 2 range.

In addition to the location and power assumptions, eVMT estimates are generated assuming charging at different times of day. This dimension is included to generate scenarios where electric utilities offer customers incentives to shift PEV charging to off-peak hours, referred to as timed charging in this analysis (charging restricted from 5 p.m. to 10 p.m. during simulations). Scenarios in which charging is made available regardless of time of day are referred to as opportunity charging.

Table 7. Charging Scenario Matrix

EVSE Location	EVSE Type	Power (kW)	Charge Strategy	Availability
Home (SUD)	L1	1.4	Timed	10 p.m.–5 p.m.
			Opportunity	24 h
	L2	3.3	Timed	10 p.m.–5 p.m.
			Opportunity	24 h
Home (MUD)	L1	1.4	Timed	10 p.m.–5 p.m.
			Opportunity	24 h
	L2	6.0	Timed	10 p.m.–5 p.m.
			Opportunity	24 h
Work	L1	1.4	Opportunity	24 h
	L2	6.0	Opportunity	24 h

Simulation of incremental eVMT is conducted using NREL's BLAST-V tool. For the sample of 100,785 NHTS vehicles 5 years old or less, travel data were recorded for 70,669 vehicles on their survey day (70%). Travel data for these vehicles (trip times, distances, and destination types) were input into BLAST-V and simulated under all combinations of charging scenarios shown in Table 7, and incremental eVMT was calculated relative to a simulation assuming once-per-day charging at home with no intra-day charging. Average incremental eVMT was used to backfill results for NHTS vehicles that did not record any travel on their survey day.

2.3 Vehicle Sales, Stock, and Economic Accounting (SERA)

The analytic framework used to track vehicle adoption rates, fuel demand, fuel supply, and the costs and benefits underlying the economic valuation is the Scenario Evaluation and Regionalization Analysis model (SERA) (Bush et al. 2013). The SERA scenario disaggregation tool reconciles national PEV market shares for new vehicle sales through 2035 with a number of trends associated with the prevalence of different PEV types on a regional level. SERA's geographically detailed vehicle stock model then translates PEV market shares into region- and urban area-specific vehicle stocks over time as market shares increase. The vehicle stock is computed using the default vehicle-survival functions of the SERA model (Bush et al. 2013), which is consistent with the vehicle-survival function in the Argonne VISION model (Zhou and

Vyas 2014): over a 20-year period vehicles are retired from the vehicle fleet at an increasing rate. The vehicle-stock computations are regionalized to ZIP code level as reported in the NHTS database reviewed in the previous section. Baseline fuel costs are taken from AEO 2015, vehicle cost and performance trends are taken from the BLAST-V analysis discussed in section 2.2 (Moawad et al. 2016), and external costs are from standard references in the literature, including the social cost of carbon (IAWG 2015) and an energy security premium estimate (Leiby 2012).

2.3.1 PEV Market Share Allocation

Consumer vehicle purchase decisions with respect to advanced and alternative fuel vehicles have been a focus of many analytic and behavioral studies (Greene 2001; Axsen and Kurani 2013). DOE maintains and develops multiple quantitative consumer choice models that have been improved over time as an increasing volume of real-world market data on PEVs and other alternative fuel vehicles becomes available for model calibration. However, agencies such as the EPA have been reluctant to embrace consumer choice methods to assess regulatory mechanisms, partly due to the wide variability in approaches and results, which has been demonstrated in a recent review of DOE models (Stephens et al. 2016).

The present study does not rely upon a formal consumer choice model to predict future PEV market shares. Instead, the analysis relies upon an optimistic market share aligned with results from a National Academies study of the potential to achieve an 80% reduction in LDV GHG emissions by 2050 (NRC 2013). The high rate of PEV market share growth in the *PEV Intensive* scenario from the NRC study is a useful reference for the present study for multiple reasons:

- Strong market transformation dynamics and policy support mechanisms would be required over the two decades leading up to 2035 to achieve such high PEV market shares. After achieving market success, these dynamics might have become more stable. For example, vehicle component costs would be manufactured at scale, deficiencies in the availability of public EVSE would likely be resolved, and a consistent and enduring policy framework for PEVs would be in place. This post-transition period is an appropriate focus for an assessment of the long-term economic benefits of PEVs.
- A high future market share allows the assessment to examine large regional LDV markets at scale, deployment of PEVs in average households with typical driving patterns, and dominance of mainstream consumer preferences for vehicles instead of early adopter preferences.
- The scenario approximates PEV market growth necessary to achieve an 80% GHG emissions reduction in the LDV sector.
- The high PEV market share allows for an assessment of significant demands on a future low-carbon electricity grid in terms of total kWh used and peak demand periods. It is anticipated that exploring larger PEV electricity demands is more likely to reveal relevant impacts on the electricity grid. In addition, accounting for carbon intensity reductions provides a more complete assessment of the long-term economic value of PEVs.

The NRC's *PEV Intensive* scenario results in 14% of total LDV VMT being e-miles by 2035. An adjustment of 4 years is assumed to account for the present day PEV sales rate (approximately 110,000 PEVs per year; see Figure 1) compared to the rate of growth in sales from the NRC

2013 analysis. The assumption of 14% of VMT as e-miles by 2035 is then combined with the vehicle-EVSE utility results from BLAST-V to determine regional PEV sales requirements in the SERA model. The SERA model's LDV stock dynamics and VMT trends are calibrated to those reported in AEO 2015.

It is important to note that the 14% VMT requirement is assumed for each individual census division rather than fixing 14% VMT at the national level and allowing more or less PEVs to be adopted in different regions based upon relative utility functions and differences in regional fuel prices. Applying this 14% eVMT requirement across all regions establishes a basis to examine the relative economic value of PEVs across different regions.

In addition to the vehicle cost and performance trends and BLAST-V utility results, it is assumed that consumers perceive BEVs with lower range as being less valuable than comparable vehicles with full range (e.g., about 350 miles on a tank of gasoline). There is very little data supporting quantitative estimates of this "range penalty" factor, which in reality may correspond to multiple vehicle attributes, such as the perceived inconvenience of vehicle charging, lack of EVSE availability, and charging wait times. The penalty may also be due to a lack of consumer awareness of PEVs and BEVs in particular—a recent survey found that consumers who were able to name one of the top nine best-selling PEVs were more likely to view PEVs positively. However, the same survey also found that a majority of respondents (56%) would only be willing to consider purchasing a BEV if the electric range was at least 300 miles (Singer 2016).

Quantitative estimates of penalties for limited range are sparse. Helveston et al. (2015) reported a stated preference survey result of an $18,000–$19,000 penalty for BEVs with a range of 75–100 miles. This result suggests that BEVs with that level of all-electric range, with all other vehicle attributes being equal, appear to consumers to be approximately $18,000–$19,000 more expensive than a comparable CV. Similarly, relying on revealed preferences based upon analysis of ZIP code vehicle registration data, and correcting for major vehicle attributes such as purchase price, acceleration, and interior volume, Brooker at al. (2015) report a range penalty of approximately $9,600 per vehicle for an all-electric range of 70 miles. Brooker et al. report this penalty as the purchase price-equivalent value as a function of BEV range. The resulting equation and trend are indicated in Figure 16, along with the same penalty reduced by 60% as applied in the PEV allocation algorithm in the present study (see below). This range penalty is applied along with the BLAST-V utility functions as an increase in the perceived cost of BEVs.

In addition to this range penalty, which is an inherent attribute of BEVs, the additional fuel cost for long-distance trips that cannot be fulfilled by BEVs is taken into consideration for single-vehicle households when allocating PEVs by type to meet the percent eVMT requirement by 2035. For households with more than one vehicle, the cost of gasoline in fulfilling those trips is not counted as a penalty when allocating PEVs to households. It is assumed that a second or third vehicle would be relied upon to fulfill these long-distance trips without diminishing the perceived value of BEV fuel savings (however, these additional gasoline costs are accounted for in the economic valuation calculations for BEVs). For households with a single vehicle that is being replaced with a new vehicle, these long-distance gasoline costs are counted against the purchase price of a limited range BEV, with the total value being dependent upon the BEV range and regional gasoline price. The result is a relatively large penalty against the option of purchasing a limited range BEV for single-vehicle households with a high frequency of long-distance trips.

The BEV range penalty shown in Figure 16 is adjusted downward in the Aggressive scenario due to the high levels of workplace and commercial charging availability, including the relatively high frequency of DCFC stations (see section 2.1). As discussed above, the exact relationship between the perceived consumer price penalty or limited BEV range and the availability, convenience, and reliability of public charging infrastructure is poorly understood. However, in a future with high EVSE availability such as the Aggressive scenario, some reduction in this penalty (which reflects existing market conditions today, with relatively sparse public EVSE) is anticipated. As a rough approximation, and lacking empirical data to suggest a more precise estimate, it is assumed that the high availability of public EVSE networks in the Aggressive scenario translates to a 40% reduction in the range penalty for BEVs. This is a significant reduction, and it results in a significant increase in total BEVs allocated to fulfill the percent eVMT input assumption for the Aggressive scenario. Variations in the allocation of different PEVs by type as a result of varying this 40% reduction assumption are discussed in section 4.8. It should be kept in mind that the PEV allocation algorithm itself is a means of economically distributing PEVs based upon household driving patterns, climate impacts on LDV performance, and regional gasoline and electricity prices, and that the array of different PEV costs and fuel economies discussed in sections 2.1.1 and 2.2.1 are major inputs to the economic valuation calculations. In addition, as noted in the review of scenario highlights and insights in section 5.2, there are a number of factors not taken into account in the present study that could increase the future economic of BEVs relative to PHEVs.

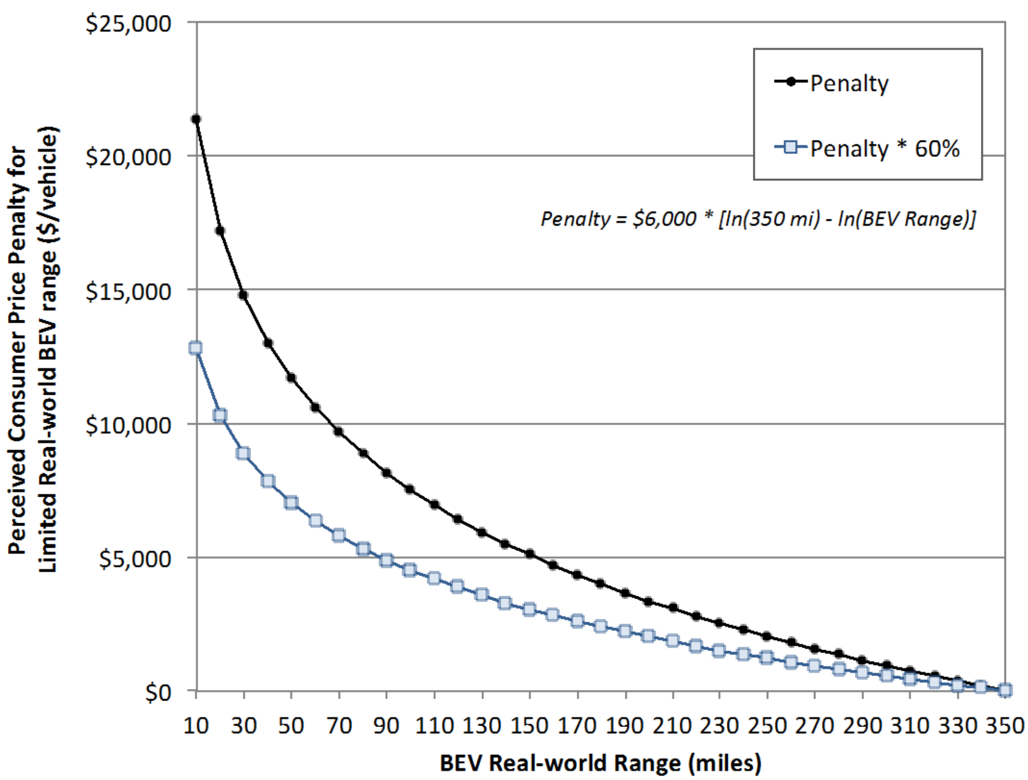


Figure 16. Perceived vehicle purchase price penalty as a function of BEV range

After accounting for the BEV range penalty, vehicle adoption choices are made through a single nested logit function (for an overview of vehicle choice modeling methods, see Greene 2001). The first level of nesting is the choice between four vehicle categories, where the choice is determined by the weighted-average utility of the second level of choices within each category: CV, HEV, PHEV, and BEV.

The multinomial logit function used to determine the allocation of LDVs by household has the following form:

```
market share ∝ exp(mu * utility)

mu = demand elasticity / price point / (1 - base share)
```

Following Greene (2001), values of the constants in this formula are given in Table 8.

Table 8. Logit Function Parameters

Parameter	Value
price point	$35,000
demand elasticity	-7
base share	0.25

See section 4.8 for a discussion of the sensitivity of the results with respect to the elasticity parameter. If a PHEV or BEV is chosen, then the consumer is faced with choices for the all-electric vehicle range, with four PHEV ranges, four BEV ranges, and eighteen charging options (Section 4.8 also discusses the sensitivity of net benefits to BEV range). Market shares are computed using the same multinomial logit function. The utility of the PHEV and BEV categories is computed as the log-sum of the utility of the various PHEVs or BEVs in those categories. The utility of the non-PEV categories relative to the PEV ones is determined by the calibration to the defined scenario (i.e., the AEO 2015 and eVMT constraints). No statistical testing of alternative logit formulations (e.g., flat versus nested) was performed.

Gasoline and electricity prices, vehicle cost and performance attributes, and electricity carbon intensities all vary by year, hence market shares also vary by year. As a first step toward computing the composition of the vehicle stock in any given year, we compute, at five-year intervals, the vehicle sales using the NHTS household weighting factors and the market share computations described above. These time-dependent vehicle sales do not necessarily constitute a plausible PEV introduction scenario, however, until they are re-weighted to match the overall PEV scenarios of interest.

Overall PEV sales for the main Aggressive scenario (based upon the optimistic LDV fuel economies of the high vehicle technology uncertainty case from Moawad et al. 2016, the medium vehicle and charger costs, and AEO 2015 Reference gasoline prices) are set to exactly match 14% of all LDV VMT being eVMT by 2035. This is accomplished by weighting the sales inferred from BLAST-V/NHTS separately for PEVs and non-PEVs, so that PEV sales are exactly sufficient to match the target eVMT for the entire PEV stock in 2035. Absolute and relative PEV shares in scenarios other than the Niche and Breakthrough scenarios (which are also determined by percent eVMT targets) are allowed to vary in response to the allocation algorithm results due to changes in gasoline prices (High Oil Price and Low Oil Price scenarios) or vehicle and EVSE costs (Low Cost and High Cost scenarios). These variations are presented and discussed in section 4.8.

Consequentially, the statistics computed for the PEV stock represent the age-weighted average for vehicles of each type, not the statistics for new vehicles sold in a particular year. PEV market share results are presented in section 3.2.

2.3.2 EVSE Network Assumptions

The cost of supplying electricity to PEVs is based upon an assessment of EVSE requirements for home, workplace, and public charging as well as an analysis of the marginal increase in electricity supply due to PEV electricity demands and variations in time-of-day charging. Table 9 provides a review of the average EVSE costs and nominal capacity values assumed in this analysis. In general, these costs are lower than the average costs seen for EVSE today, under the assumption that both capital costs and installation costs will decline over time due to equipment manufacturing experience, market competition, streamlined permitting, and cost reduction planning measures such as ready-made housing developments and parking structures. The medium costs indicated are considered average values for all EVSE of the type and location indicated. To explore possible increases or decreases in future average EVSE capital and installation costs, these medium costs are varied in round numbers at approximately 10%–20% increases or decreases (with the exception of L1 charger costs, which are not varied). The majority of the medium average costs are derived from empirical data collected and reported by New West Technologies for DOE's Vehicle Technologies Office (EERE 2015). Exceptions are the $200 L1 cost, which is based upon the CalETC Phase 2 study (CalETC 2014b), and the DCFC station cost, which is based upon the NRC 2015 study (NRC 2015). As additional data on future EVSE costs are revealed and scrutinized, these types of projections will be improved (RMI 2014).

Table 9. EVSE Cost Breakdown by Location and Type

EVSE Type and Location		Nominal Capacity (kW)	Cost Uncertainty Range	EVSE Costs in 2035		
				Capital	Installation	Total
Home	L1	1.4	Low	$50	$150	$200
			Medium	$50	$150	$200
			High	$50	$150	$200
	L2	3.3	Low	$800	$1,200	$2,000
			Medium	$900	$1,300	$2,200
			High	$1,100	$1,600	$2,600
MUD	L1	1.4	Low	$50	$150	$200
			Medium	$50	$200	$200
			High	$50	$150	$200
	L2	6.0	Low	$800	$1200	$2,000
			Medium	$900	$1,300	$2,200
			High	$1,100	$1,600	$2,600
Work	L1	1.4	Low	$650	$650	$1,300
			Medium	$700	$700	$1,400
			High	$850	$850	$1700
	L2	6.0	Low	$2,200	$2,000	$4,100
			Medium	$2,400	$2,200	$4,600
			High	$2,900	$2,600	$5,500
Public	L1	1.4	Low	$650	$900	$1,550
			Medium	$700	$1,000	$1,700
			High	$850	$1,200	$2,050
	L2	6.0	Low	$2,200	$2,800	$5,000
			Medium	$2,400	$3,100	$5,500
			High	$2,900	$3,700	$6,600
	DCFC	100 (70-350)	Low	$50,000	$47,700	$97,700
			Medium	$55,500	$53,000	$108,500
			High	$66,600	$63,600	$130,200

NOTES: Medium value estimates based upon EERE 2015, CalETC 2014b, and NRC 2015. Low and high values are simple round number increases or decreases by approximately 10%–20%.

An appreciation of the wide range in EVSE costs seen today is apparent from the summary of costs reported by New West (EERE 2015) and NRC (2015) in Figure 17. The blue diamond symbols with numeric labels match the medium values in Table 9, while the blue and green bars indicate the approximate ranges of the cost ranges reported in each publication. The DCFC costs, shown in an independent vertical axis scale, are an exception to the medium cost falling within ranges reported from each study. The $108,500 per DCFC unit is an estimate for a particular unit, while the report acknowledges a wide variability in costs among DCFC units in general. However, many of these cost estimates are for lower power levels, as low as 25–70 kW, and are therefore likely underestimates of a contemporary 100 kW system. Given that future DCFC units may exceed 100 kW, and may be as high as 350 kW, the $108,500 cost is used as a proxy for future higher-power DCFC stations with robust designs and configurations capable of supporting an active fleet of PEVs in 2035.

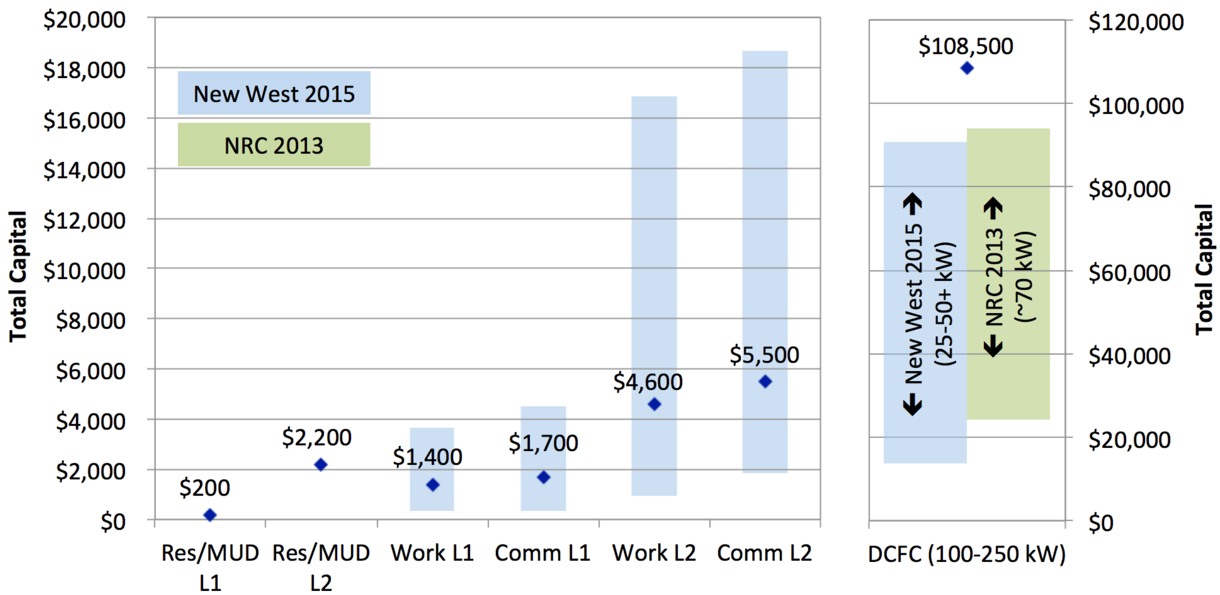


Figure 17. Total equipment and installation capital costs for EVSE by type and location

2.3.2.1 Allocation of Home and Work EVSE

Various combinations of charging locations (such as home only, home and workplace, home and workplace and some public) and EVSE power levels result in different utility factors when combined with specific vehicle operation trends. The allocation of charging infrastructure, and vehicle-charging combinations, is therefore integrated with the same logit function calculations that determine PEV market shares (see section 2.3.1). Some additional EVSE allocation assumptions are summarized in Table 10, including a reduction in electricity price for PEV-EVSE combinations that include timed charging. Timed charging profiles discourage the use of charging during the evening peak to relieve high demand congestion, especially during the summer. Utilities are increasingly developing rate structures or demand response programs that encourage the use of delayed, or smart, charging. As part of the vehicle adoption and charger selection calculations, a 20% electricity cost incentive was included when deciding to select opportunity or timed charging. However, the incentive is not used in the benefit and cost calculations; it is only used in the allocation of EVSE by type to households. This assumption is used as a proxy for anticipated future electric vehicle rate structures. The result is a slight increase in uptake of timed charging compared to opportunity charging.

Other input parameters indicated in Table 10 include the average number of EVSE units per PEV served, which is distinct from the number of EVSE per total PEVs, and the split between L1 and L2 chargers assumed for MUD households. As shown, it is assumed that a single EVSE unit serves as single PEV, on average, in non-MUD households, and that on average one EVSE unit serves two PEVs in MUD households. Similarly, there are three L1 workplace EVSE for every four PHEVs or BEVs that use L1 workplace EVSE, and an identical ratio for PEVs that use L2 workplace EVSE. The split between L1 and L2 EVSE in the final results is determined by the BLAST-V calculations, resulting in 63% L1 and 37% L2.

The implications of allocating EVSE translates to the cost burden incurred per PEV in the economic valuation calculations. Additional detailed assumptions, such as the number of connectors or cords per EVSE unit, panel replacements required, parking spaces in MUDs, PEVs per non-MUD household, non-MUD households without garages, or levels per parking structure in MUDs, are not addressed explicitly in determining these allocation assumptions. In theory, including these types of detailed assumptions could improve the cost estimation methodology, but a lack of consistent and nationwide empirical data to back up these types of assumptions diminishes the analytic value of such an approach. Efforts to refine such assumptions as explicit parameters could be informative for an improved understanding of the variability of costs across different housing types and the suitability of different PEV-EVSE combinations for housing types.

Table 10. Input Parameters for Non-Public EVSE Allocation

Vehicle Type	Home L1	Home L2	MUD L1	MUD L2	Work L1	Work L2
Percent reduction in electricity cost to households for timed charging (for allocation only)						
PHEV	20%	20%	20%	20%	n/a	n/a
BEV	20%	20%	20%	20%	n/a	n/a
Average number of EVSE units per PEV served, given that the particular PEV is using the stated charging level						
PHEV	1	1	0.5	0.5	0.75	0.75
BEV	1	1	0.5	0.5	0.75	0.75

2.3.2.2 Allocation of Public EVSE

In each scenario it is assumed that some basic level of public charging is available. While some workplace charging can also serve as public charging, the public EVSE units are located in public spaces, such as retail stores, parking lots, street curbs, and airports, and are therefore dedicated to public charging by any PEV. A relatively simple allocation is assumed with the number of EVSE units required being proportional to the total kWh used by either PHEVs or BEVs. These proportions and the overall allocation algorithm are derived from scenarios developed for the 2014 California Energy Commission's Statewide PEV Infrastructure Assessment (Melaina and Helwig 2014). The general equation is the following:

$$N_{i,j} = (Demand_{i,j} \cdot fPub_{Pi,jub}) / (kWh/Unit_{i,j})$$

where

$N_{i,j}$ = number of EVSE units for vehicle type *i* and EVSE type *j* (no. units)

$Demand_{i,j}$ = kWh demand per year for vehicle type *i* and EVSE type *j* (kWh)

$fPub_{i,j}$ = fraction of demand as public for vehicle type *i* and EVSE type *j*

$kWh/Unit_{i,j}$ = average kWh demand per EVSE unit per year for vehicle type *i* and EVSE type *j* (kWh/unit)

i = vehicle type: BEV or PHEV

j = EVSE type: L1, L2, or DCFC

The allocation values for the fraction of total electricity demand (*fPub*) provided by public charging and average kWh per EVSE unit (kWh/unit) for PHEVs and BEVs are shown in Table 11. The fraction of demand values are derived from those reported in the 2014 California assessment report (Melaina and Helwig 2014), with the exception of the 1.0% value for the percent of BEV electricity demand provided through DCFC stations. In the 2014 California assessment report the Home Dominant scenario assumed 0.2% of BEV demand is provided through DCFC stations, and the High Public Access scenario assumed 0.5%. The assumption of 1.0% for the Aggressive scenario is therefore higher than both scenarios and is adopted here in part due to the very high total market growth rate assumed in the Aggressive scenario. As discussed in section 2.3.1, a significant reduction in the perceived purchase price barrier for limited BEV range was made, in part, due to high availability of public charging infrastructure.

Table 11. Input Parameters for Public EVSE Allocation

Vehicle Type	L1	L2	DCFC
Percent of demand as public charging			
PHEV	0.080%	1.22%	Not Applicable
BEV	0.050%	4.60%	1.00%
Average kWh demand per EVSE unit per year			
PHEV	1,800	6,200	Not Applicable
BEV	2,200	7,800	36,500

The public EVSE station utilization rates, shown as average kWh demand per EVSE unit per year in Table 11, were determined using nominal average hours of use per weekday and then checking those nominal hours against the price per kWh that would need to be charged to consumers to cover upfront capital costs at two different internal rates of return (IRR). For L1 and L2 public stations, the nominal average hours per weekday are assumed at 52 weeks per year and 5 days per week in the IRR calculation. Accounting for holidays and charging on weekends would alter these nominal hour/weekday values, but lacking empirical data on mainstream PEV driver charging behavior on weekends and holidays, they are assumed to be acceptable estimates for average annual utilization rates.

The results are summarized in Table 12, which shows that L1 and L2 EVSE units are used an average of 4–6 nominal hours per weekday and DCFC units are used an average of 1.4 nominal hours per weekday. Given these average utilization rates, and the capital costs indicated, the resulting markup prices in $/kWh for IRR values of 6% or 10% are shown at the bottom of the table. These markup prices range from $0.07 to $0.12 per kWh for L1 and L2 units and $0.31 to $0.39 per kWh for DCFC stations.

The variability around these average values could be significant. For the present analysis the average values for public L1 and L2 EVSE are assumed to be constant across all regions, though the BLAST-V allocation results provide some variability across the total number of PEV-EVSE combinations regionally. The average utilization results for DCFC stations are based upon an investigation into what might be a representative distribution of utilization rates across a fully developed regional network of DCFC stations, as shown in Figure 18. The left-hand vertical axis is the average kWh provided per DCFC station per year, indicated by the blue bars, and the right-hand vertical axis is the markup price required to recover capital costs per station (based upon a single nominal capital cost for all stations, for the sake of simplicity in presentation) at two different IRR values. The horizontal axis represents bins of total DCFC stations in a network, in 5% bins of total kWh provided by the network. The distribution of DCFC stations by utilization is based upon empirical data collected from existing gasoline station networks, which is assumed here to be a reasonable approximation of a fully developed network of DCFC stations covering a relatively large geographic region with multiple large and small metropolitan regions (Melaina and Bremson 2006). This distribution suggests about 25% of total kWh provided by the network through DCFC stations with utilization rates above 50,000 kWh per year, and 20% of total kWh provided by DCFC stations with utilization rates less than 20,000 kWh per year. The input assumption of an average of 1.4 hours per nominal weekday shown in Table 12 is based upon the average DCFC station within this proposed distribution of utilization rates across the entire network.

Table 12. Parameters Used to Determine Average Commercial EVSE Utilization Rates

Nominal Average Hours per Weekday			
PEV type	**L1**	**L2**	**DCFC**
PHEV	5.0	4.0	*na*
BEV	6.0	5.0	1.4
EVSE Station Attributes			
Attribute	**L1**	**L2**	**DCFC**
Capacity (kW)	1.4	6.0	100
Capital cost ($/unit)	$1,700	$5,500	$108,500
Markup Price ($/kWh) for 15-year Financial Life and 6% or 10% IRR			
Target IRR	***Markup Price by Charger Type ($/kWh)***		
PHEV chargers	**L1**	**L2**	
6%	$0.10	$0.09	
10%	$0.12	$0.12	
BEV chargers	**L1**	**L2**	**DCFC**
6%	$0.08	$0.07	$0.31
10%	$0.10	$0.09	$0.39

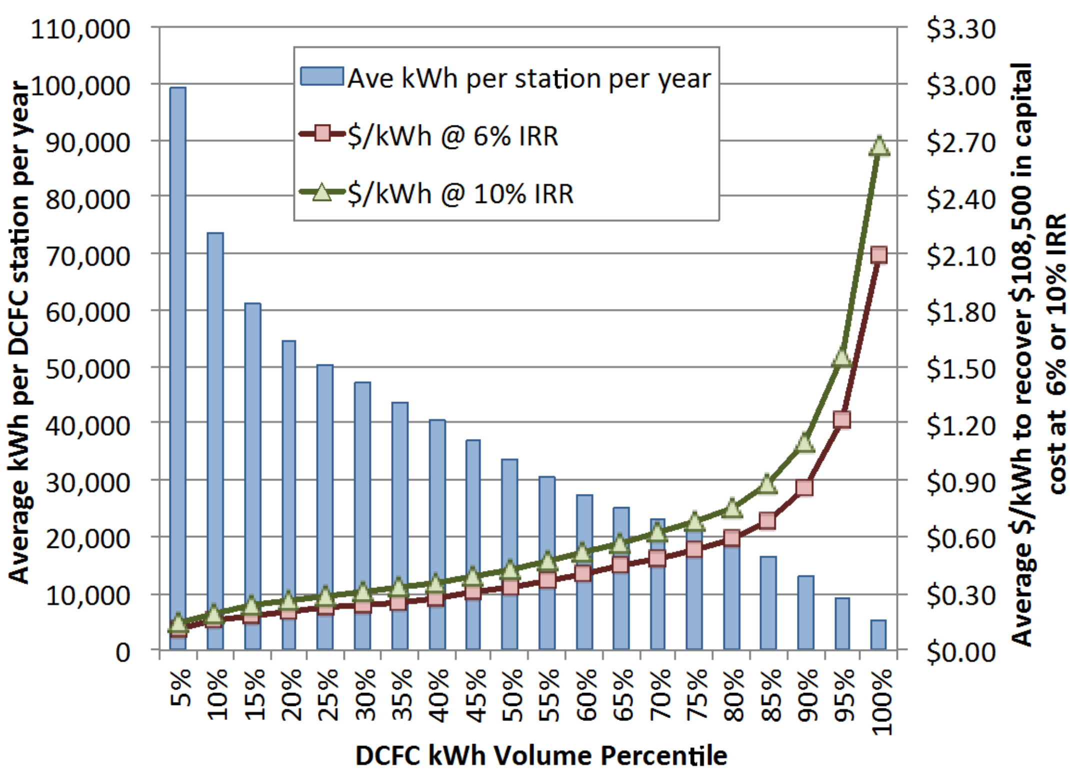


Figure 18. Nominal distribution of demands across a fully developed network of DCFC stations

2.3.3 Economic Value Assessment

The economic value assessment is composed of results generated by the BLAST-V and ReEDS models and integrated into the internally consistent and geographically disaggregated LDV stock and fuel use modeling framework of the SERA model. Figure 4 provides an overview of how the data and calculations in each model relate to and build upon each other to develop the economic value assessment results. Additional detailed descriptions of the valuation calculations in the SERA model are provided below.

The BLAST-V analysis of the NHTS data provides the information indicated in Table 13 for each potential vehicle purchase and charging pattern, for each household involved in a new LDV purchase. These inputs to the SERA model are used in a series of calculations to determine the economic value of increased PEV market share. A simplified version of these calculations is described below.

Table 13. BLAST-V Output Values

BLAST-V/NHTS Parameter	Description
annual miles	total
fraction electric	fraction of annual miles provided by electricity
single-vehicle household	whether the household has only one vehicle
average ambient temperature	average ambient temperature where the household is located
NHTS weight	the household weighting factor from NHTS

The annual miles for the two fuels is computed as follows:

```
e-miles = miles * fraction electric

g-miles = miles - e-miles
```

For gasoline vehicles and PHEVs, gasoline consumption is computed as follows:

```
gasoline consumption = g-miles / gasoline fuel economy
```

For BEVs, however, gasoline consumption is computed by assuming a generic conventional gasoline vehicle is used for the trips that cannot be realized with the BEV:

```
gasoline consumption = g-miles / conventional-vehicle fuel economy
```

The electricity consumption, fuel costs, and avoided gasoline consumption are computed as follows:

```
gasoline cost = gasoline price * gasoline consumption

electricity consumption = e-miles / electric fuel economy

electricity cost = electricity price * electricity consumption * (1000
kW/MW)
```

```
displaced consumption = e-miles / conventional-vehicle fuel economy
```

For purposes of consumer decision-making, the cost of ownership, averaged over the payback period, is as follows:

```
cost of ownership = (vehicle cost + home charger cost) / payback period
+ gasoline cost + electricity cost
```

In the above equation, the gasoline cost is not included in determining the relative value of BEVs for households with more than one vehicle. Gasoline costs associated with trips not fulfilled by a BEV (which depends upon the household driving patterns, regional climate adjustment, and all-electric range of the BEV considered) are included in determining if a household with only one vehicle would replace that vehicle with a BEV.

See section 2.1.3 for a discussion of how the payback period assumption is used to reconcile upfront vehicle and EVSE costs with fuel and electricity consumption costs.

The emissions and displaced emissions are computed from fuel consumption:

```
emissions = carbon intensity of petroleum * gasoline consumption +
carbon intensity of electricity * electricity consumption * (1000 kW/MW)

displaced emissions = carbon intensity of petroleum * displaced
consumption - carbon intensity of electricity * electricity consumption
* (1000 kW/MW)
```

The overall private cost includes the costs of non-home chargers, which could be either workplace or MUD chargers. (Note that workplace and MUD chargers are shared among vehicles, so the costs below are already divided by the number of vehicles per charger.) The social costs of petroleum and carbon are also estimated as follows:

```
private cost = (vehicle cost + home charger cost + non-home charger
cost) / vehicle lifetime + electricity cost

petroleum cost = gasoline consumption * social cost of petroleum

ghg cost = emissions * social cost of carbon
```

Table 14 provides key input assumptions used to estimate public costs for petroleum and GHG emission reductions. When incorporating these additional costs, net reductions in GHG emissions and petroleum (e.g., gasoline) use compared to the Baseline scenario results in positive public benefits. Gasoline prices are derived from the AEO 2015 Reference and High Oil cases. The petroleum reduction benefit is drawn from Leiby (2012), and the social cost of carbon escalates each year according to the Interagency Working Group’s estimates for a 3% (average) discount rate (IAWG 2015).

Table 14. Public Benefit Assumptions

Property	Value	Units	Reference
Gasoline Price (reference)	\$2.23–\$2.75	2013\$/gal (2015–2035)	AEO 2015
Gasoline Price (high oil)	\$3.51–\$5.89	2013\$/gal (2015–2035)	AEO 2015
Petroleum Reduction Benefit	\$0.18	2013\$/gal gasoline displaced	Leiby 2012
GHG Reduction Benefit	\$39.6–\$60.5	2013\$/tonne CO2 (equivalent)	IAWG 2015

Table 15 lists a number of additional parameters used to complete the economic valuation calculations. Gasoline prices are taken from the Reference, High Oil, and Low Oil cases of the AEO 2015, converted to 2013\$/gal. They are resolved at the level of census division. Graphic representations of gasoline price trends by scenario and census division are presented in Figure 19. Electricity prices and carbon intensities are taken from ReEDS ("final prices" and "average CO_2 intensity") and converted to 2013\$/kWh and tonne CO_2e/kWh. They are resolved at the level of ReEDS balancing area and time slice.

Gasoline and electricity prices vary regionally, and these differences are accounted for in the SERA model based upon AEO 2015 trends and ReEDS model outputs. The degree of variability can be seen in the historical prices shown in Figure 20, with the average electricity retail prices shown by state (top) and average retail gasoline prices shown by region (bottom). Generally speaking, these geographic variations tend to persist into the future for the prices used in the economic valuation calculations. One interesting disparity, which shows up in the economic valuation results, is relatively high electricity prices in both California and the Northeast states combined with high gasoline prices in California and only moderately high gasoline prices in the Northeast.

Table 15. Parameter Assumptions to Calculate Social and Public Costs

Parameter	Value
carbon intensity for petroleum	0.01245 tonne CO2e/gal
social cost of petroleum	0.18 \$/gge
social cost of carbon	varies by year with 3% discount rate data in http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html
payback period for consumer choice	7.5 years
vehicle lifetime (physical) vehicle lifetime (economic valuation)	15 years 11.68 years
electricity discount for timed charging	20%
gasoline use penalty for BEVs in single-vehicle households	100%
maximum mileage allowed for BEVs	20,000 miles/year

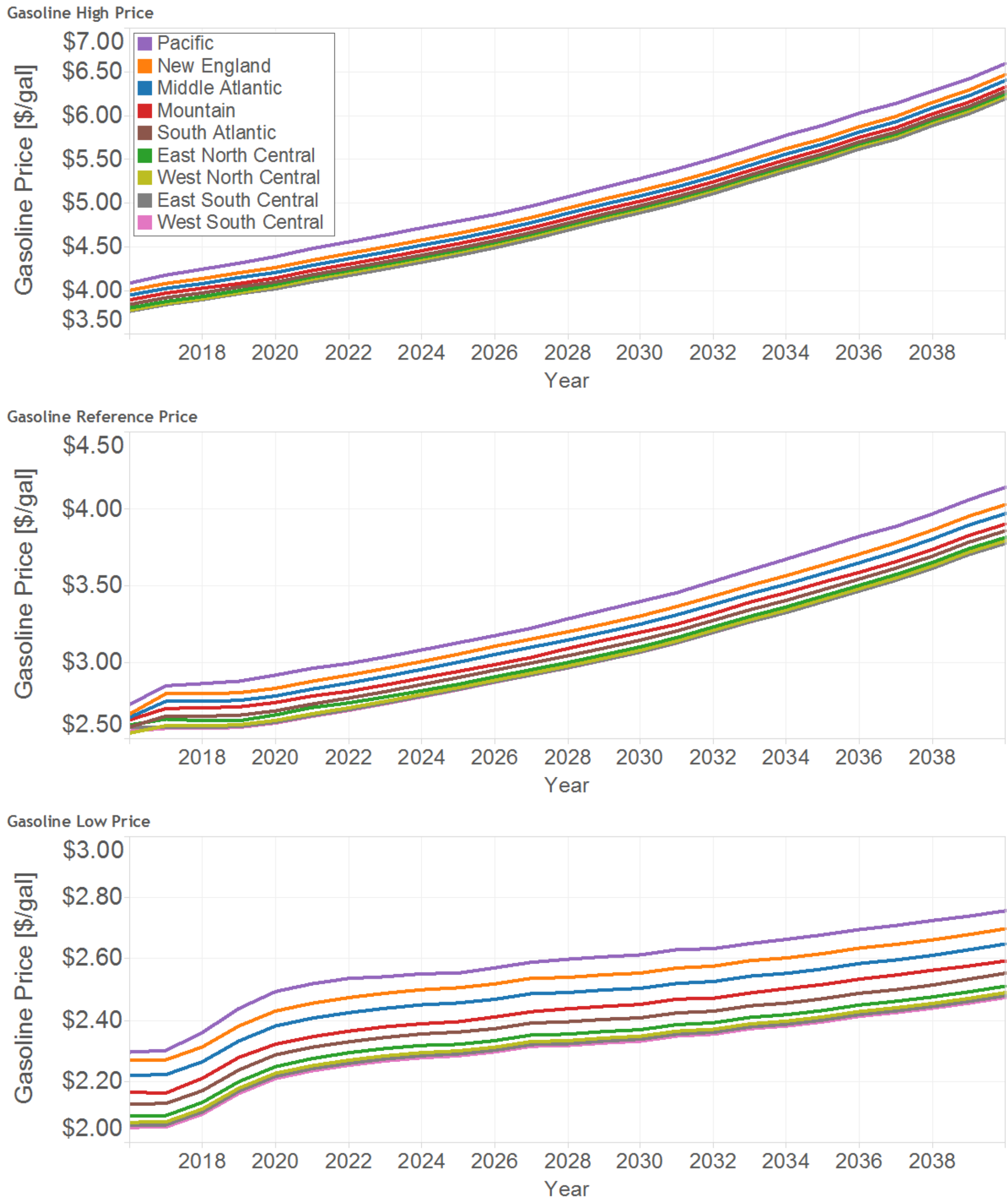


Figure 19. High, reference, and low gasoline price projections by region

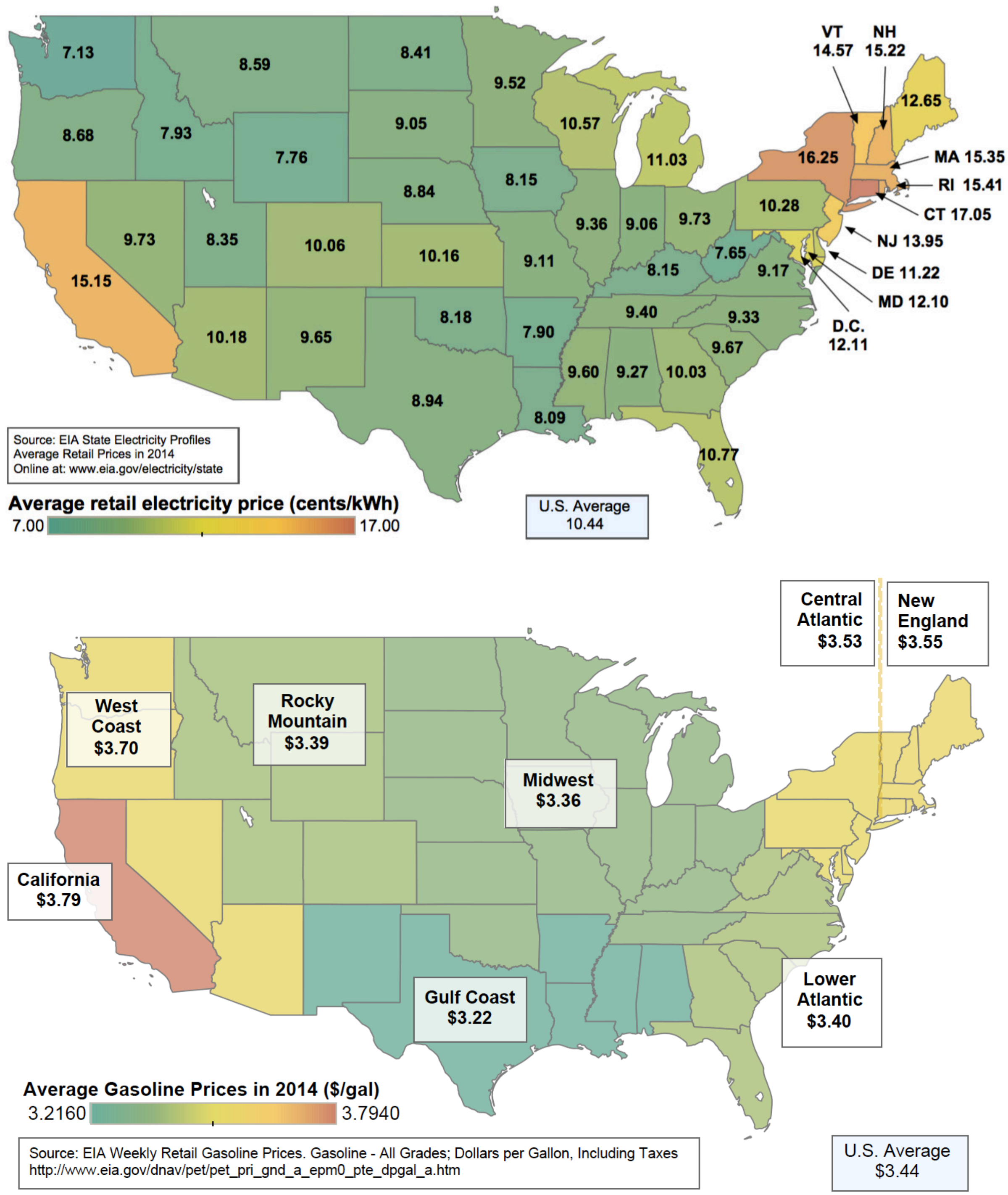


Figure 20. Average retail electricity prices by state (top) and gasoline prices by region (bottom)

2.4 Electricity Generation Costs and Emissions (ReEDS)

ReEDS is an electricity system capacity expansion model that develops scenarios of future investment and operation of generation and transmission capacity to meet U.S. electricity demand (Sullivan et al. 2015). The model performs system-wide least-cost optimization to provide estimates of the type and location of fossil, nuclear, renewable, and storage resource deployment; the transmission expansion requirements; and the generator dispatch and fuel needed to satisfy regional demand requirements and to maintain grid system adequacy. The model also considers technology, resource, and policy constraints including state renewable portfolio standards. ReEDS models scenarios of the continental United States electricity system in 2-year solve periods from 2010 out to 2050.

Within ReEDS, the continental United States is divided into 356 resource regions and 134 balancing areas (BAs), as shown in Figure 21. The 356 resource regions are where wind and solar resource availability and quality are evaluated and their capacity expansion is modeled. The 134 BAs are where all other generation technologies are deployed in the model and where electricity demand and reserves need to be met. Long-distance transmission is represented between adjacent BAs. ReEDS also models the intra-BA transmission costs required to interconnect renewable capacity from their region to the transmission grid. Capturing the resource cost and quality at such a high geographical granularity enables ReEDS to find the least-cost renewable resource expansions by interconnecting high quality resources through appropriate long-distance inter-BA transmission expansions. The existing transmission infrastructure is shown in Figure 22. There are also larger sets of regions within ReEDS: 48 states, 18 curtailment regions designed loosely after existing regional transmission operator and other reliability regions, 13 North American Electric Reliability Corporation regions, nine census divisions, and the three major interconnections—Western, Eastern, and Electric Reliability Council of Texas.

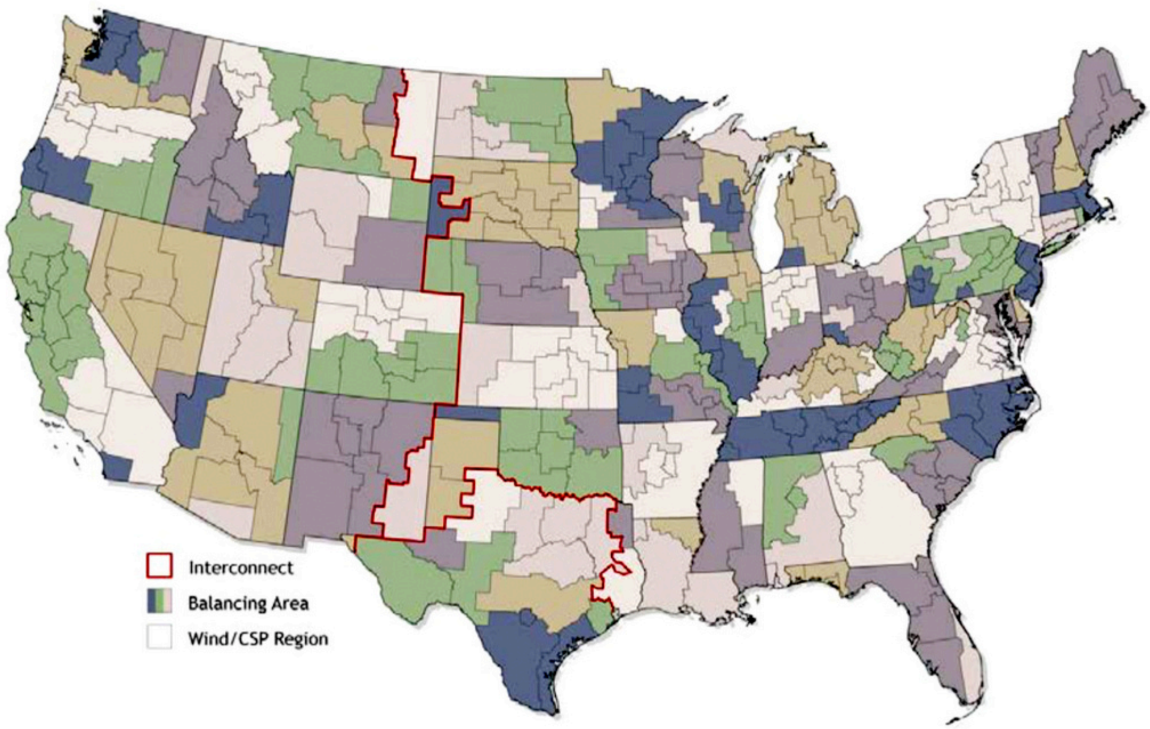


Figure 21. Regional structure including 365 resource regions, 134 BAs, and three interconnections

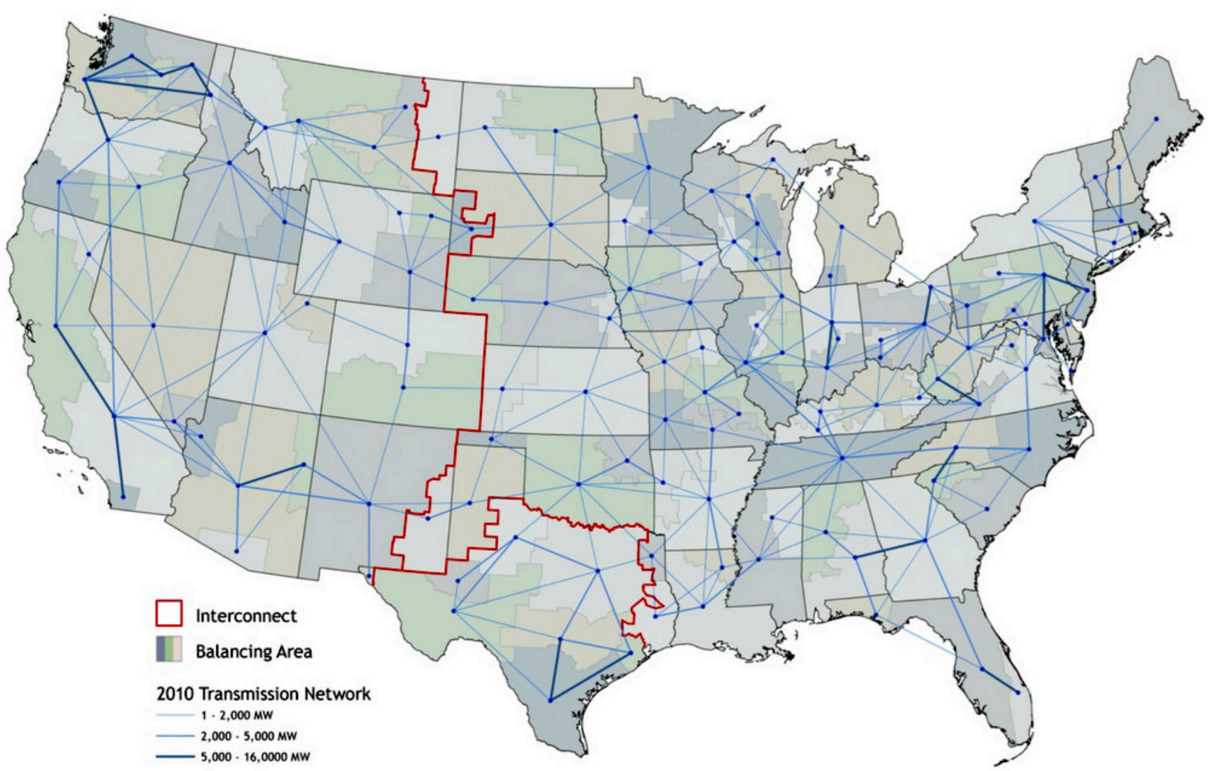


Figure 22. Representation of existing long-distance infrastructure in ReEDS

ReEDS includes a full suite of major generation and storage technologies, including coal-fired, natural gas-fired, oil and gas steam, nuclear, wind, biopower, geothermal, hydropower, utility-scale solar, pumped-hydropower storage, compressed-air energy storage, and batteries. ReEDS dispatches all generation using multiple time slices to capture seasonal and diurnal demand and renewable generation profiles. The following cost, performance, and incentive parameters are used to characterize each conventional technology in ReEDS:

- Cost
    - Capital cost ($/MW)
    - Fixed and variable operating costs ($/MWh)
    - Fuel costs ($/MMBtu)
    - Construction period (years) and expenses
    - Equipment lifetime (years)
    - Financing costs (such as interest rate, loan period, debt fraction, and debt-service-coverage ratio)
- Performance
    - Heat rate (MMBtu/MWh)
    - Minimum turndown ratio (%)
    - Quick-start capability and cost (%, $/MW)
    - Spinning reserve capability
    - Planned and unplanned outage rates (%)
- Policies and incentives
    - Tax credits (investment or production).

For generation dispatch, each solve year is divided into 17 time slices that represent four diurnal time slices (morning, afternoon, evening, night) for each of the four seasons (winter, spring, summer, fall), plus a summer peaking time slice. To further elaborate, ReEDS defines time intervals as follows: T1 (10 p.m.–6 a.m.), T2 (6 a.m.–1 p.m.), T3 (1 p.m.–5 p.m.) and T4 (5 p.m.–10 p.m.). Of the 17 time slices from H1 to H17, time slices H1–H4 pertain to T1–T4 in summer. Likewise, H5–H8 to T1–T4 in fall, H9–H12 to T1–T4 in winter, and H13–H16 to T1–T4 in spring. Time slice H17 pertains to 40 hours in summer peak (taken from time slice H3). However, this time resolution is insufficient to capture some of the shorter timescale phenomena associated with high variable generation penetration. To capture those, ReEDS includes statistical parameters (such as capacity value for peak hour planning reserve, forecast error reserve requirements, and curtailment estimates) to address variability and uncertainty of wind and solar within each time slice.

Although ReEDS scenarios are not forecasts, they provide a framework for exploring internally consistent future electricity systems and for considering the potential impacts of technological development, policy changes, or economic conditions. Annual electric loads and fuel price supply curves are exogenously specified (based on AEO scenarios [AEO 2015]) for each period of the optimization. Additionally, ReEDS inputs include an equipment lifetime for each technology that partly drives the generation retirement decisions. In certain types of scenarios, some existing coal-fired capacity can be underutilized due to, for example, high fuel prices or emissions standards. ReEDS facilitates "economic" retirements of underutilized generator types if their usage falls below a certain threshold. ReEDS applies standardized financing assumptions for investments of all technologies represented in the model. All costs, including new capital investments, operation and maintenance costs, fuel costs, and transmission investments, are considered on a 20-year net present value basis. The discount rate used in the present value evaluation is the weighted average cost of capital of 8.1% nominal or 5.4% real. In addition to the general financial assumptions, there are some technology-specific parameters such as construction periods, tax credits, accelerated tax depreciation rules, and project debt-to-equity fractions. Among the policies, ReEDS models tax credits (production and investment tax credits), state renewable portfolio standards, the Cross-State Air Pollution Rule that controls SO_2 and NO_x emissions, and the Clean Power Plan under its business as usual scenario. A complete description of the ReEDS model and the values used for each for the cost, performance, incentives, etc. can be found in Sullivan et al. (2015).

With a system-wide central-planner perspective, ReEDS is not designed to evaluate distributed technology adoption decisions. For instance, in the case of rooftop solar adoption, ReEDS analysis is supported by the distributed generation market demand model (dGen) that produces scenarios of market uptake of distributed solar photovoltaics (PV) (Sigrin et al. 2016). Similarly, in this study ReEDS takes in the PEV charging data from the BLAST-V model.

The major outputs of ReEDS include the amount of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric sector costs, electricity price, fuel demand and prices, and direct combustion CO_2 emissions. Most of these outputs can also be obtained at BA and time slice resolutions. The 2015 Standard Scenarios annual report (Sullivan et al. 2015) and ReEDS documentation (Short et al. 2011) provide more detailed description of the model structure and equations. Among many significant publications using ReEDS, a few selected ones include the SunShot Vision Study (DOE 2012), the Renewable Electricity Futures study (Mai et al. 2012), and the Wind Vision Study (DOE 2015).

2.5 Jobs and Economic Impact Modeling (IMPLAN)

Jobs and economic impacts were estimated using the IMPLAN input-output (I-O) model. Each scenario contains a set of expenditures on services and commodities such as vehicles, electricity, petroleum products, and chargers. Economic impacts consist of two components: changes in domestic economic activity as a result of these expenditures and changes in household spending as a result of changes in net disposable household income.

Net disposable household income changes because of increased spending on vehicles in each scenario compared to baseline, which occurs due to different vehicle prices. Meanwhile, consumption of petroleum decreases and expenditures on electricity increase. Domestic economic activity resulting from these expenditures occurs as demand for domestically produced electricity increases, demand for domestically produced petroleum decreases, and demand for domestically produced charging stations increases.

2.5.1 IMPLAN Application Overview

The scenarios introduced in this study involve changes in expenditures for vehicles, petroleum, electricity, and charging stations. There are economic implications to producers of these commodities, which could increase or decrease their business depending on if the changes are positive or negative. There are also implications to households, which may need to reduce non-transportation spending in order to purchase more expensive vehicles.

The portion of each production that is domestic is obtained from IMPLAN. All electricity expenditures are domestic while 49% of petroleum, 62% of vehicles, and 71% of vehicle chargers are produced domestically (IMPLAN 2012). Even when petroleum, vehicles, and vehicle chargers are assumed to be imported, impacts to the U.S. retail establishments that sell these items are considered.

2.5.2 Methodology

There are a number of different ways to calculate the economic impacts from changes in how consumers spend their money. Anderson et al. (2014) provide a comprehensive analysis of different modeling techniques ranging from highly complex to relatively simple economic models. The authors find that the most commonly used technique is I-O modeling. There are more complex, comprehensive techniques such as computable general equilibrium or econometric modeling, but these come at the cost of reduced transparency. All methodologies have assumptions and limitations.

I-O models characterize the economy in terms of sales and purchases by sectors, which include businesses, households, investors, governments, and the rest of the world (via imports and exports). Electricity purchased by a vehicle manufacturer, for example, is an input to the vehicle manufacturing sector and an output from the electricity generation sector. All of these linkages allow modelers to estimate economy-wide impacts of a single expenditure.

The “ripple effect” is shown in the types of results that the model shows. These are direct, indirect, and induced effects. Direct effects are those immediately associated with an expenditure. The direct output effect of a $50 purchase of electricity, for example, is $50 in the electricity generation industry. The indirect effect captures activity throughout the supply chain. In the previous example, this may be for business to business services, fuel, contractors, and many other expenditure categories. Induced effects are those supported by household expenditures. Direct and indirect effects result in workers being compensated. These workers then make expenditures, resulting in induced effects. These are often in retail sales, leisure and hospitality, and health care.

There are four impact metrics in this report: employment, earnings, output, and gross domestic product (GDP).

- Employment is defined as the number of employees supported by an industry. This is not the same as full time equivalence, which adjusts employment figures based on the number of part time or seasonal employees.
- Earnings are total compensation to workers and include all benefits such as retirement and health insurance.

- Output is a measure of total economic activity. It includes all sales and purchases. At a company level, it may be thought of as revenue.
- GDP is a measure of the value of production. It is an industry's sales less its purchases of inputs from other businesses. It includes payments to workers, tax payments, and property-type income such as profits.

All impacts are for the equivalent of one year.

The impact scenarios themselves are set up in terms of expenditures, or changes in demand for specific commodities: petroleum, electricity, vehicles, and vehicle chargers. This is modeled as demand for output from industries within IMPLAN. Table 16 shows the associated industries.

Table 16. Expenditures and Associated IMPLAN Industry Codes

Expenditure Category	IMPLAN Industry Code(s)	Industry Description(s)
Electricity generation	31	Electric power generation, transmission, and distribution
Petroleum	20, 28, 29, 326	Extraction of oil and natural gas; drilling oil and gas wells; support activities for oil and gas operations; retail stores—gasoline stations
Vehicles	276, 320	Automobile manufacturing; retail stores—motor vehicle and parts
Chargers	265	Other major household appliance manufacturing

This analysis assumes that petroleum and vehicles are purchased from retail outlets. The price that consumers pay for fuel and vehicles, then, differs from the price that sales outlets pay. The difference—the retailer margin—is modeled as accruing to the retailer while the remainder of expenditures accrues to the manufacturer or producers (IMPLAN documentation). This assumes that the margin is 2.5% for gasoline retailers (Biery 2014; Fahey 2014) and 10% for vehicle retailers (Henry 2012).

This does not assume that all expenditures accrue to U.S. producers. All expenditures are adjusted based on IMPLAN regional purchase coefficients. These coefficients compare sales by U.S. producers with purchases made within the United States by consumers and other producers. All electricity expenditures are domestic while 49% of petroleum, 62% of vehicles, and 71% of vehicle chargers are produced domestically (IMPLAN 2012). Impacts from the remaining expenditures are not estimated.

Changes in expenditures are both positive and negative. Increases in electric vehicle sales, for example, result in increased expenditures for vehicles, chargers, and electricity while expenditures for petroleum decrease.

All changes in expenditures sum to zero—increases in one area are balanced out by decreases in others. If households must make a net increase in expenditures for transportation, they must decrease expenditures in other areas. This is modeled as changes in household income. IMPLAN contains nine household groups that are categorized by income; changes in household expenditures are set up according to household expenditure on vehicles.

3 Intermediary Results

The following sections review intermediary results obtained from each of the modeling methods discussed above. These results feed into the final economic value calculations, but they are of interest in and of themselves as they provide insight into trends underlying the final results. The sections below review the following:

- PEV utility and charging profile results from the BLAST-V model (section 3.1)
- Vehicle substitution results from the LDV allocation algorithm (section 3.2)
- Electricity grid and criteria pollutant emissions impacts from the ReEDS model (section 3.3)
- Macroeconomic impacts from the IMPLAN model (section 3.4).

The final economic valuation results are presented in section 5.

3.1 PEV Utility and Charging Profile Results (BLAST-V)

3.1.1 Aggregate eVMT Results

Average individual utility factor results are presented in Figure 23 for the sample of 100,785 NHTS vehicles. Average results are presented by vehicle type and charging option. This utility function represents the potential to provide all required VMT as eVMT. The shortfall below 100% for PHEVs is made up by driving in hybrid mode and the shortfall for BEVs is made up by driving alternate vehicles, relying upon gasoline in both situations.

It is worth noting that average individual utility factors shown in Figure 23 include travel from all 100,785 NHTS vehicles. In reality, consumers are likely to self-select vehicles and charging scenarios that best match their individual needs. As a result, a simplified representation of average utilities could potentially underestimate PEV utility by aggregating travel from a representative cross-section of all drivers (not just those well suited to PEVs). In reality it is the individual vehicle utilities rather than averages that are fed to SERA from BLAST-V. Variations around the averages are therefore discussed in more detail below.

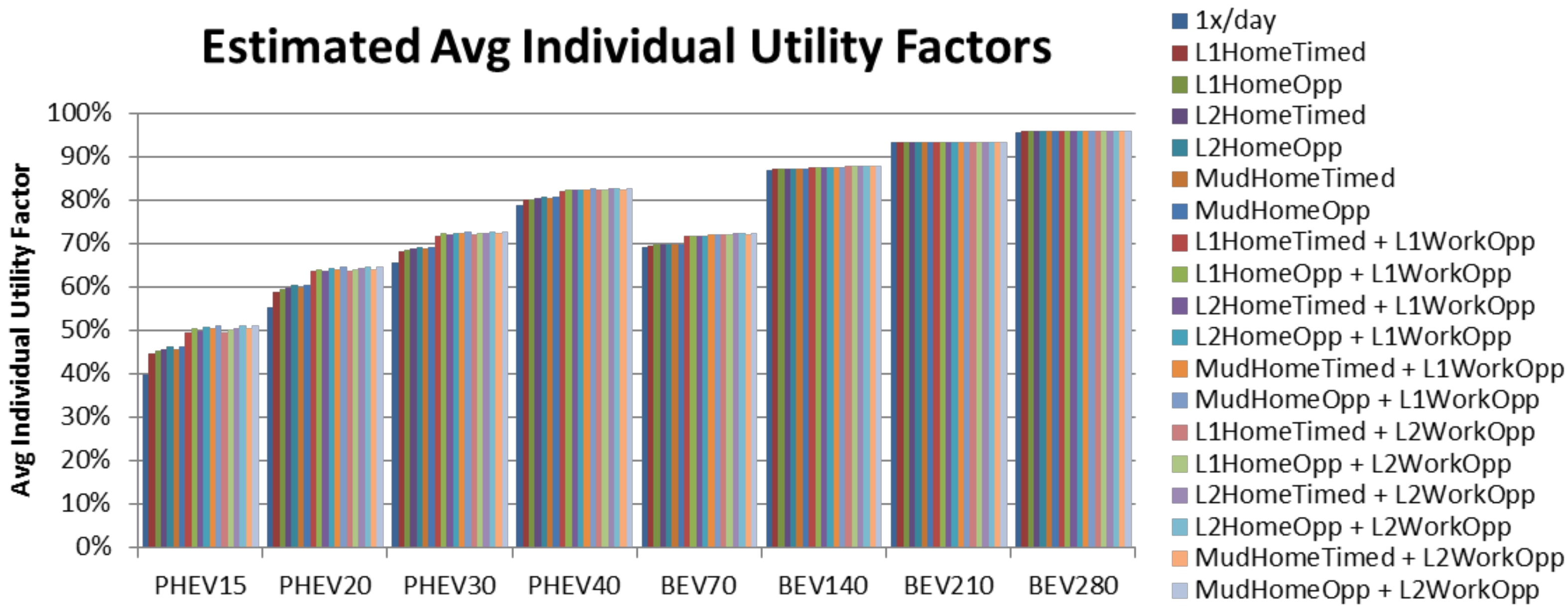


Figure 23. Average individual utility factors for the sample of 100,785 NHTS records by simulated vehicle type and charging option

To demonstrate the sensitivity of PEV utility factors to individual travel patterns, Figure 24 shows boxplot distributions of individual utility factors for all PEVs under study in a once-per-day charging scenario (whiskers show maximum/minimum values and boxes represent $25^{th}/50^{th}/75^{th}$ percentiles). The distribution of individual utility factors for all vehicles under study is significant. Absolute spreads between the best and worst performers are at least 95 percentage points for all vehicles, and interquartile ranges are between 10 and 35 percentage points. Recall that the shortfall below 100% for PHEVs is made up with driving in hybrid model and the shortfall for BEVs is made up by driving alternate vehicles (relying on gasoline in both cases).

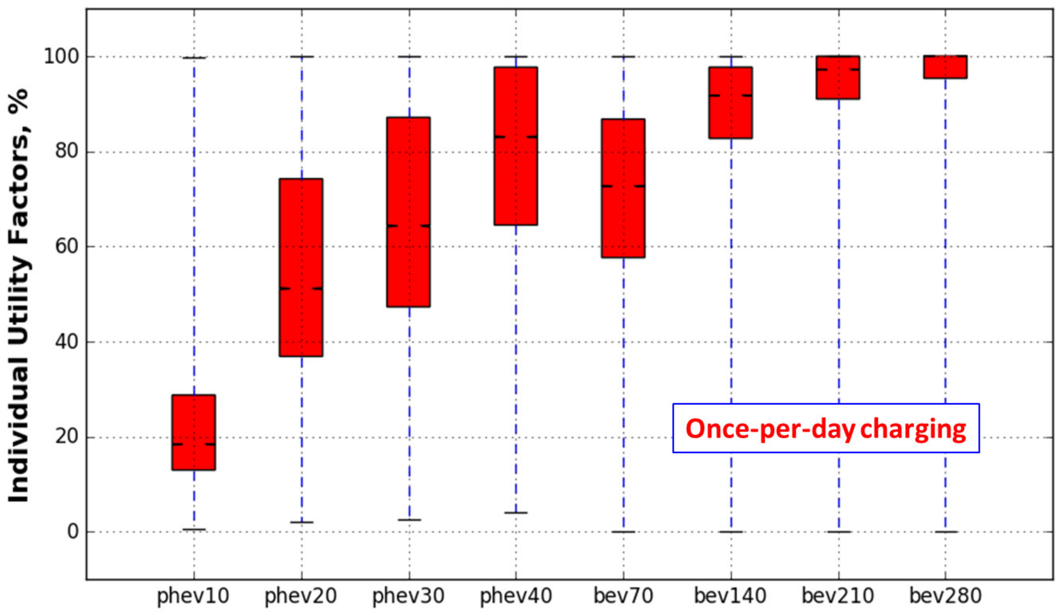


Figure 24. Estimated distributions of individual utility factors for all PEVs under study. Boxplots are specific to the once-per-day charging scenario.

In order to better understand the sensitivity of individual utility factors, several plots of average individual utility factors versus various vehicle attributes are presented.

Figure 25 displays average individual vehicle utility factors versus A-VMT for the PHEV options. In all scenarios, average individual vehicle utility factors decrease with increasing A-VMT. Average individual utility factors also increase with greater electric range (BEV results show similar trends).

Inherent to the methodology employed in this study, ambient temperature impacts individual utility factors. The 100,785 NHTS vehicles were spatially linked to the nearest of 1,020 TMY3 weather stations. Effective annual range derate factors are calculated for all TMY3 stations and plotted in Figure 26 against average ambient temperature. As expected, energy efficiency can be seen to drop on either side of approximately 20°C, emulating impacts of cabin heating/cooling and powertrain viscosity increases at low temperatures. Variations in effective annual range derate values at any specific annual average ambient temperature are attributed to daily variation in ambient temperature. Locations with low levels of daily temperature variation are less penalized due to the absence of seasonal extremes that depress annual average efficiency.

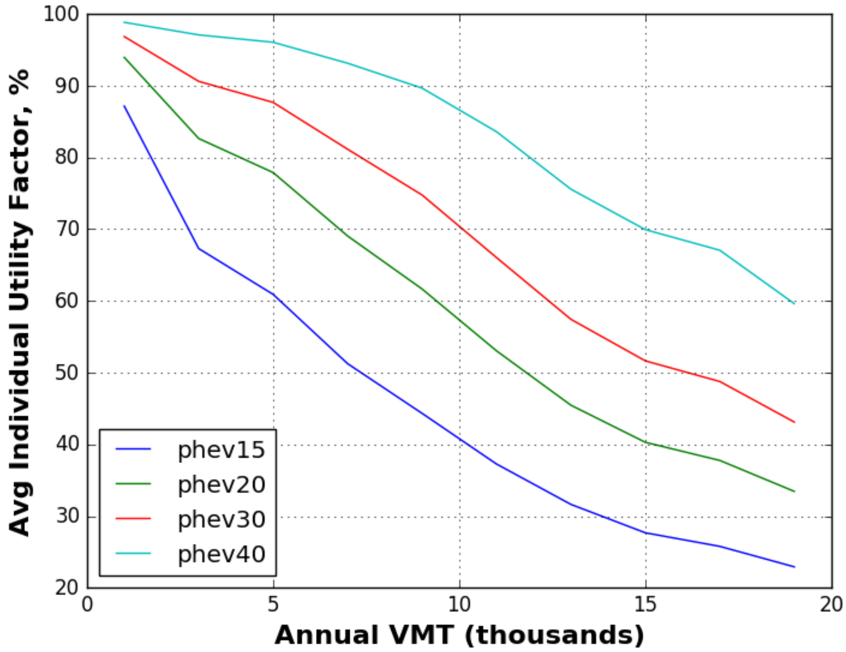


Figure 25. Estimated PHEV average individual utility factor versus A-VMT for the weighted sample of NHTS vehicles (specific to the once-per-day charging scenario)

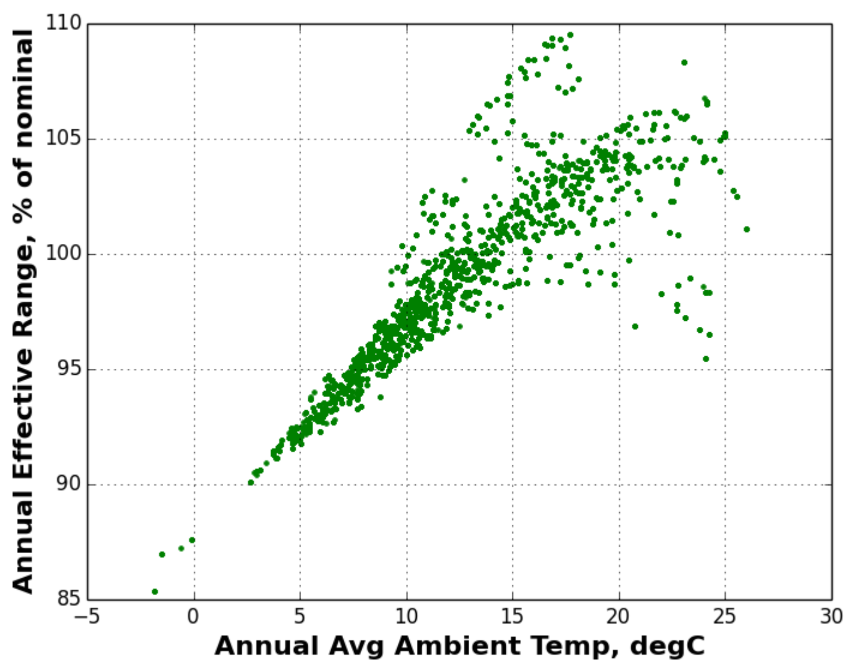


Figure 26. Effective range derate factors for all 1,020 TMY3 weather station locations

While individual travel profiles are observed to have a first order effect on PEV utility factors, Figure 27 shows that ambient temperature likely has a second order effect. Estimated average individual utility factors are plotted versus annual average ambient temperature for all PHEVs under study (BEV scenarios are excluded but show similar trends). Average individual utility factors increase by approximately 5 percentage points for all PHEVs when moving from an annual average ambient temperature of 2.5°C to 22.5°C.

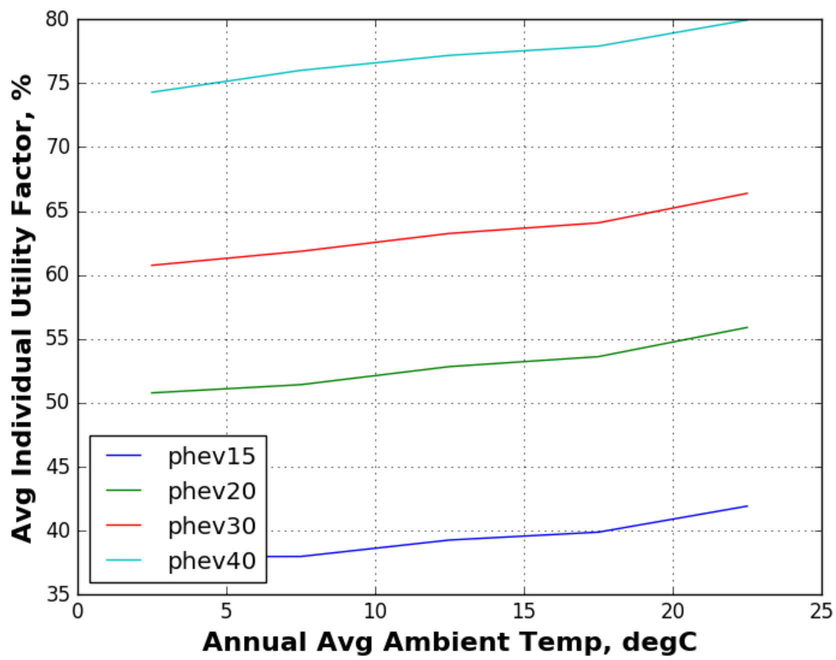


Figure 27. Estimated PHEV average individual utility factor versus annual average ambient temperature for the weighted sample of NHTS vehicles (specific to the once-per-day charging option)

Figure 28 presents PHEV average individual utility factors plotted by U.S. state (BEV scenarios are excluded but show similar trends). Plotting results by geography simultaneously captures differences in regional travel patterns and ambient conditions. These coupled effects result in at least a 10 percentage point difference in average individual PHEV utility factor between the best and worst performing states (Hawaii and Vermont respectively).

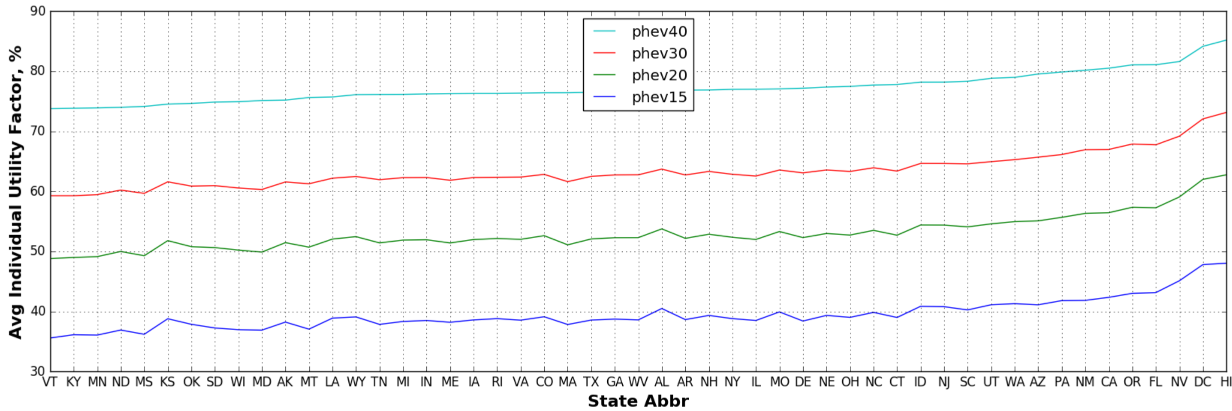


Figure 28. Estimated PHEV average individual utility factor by U.S. state (specific to the once-per-day charging scenario)

3.1.2 Hourly Charging Profiles

Using the method described above, BLAST-V creates highly time resolved charging profiles to enable the greatest eVMT possible given the driver, vehicle, and charging constraints. Figure 29 shows charging profiles for a subset of the configurations used in this report. Notice that adding work charging enables an increase in morning charging for commuters after the morning commute; all configurations then follow roughly the same profile until the evening where the vehicles charged at work do not have to recharge as much using their home charger. Also, the use of timed (i.e., delayed) charging reflects a utility tariff trying to reduce the evening peak. The parameters and charging configurations are detailed in Table 7 and the corresponding section.

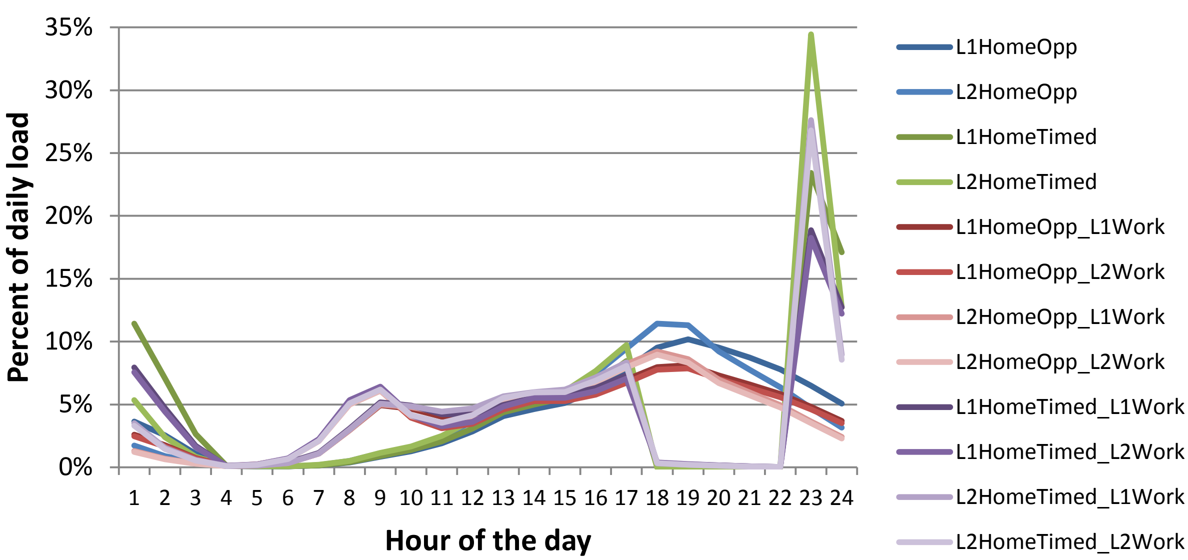


Figure 29. Charging profiles for various charger sizes and configurations

As discussed in section 2.2, BLAST-V provides an hourly charging profile for each of the 18 charging plans (the complete list is shown in Figure 23) for each ReEDS balancing area for a variety of average ambient temperatures. For each household, the appropriate charging profile is applied to the vehicles that have selected that profile, summarized as total hourly demand for electricity from PEVs for each ReEDS balancing area. These annual average hourly electricity demands are then re-aggregated into the time slices used by the ReEDS model.

Figure 30 shows the distribution of charging energy by charging configuration for each scenario. Notice that there are three distinct tiers: level 1 home charging configurations, level 2 home charging configurations and multi-unit dwelling configurations. Within each of these there are variations in total energy consumption based on the type and operation of the selected technology. There are slight variations between scenarios. As mentioned earlier, this study does not include a vehicle choice model so the proportion of vehicle types selected are similar between scenarios, which results in similar charging preferences.

Once substantial levels of PEVs are installed there is a need to consider how the aggregate charging pattern and each charger are synchronized in order to avoid unwanted charging behavior including spikes and ramping events. This is partially accomplished by drivers because all drivers do not arrive and charge their vehicles at the same moment. Additionally, smart charging infrastructure can further stagger the charging rate to avoid negative impacts to the grid. For this study the resulting hourly charging profiles from BLAST-V are aggregated into four intervals per day for use in ReEDS. This effectively distributes artificial peaks over each ReEDS interval while retaining the total energy requirement.

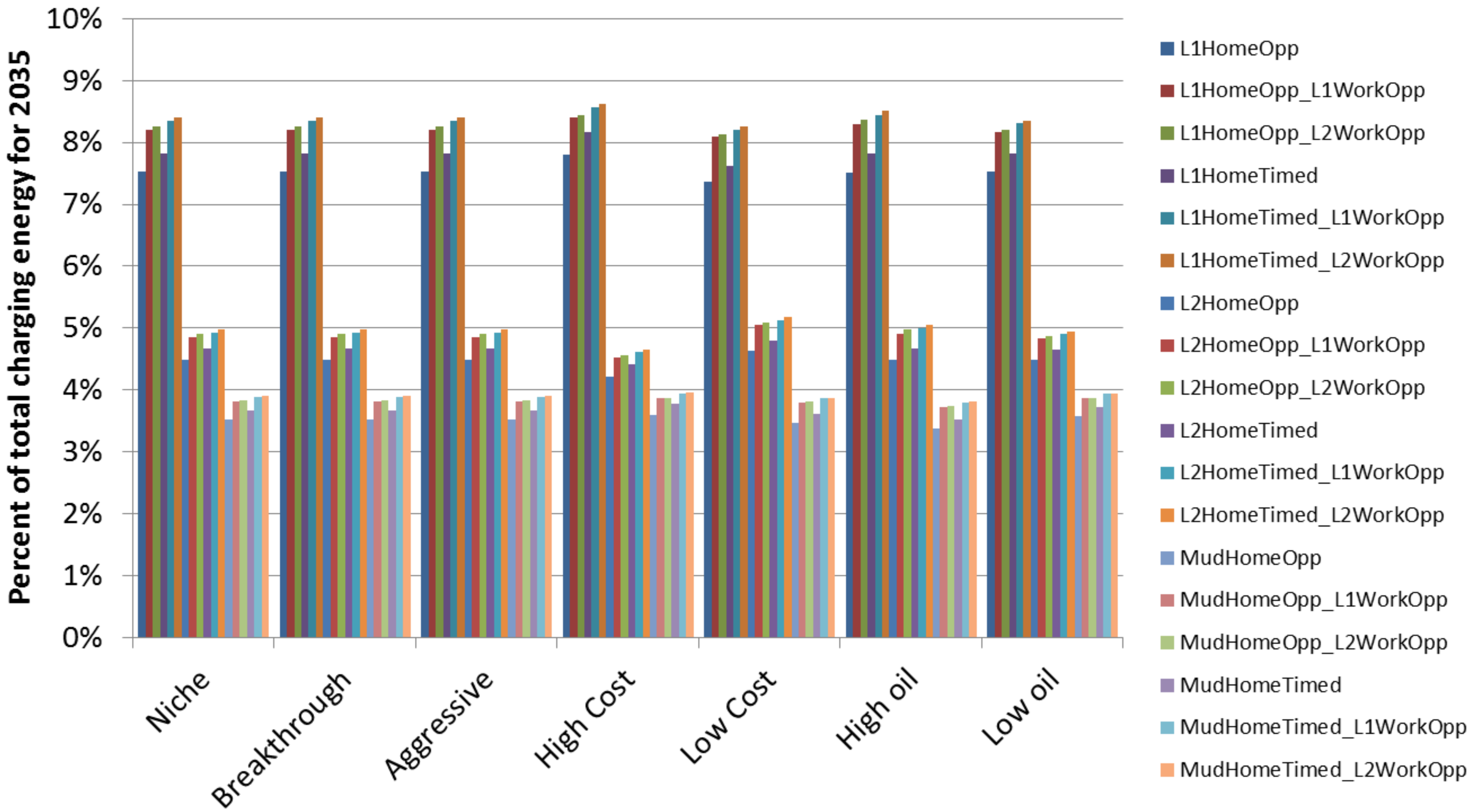


Figure 30. Fraction of total yearly charging energy by charger configuration for each scenario

3.1.3 Methodology Validation to EV Project Data

Estimated eVMT values derived for this analysis are compared to on-road measurements made as part of the EV Project (INL 2015), as shown in Figure 31. Nissan Leafs (with an EPA-rated range of 84 miles) participating in the EV Project report an annual average eVMT of 9,697 miles. The NHTS-based methodology presented in this analysis results in an annual average eVMT of 8,717 miles for the simulated BEV70 under the once-per-day charging scenario (10% less than the average EV Project Leaf). However, this simulated result is sensitive to input assumptions regarding which NHTS households vehicles are assigned to and how those vehicles are charged. Annual average eVMT for the simulated BEV70 jumps to 9,246 miles under the assumption of Level 2 opportunity charging at home and work (5% less than the average EV Project Leaf). Simulated eVMT jumps again to 10,137 miles per year (5% greater than the average EV Project Leaf) when restricting BEV70 assignment to only households with A-VMT greater than 5,000 miles.

Chevrolet Volts (with an EPA-rated range of 35–38 miles depending on model year) participating in the EV Project report an annual average eVMT of 9,112 miles with an average total VMT of 12,238 miles, resulting in a fleet utility factor of 74% (see SAE J2841 2010). The NHTS-based methodology presented in this analysis results in an annual average eVMT of 8,552 miles with an average total VMT of 13,572 miles for the simulated PHEV40 under the once-per-day charging scenario (resulting in a fleet utility factor of 63%). As with the simulated BEV70, the PHEV40 is sensitive to input assumptions regarding which NHTS households vehicles are assigned to and how those vehicles are charged. Annual average eVMT for the simulated PHEV40 jumps to 9,296 miles with an average total VMT of 13,572 miles under the assumption of Level 2 opportunity charging at home and work (resulting in a fleet utility factor of 68%). Restricting PHEV40 assignment to only those NHTS households with A-VMT less than 32,000 miles depresses both eVMT to 9,103 miles and total VMT to 12,215 miles (resulting in a fleet utility factor of 75%).

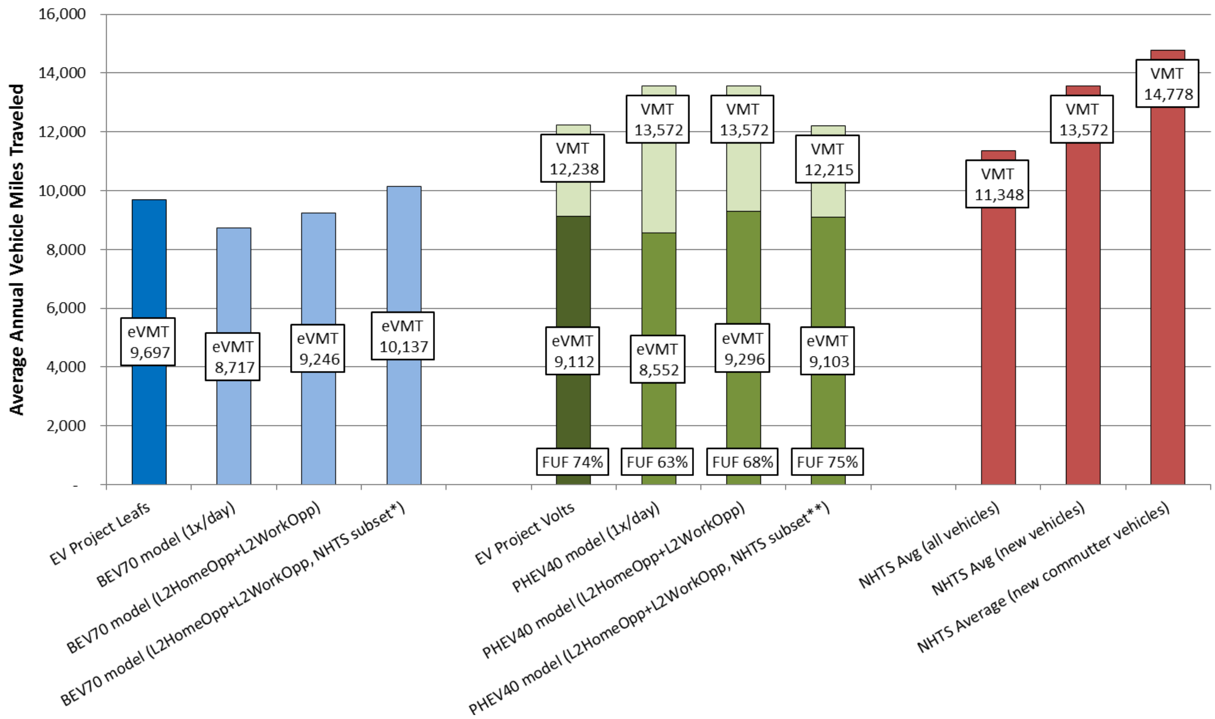


Figure 31. VMT and eVMT comparisons between Nissan Leafs and Chevy Volts in the EV Project and modeled NHTS BEV70s and PHEV40s (NHTS subset* = vehicles with A-VMT greater than 5,000; NHTS subset = vehicles with A-VMT less than 32,000)**

3.2 Total PEV Sales and Substitution of PEVs for CVs and HEVs

Households that drive more miles per year can achieve greater fuel savings as a result of purchasing a more efficient or plug-in LDV. One of the key analytic contributions of the present study is an allocation of more efficient HEVs and PEVs to households that will attain higher fuel savings while still tolerating the limited range of BEVs. Given the input assumptions for LDV costs and performance, summarized in Figure ES-1 and section 2.2.1, the total share of PEVs and the relative shares of different types of PEVs are key intermediary results in determining the economic value of future PEV deployment. The Aggressive scenario utilizes the consumer choice algorithm described above to allocated PEVs by type, with the total number of PEVs deployed determined by the 14% eVMT requirement. However, variations from the Aggressive scenario due to different projections of gasoline prices (High Oil and Low Oil scenarios) and LDV and EVSE costs (Low Cost and High Cost scenarios) are not constrained by this percent eVMT requirement and as a result have different total and relative PEV market shares.

This variation is demonstrated by the evolution of PEVs on the road by scenario, as shown in Figure 32. Total PEVs on the road by 2035 ramp up from zero (by definition) in the Baseline scenario to 12 million in the Niche scenario, 24 million in the Breakthrough scenario, and 73 million in the Aggressive scenario. Variations in vehicle and EVSE costs result in a reduction of total PEVs by 2035 to 69 million in the High Cost scenario and an increase to 79 million in the Low Cost scenario. Even larger deviations from the Aggressive scenario are seen with changes in the future price of gasoline, with 92 million PEVs by 2035 in the High Oil scenario and 66 million PEVs by 2035 in the Low Oil scenario.

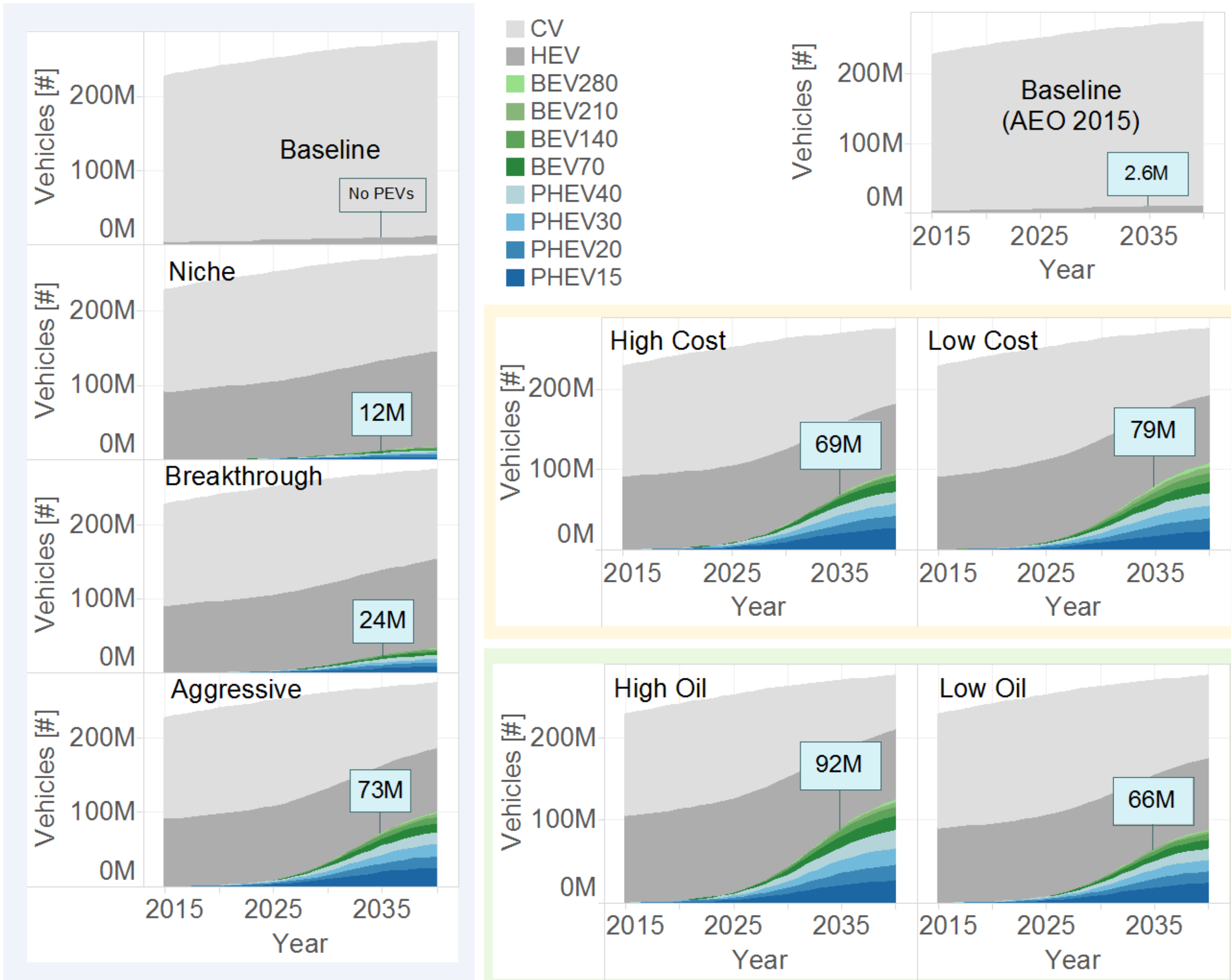


Figure 32. On-road LDVs by type and total PEVs for all scenarios

These total PEV results by 2035 are shown in greater detail in Figure 33 to indicate relative shares between different types of BEVs (top) and PHEVs (bottom).

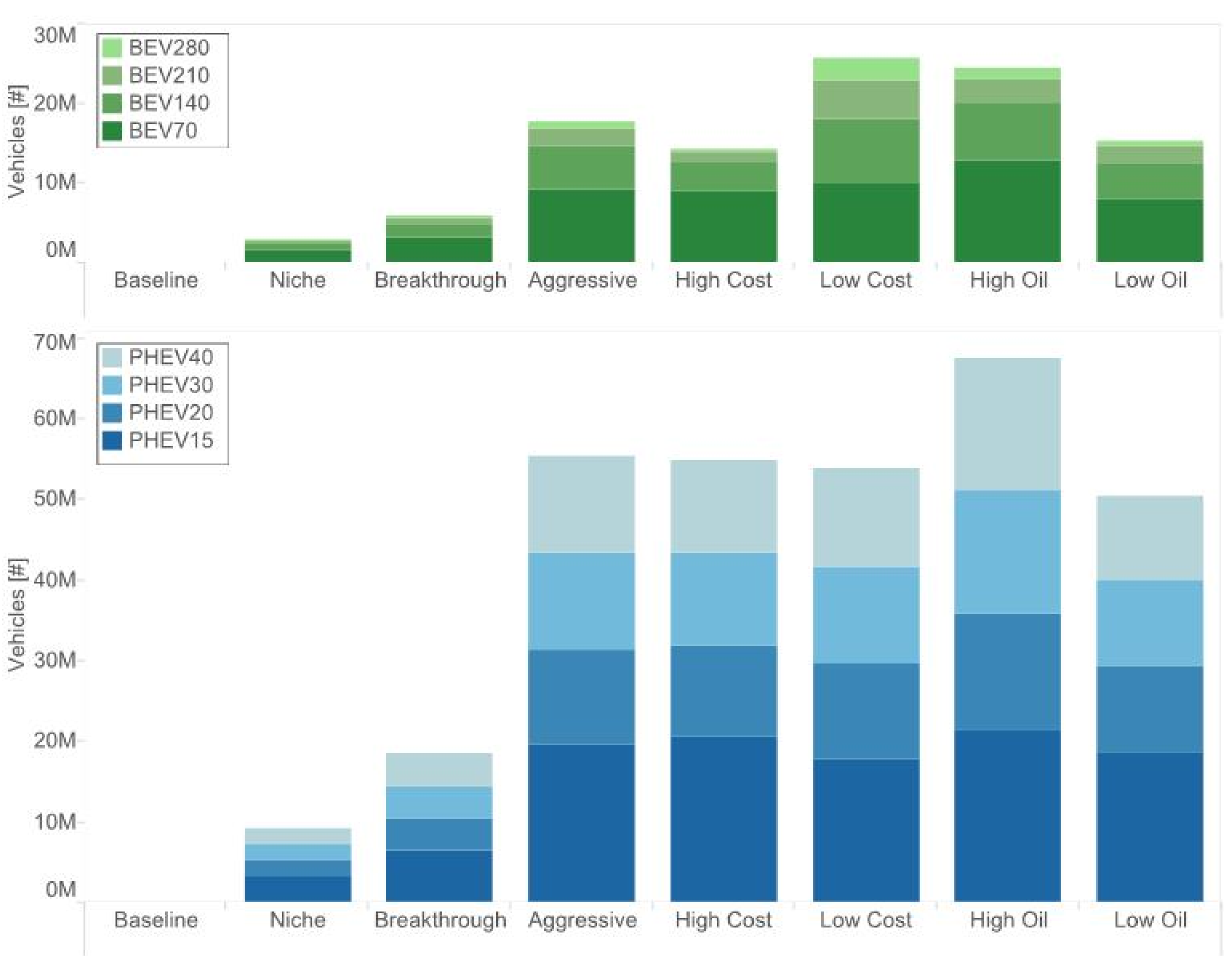


Figure 33. Variations in PEVs on the road by type in 2035 by scenario

The resulting stock of CVs and HEVs on the road in 2035 is shown by the large circle with dashed borders in Figure 34. The height of the circles on the vertical axis is the average miles driven per year, with HEVs driving more miles per year than CVs, and the size of the circles is the number of vehicles on the road, also indicated numerically within the boxes labeled "*Before PEVs*". The costs and benefits of increasing PEV market share are determined by substituting PEVs against this mix of CVs and HEVs. As indicated, the sizes of the CV and HEV circles decrease, with new numerical values indicated in the "*After PEVs*" boxes. The average miles driven per year by CVs and HEVs also decreases; each circle shifts downward on the vertical axis. The total numbers of PHEVs and BEVs are shown as blue and orange circles, respectively, with positions along the horizontal axis indicating the average number of electric miles driven by each vehicle type.

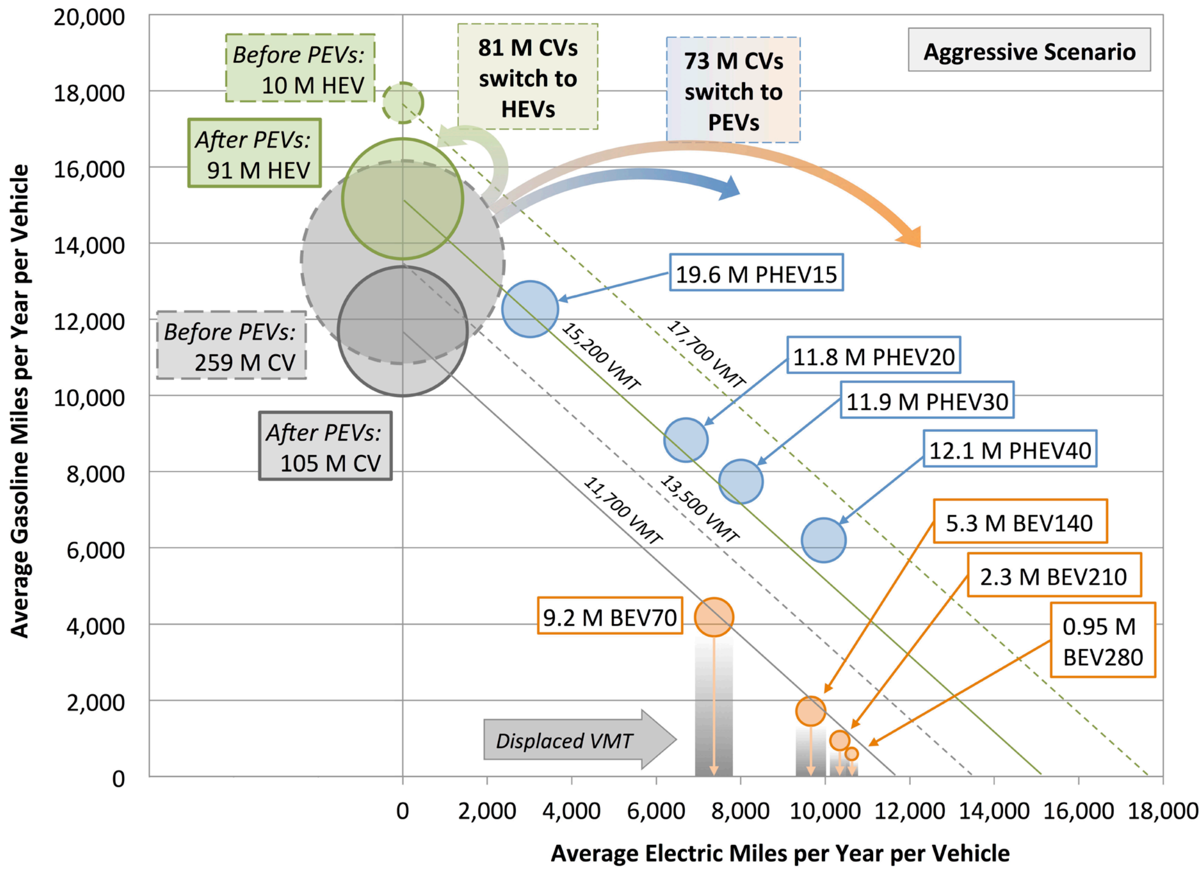
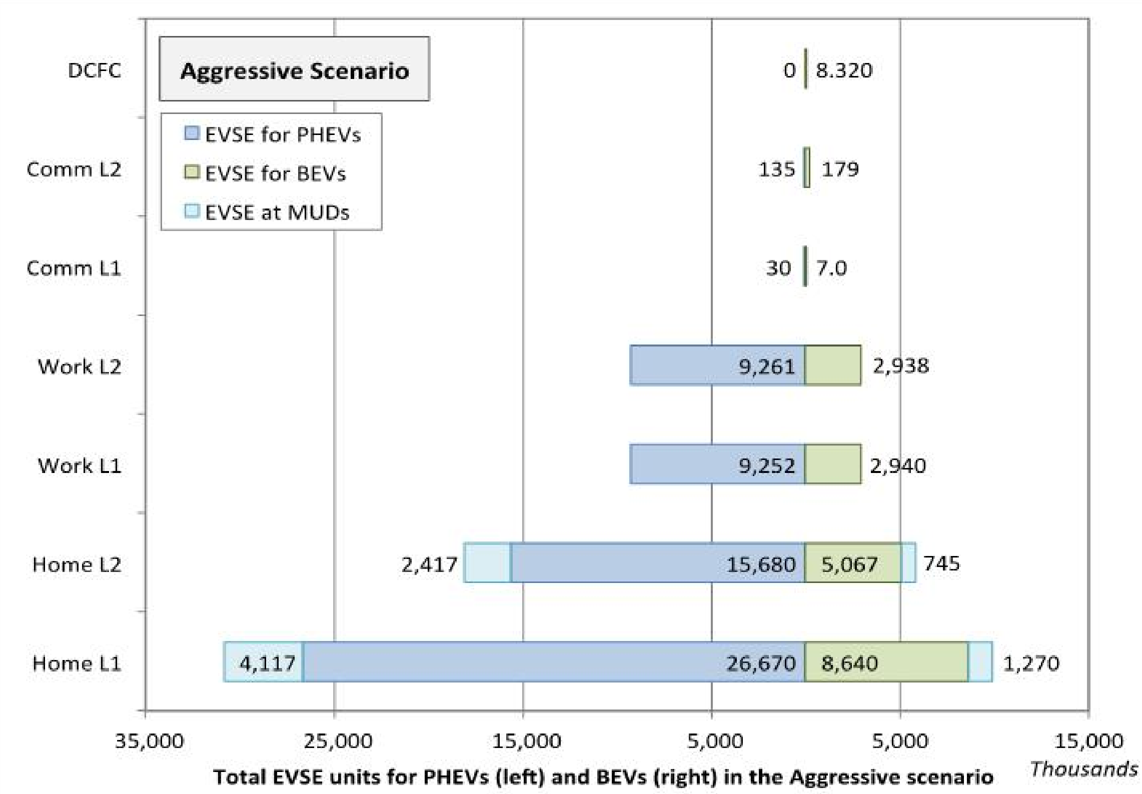


Figure 34. Shift of CVs and HEVs to PEVs from the Baseline to Aggressive scenario with annual average gasoline and electric miles by LDV type

3.3 EVSE Network Expansion

The number of EVSE units required to support PEVs deployed in the Aggressive scenario is summarized in Figure 35. The top panel indicates total EVSE units required by EVSE type and location. Bars extending to the left of zero on the horizontal axis are EVSE units supporting PHEVs, and bars extending to the right are EVSE units supporting BEVs. As indicated, Home L1 EVSE units are the most numerous, followed by Home L2 and a roughly equal split of Work L1 and Work L2 units. Home units allocated to MUDs are broken out as a separate category. DCFC stations, which are shown only supporting BEVs, total to 8,320 stations by 2035 in the Aggressive scenario. The lower panel indicates the same results but as a ratio of total EVSE per million PEVs, with EVSE units per million PHEVs indicated by bars extending to the left of zero and EVSE units per million BEVs indicated by bars extending to the right of zero. As indicated by the bottom bars, approximately 1.2 million EVSE units are required per million PEVs, which includes approximately 334,000 L1 and L2 workplace chargers per million PEVs, 3,300 L1 and L2 commercial chargers per million PHEVs, and 11,500 L1 and L2 commercial chargers per million BEVs. The public charging network also includes 8,320 DCFC stations, or about 470 per million BEVs. These results follow from the fixed input assumptions reviewed in section 2.3.2 characterizing the required base level of public charging needed to support robust PEV market growth and increase the value proposition of BEVs.



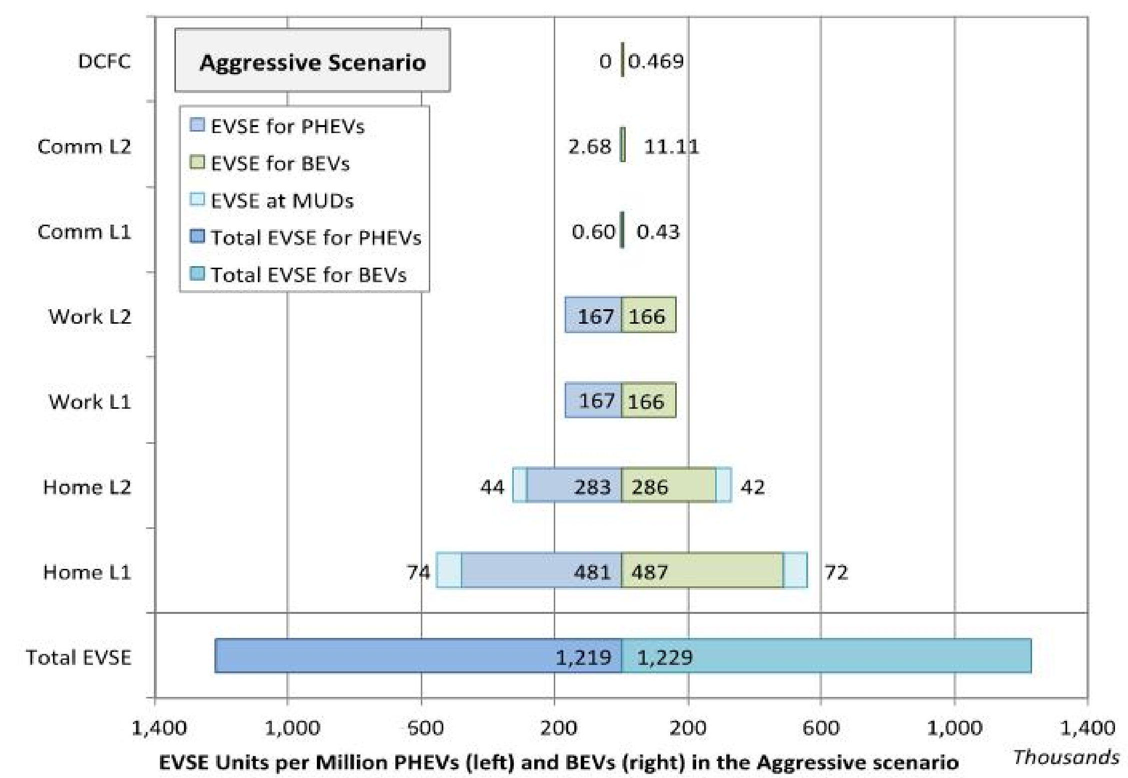


Figure 35. Number of total EVSE units (top) and per million PEVs (bottom) by type and location

3.4 Electricity Grid and Criteria Emissions Impacts

3.4.1 Demand PEV Charging

Figure 36 presents the yearly total electricity demand for PEVs from 2010 to 2040 for each scenario. The Baseline scenario has the lowest demand of all scenarios, while the Low Cost variation on the Aggressive scenario (labeled Aggressive-Low Cost) consumes more electricity than the Aggressive scenario, and the High Cost variation consumes less (all three are visually similar in the figure). Figure 37 shows the incremental electricity demand resulting from the addition of PEVs. The incremental energy demand under the different PEV penetration scenarios is with respect to the Baseline scenario. The increase in energy demand by 2020 across different scenarios ranges from about 0.11% to 1.09% (with Aggressive scenario at 0.68%). By 2035 (the focus year of this study) it ranges from about 0.64% to 5.91% (with Aggressive scenario at 3.84%), and in 2040 the range increases to 0.94%–8.78% (with Aggressive scenario at 5.62%).

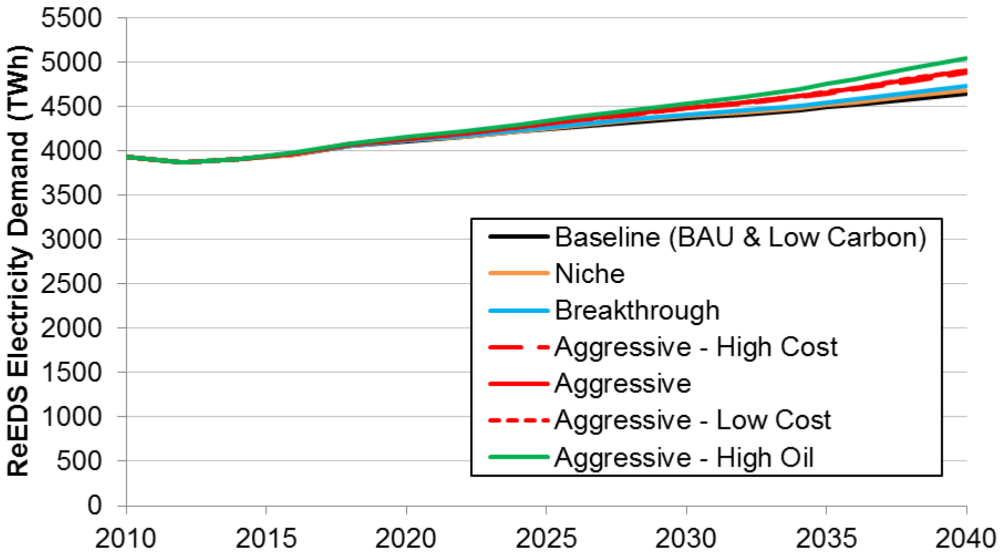


Figure 36. ReEDS yearly energy demand

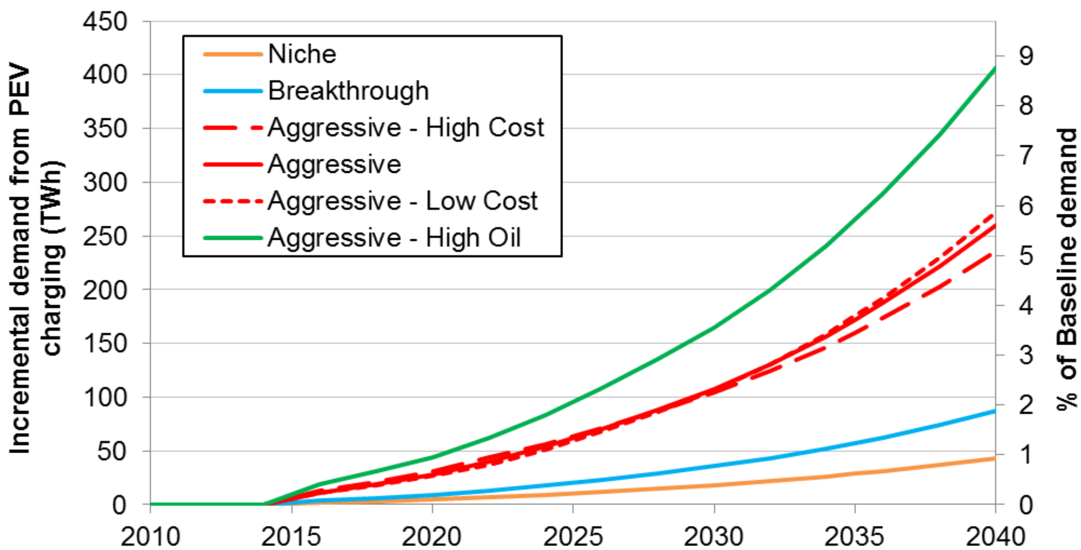


Figure 37. ReEDS incremental energy for PEV charging

Figure 38 focuses on year 2035 and presents the additional energy for charging PEVs for each ReEDS time slice. This is the format in which ReEDS obtains the PEV charging data for all the scenarios from BLAST-V. To construct these charging distributions, first, BLAST-V calculates highly resolved charging profiles and utility factors for a variety of vehicle and charging configurations. Next, the utility factors along with vehicle cost, charger cost, fuel cost, and other data are inputted into SERA to calculate the vehicle shares and charger selection. The first iteration uses electricity prices and carbon intensity values from the Baseline ReEDS scenario (i.e., no PEVs). Resulting vehicle shares and charger selections from SERA for each scenario are then combined with the charging profiles from BLAST-V. The aggregate electricity consumption from PEVs for each scenario is collected by timeslice and added to ReEDS. ReEDS is rerun to establish the impact of PEV charging on electricity prices and carbon emissions for each scenario. Figure 38 shows the Niche, Breakthrough, Aggressive, and High Oil scenarios but it does not include the Dynamic scenario, which is shown in Figure 39 along with the High Cost and Low Cost scenarios since their PEV charging inputs are very similar to the Aggressive scenario. Due primarily to delayed charging, the highest amount of charging occurs in the time interval T1 (10 p.m.–6 a.m.) in every season (H1, H5, H9, and H13).

The charging profiles in Figure 38 have roughly the same shape and only vary by magnitude across the scenarios shown. This is because the selection of vehicles and charging equipment scale similarly. In contrast, Figure 39 shows the charging behavior for several unique charging strategies. These include the Dynamic scenario, delayed (timed) charging, and opportunity (immediate) charging. Opportunity and delayed charging represent the charging profiles if all vehicles engage in those specific charging strategies and are used to provide a comparison between the Aggressive and Dynamic scenarios.

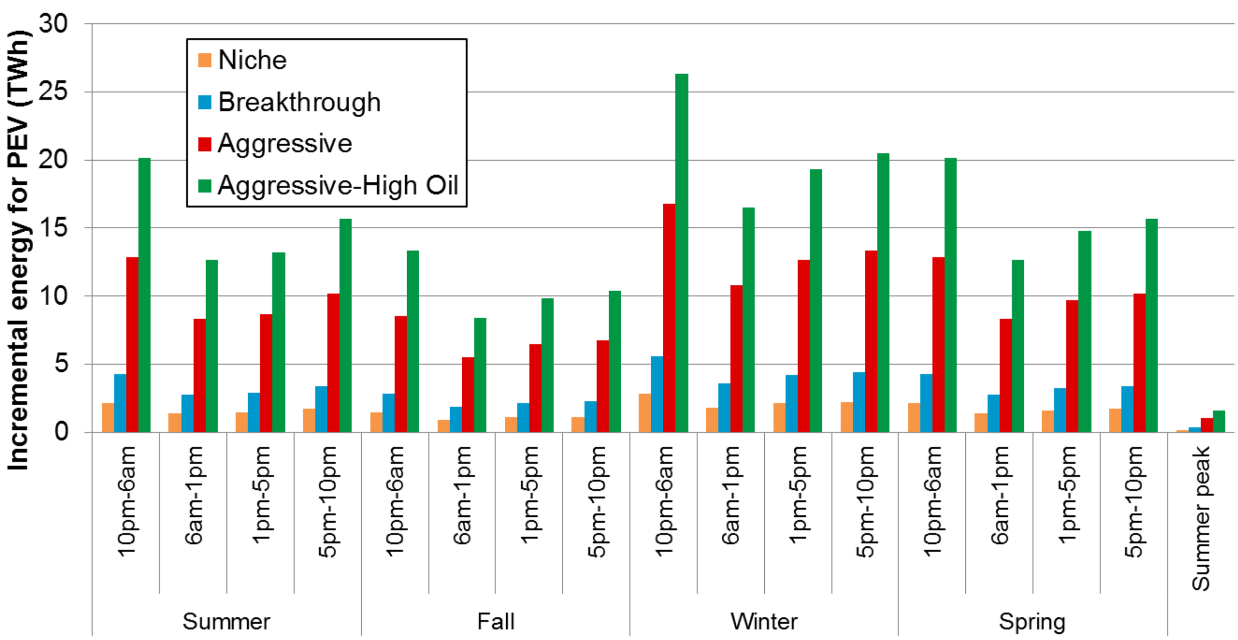


Figure 38. Additional energy demand imposed by PEVs in 2035 by ReEDS time slices

The Dynamic scenario is of particular interest with respect to shifting PEV demand to minimize incremental grid costs. In the Dynamic scenario, the charging energy required per season is the same as that of the Aggressive scenario, but the ReEDS model is allowed to optimally allocate the charging energy across the four time slices every season to minimize the system planning costs. While the maximum amount of charging in each season still occurs in the 10 p.m.–6 a.m. time interval, the distribution of charge energy in other time slices changes. The results suggest a very low utilization of late afternoon and evening hours during every season, especially the 5 p.m.–10 p.m. time interval, to minimize the total system costs. Utilization is zero during this time slice in summer and close to zero in the fall and spring. This corresponds well to the current understanding that smart vehicle chargers should avoid charging during the peak net load periods and is particularly important during the summer season when the yearly system peak demand occurs.

The delayed charging profile most closely follows the Dynamic charging profile, while the opportunity charging profile is very different from that of the Dynamic scenario. This is most notable for the 5 p.m.–10 p.m. timeframe where opportunity charging is highest and both Dynamic and delayed are lowest. The similarities between Dynamic and delayed charging serve to show that the Dynamic charging scenario is possible while still respecting driver constraints if delayed and smart charging are encouraged. Utility rate schedules and demand response incentives, among other things, have the ability to impact charging profiles. Before changes to the rates and incentives are made it is important to understand the impact on other system properties. As will be shown in the following sections, changing the charging pattern can improve certain properties while negatively impacting others (e.g., reducing system cost while increasing GHG emissions).

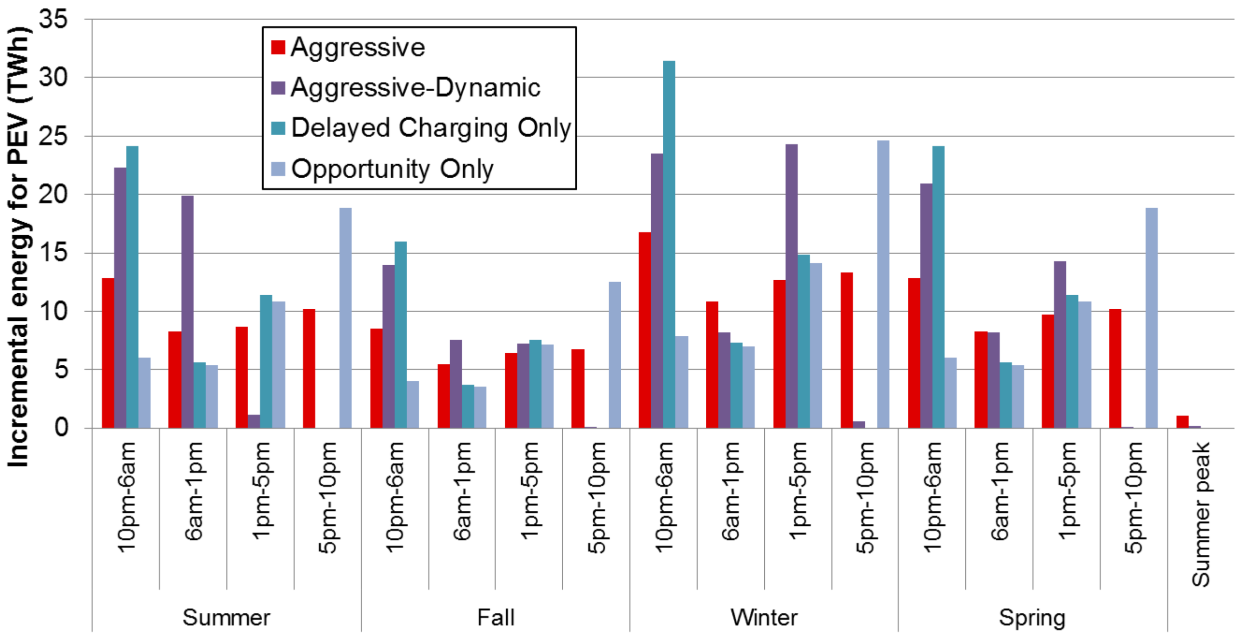


Figure 39. Additional energy demand imposed by PEVs in 2035 for unique charging scenarios

3.4.2 Generation Mixture and Costs

This section discusses the impacts of integrating PEVs on the electric sector with respect to generation and costs. In general, the higher the PEV penetration, the higher the required capacity additions to the power sector to supply the incremental demand, as shown in Figure 37. It is to be noted that the overall increase in the total demand and the cumulative installed capacity are relatively modest (note, there are no PEVs in Baseline and Baseline-Low Carbon scenarios), and so the differences in the generation mix and the associated impact on economics and emissions are not significant when seen from the electric sector point of view. However, these results provide valuable information from the PEV integration assessment point of view.

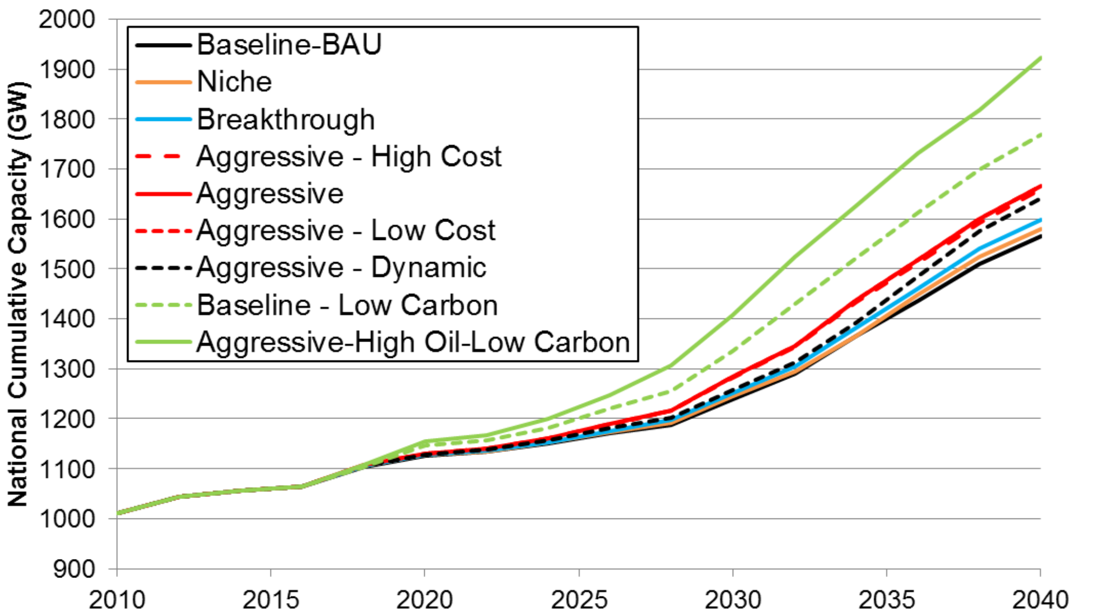


Figure 40. Yearly cumulative installed generation capacity

Before discussing the impacts of PEV penetration on generation mix, it is worthwhile to discuss the overall generation mix in the power sector under Baseline and Baseline-Low Carbon scenarios. Figure 41 presents cumulative generation capacity (in GW) by different technologies under the Baseline scenario (left) and the Baseline-Low Carbon scenario (right). Figure 42 presents yearly generation (in TWh) by different technologies under the Baseline scenario (left) and the Baseline-Low Carbon scenario (right). From Figure 41, it is observed that under the technology performance characteristics, cost, and policy assumptions in the Baseline scenario, we expect increasing penetration of renewable resources in the energy system portfolio. As observed in Figure 42, most of the incremental energy in the Baseline scenario beyond 2020 is projected to come from renewable resources (mainly wind and solar), while lower fuel prices and the need for flexibility drive some incremental generation from existing fossil plants. Over the same period, there are steady retirements in coal and oil capacities (as seen from Figure 41) primarily driven by plant lifetimes, policies (impact of Mercury and Air Toxic Standards), and underutilization of facilities. Therefore, in the 2030 time frame, while coal-based generation is still contributing to serve the system load in the Baseline scenario, any incremental system load is expected to be served by either (1) existing resources, including conventional fossil fuel-fired generation or/and (2) newly deployed generation, dominated by renewable resources. This situation is even more true under the Baseline-Low Carbon scenario, where the penetration of renewable generation increases more, as seen from Figure 41. For the Baseline scenario in 2035, renewable energy (wind, solar, hydropower, geothermal, and biopower) penetration is about 38% of the total national generation. Under the Baseline-Low Carbon scenario, it is about 49% in 2035. The addition of electric vehicles can increase the resulting renewable penetration to 39.4% for the Aggressive scenario and as high as 51.5% for the Aggressive-High Oil-Low Carbon scenario. These values include the additional generation required to charge the vehicles. Also seen from Figure 41 is the storage capacity under the Baseline scenario, which grows to about 24.6 GW in 2035 from 22.2 GW in 2010 (~2.4 GW growth). The growth of storage is much higher under the Baseline-Low Carbon scenario with higher variable renewable generation; storage is estimated to be about 39.4 GW in 2035 (~17.2 GW growth). This analysis does not address the opportunity for PEVs to provide storage services.

Coming back to the impact of PEV penetration on the incremental generation mix, Figure 43 examines the incremental capacity in 2035 and Figure 44 shows the incremental mixture of generation in 2035 under each scenario with respect to the Baseline scenario. From the generation plot, it is observed that under the Niche scenario the increase in energy demand is small; thus most of the incremental generation is met by operating fossil units (gas especially), in addition to wind generation. However, under the Breakthrough and Aggressive (including Aggressive-High Cost and Aggressive-Low Cost) scenarios, the increase in PEV charging results in an increase in renewable (wind and solar) capacity investments (Figure 43) and renewable generation (Figure 44), in addition to higher utilization of existing gas facilities. This trend is stronger in the Baseline-Low Carbon and Aggressive-High Oil-Low Carbon scenarios. The Baseline-Low Carbon scenario, without any PEV integration, already sees a higher capacity growth in wind and solar and lower utilization of existing coal. With the PEV penetration in the Aggressive-High-Oil-Low Carbon scenario, we see further increased penetration of wind and solar, including concentrating solar power (CSP), as observed from the far right bars in Figure 43 and Figure 44.

All of the PEV scenarios require additional investments in Gas-CT (natural gas combustion turbine) and some solar PV to meet the increased reserve margin (as a consequence of PEV charging) during peak loading times. However, comparing Aggressive and Aggressive-Dynamic scenarios, the model chooses to allocate PEV charging to those time intervals of the day that enable the system to experience lower incremental stress during peak loading hours and consequently reduce the need for additional Gas-CT and solar PV investments. The effect of these phenomena are also observed in Figure 40, which shows the yearly cumulative capacity, where it is observed that the Aggressive-Dynamic scenario requires lower nationwide additional capacity than the Aggressive scenario does, even though their annual electricity demand is the same. These discussions further bolster the observations made earlier that in the 2035 timeframe, most of the incremental power system demands are estimated to be served by renewable energy, with or without the introduction of PEVs.

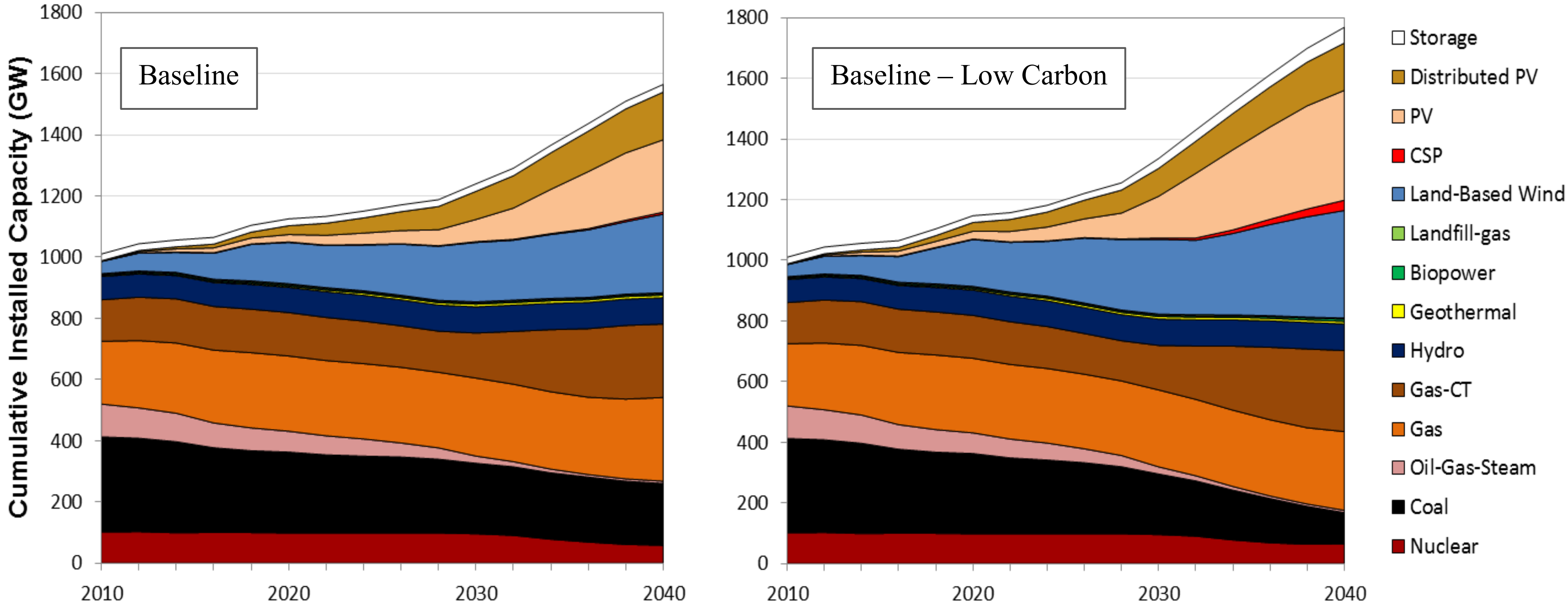


Figure 41. Cumulative capacity by generation technologies: Baseline and Baseline-Low Carbon

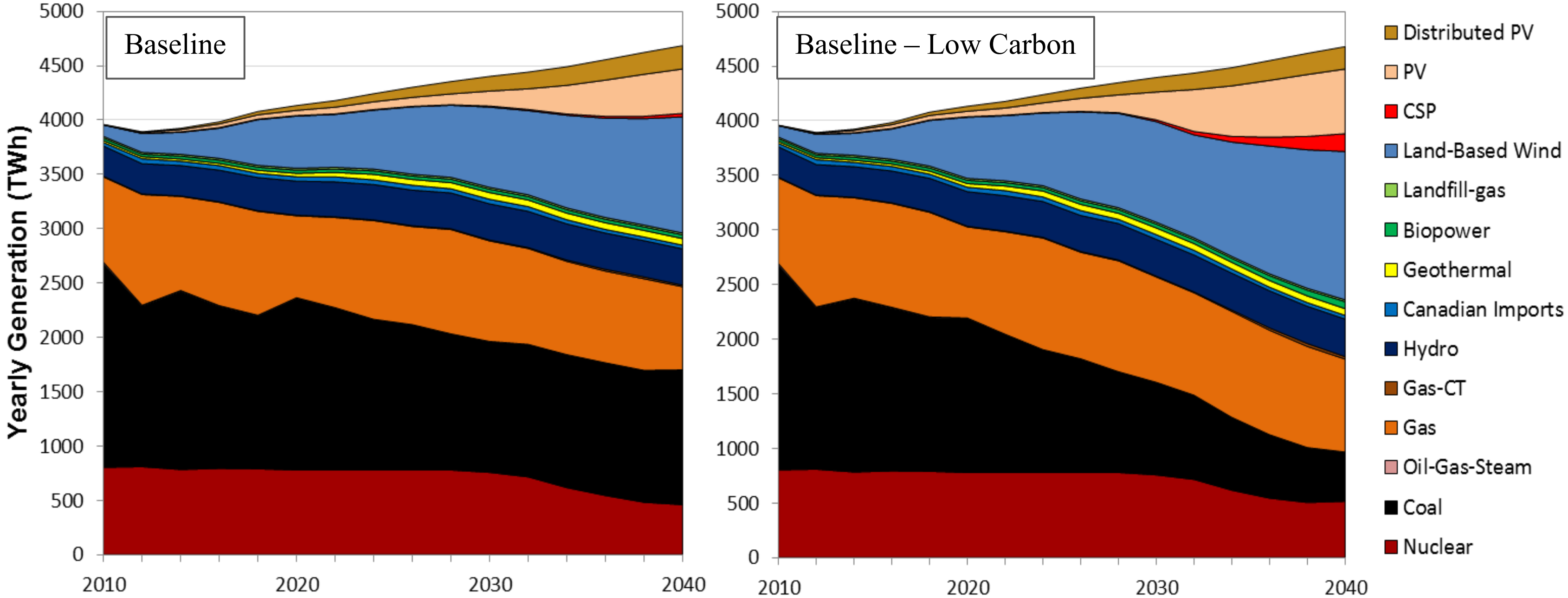


Figure 42. Yearly generation by generation technologies: Baseline and Baseline-Low Carbon

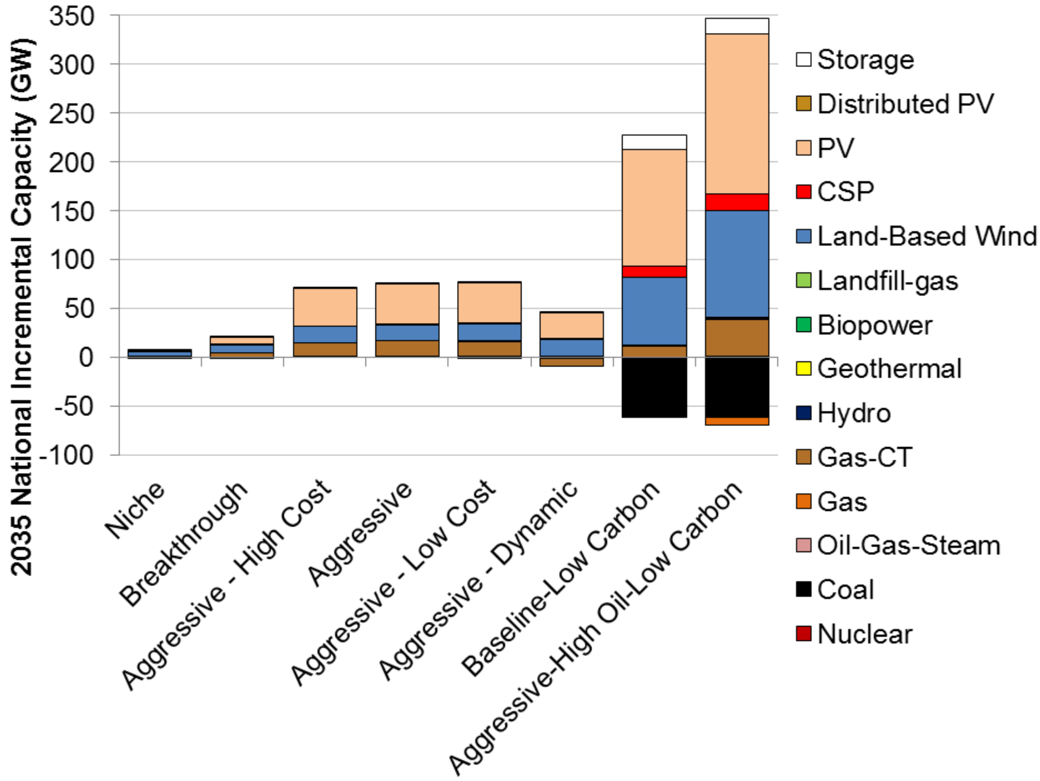


Figure 43. Year 2035: Incremental installed capacity compared to the Baseline scenario

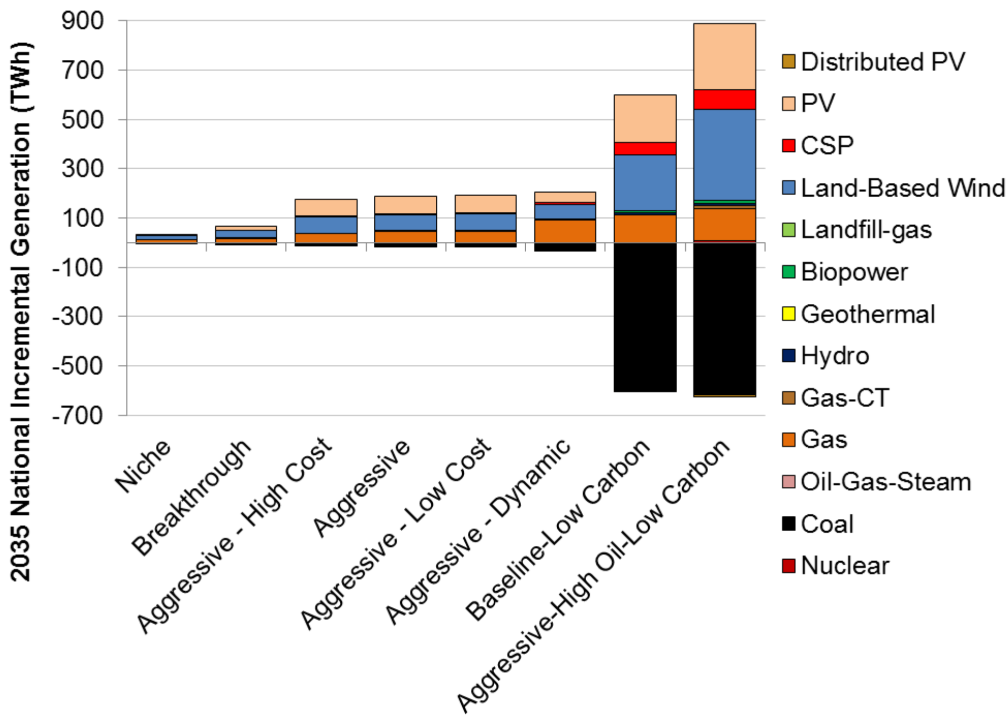


Figure 44. Year 2035: Incremental generation by type compared to the Baseline scenario

Figure 45 shows the incremental differences in system planning cost and Figure 46 shows the incremental national average electricity prices with respect to the Baseline scenario in the year 2035. The system planning cost is the net present worth in 2010$ of all the capital investment and operation costs from 2010 to 2040. The electricity prices shown are "retail prices" from a cost-of-service model that accounts for capital infrastructure, fuel, transmission, and distribution related costs. In line with earlier discussions, as PEV penetration increases the electricity system planning costs increase, especially in a low carbon grid scenario. Note that the Baseline-Low Carbon scenario does not have any PEV integration but does result in an increase in incremental system costs (4.2%) and average electricity price (1.2%) compared to the Baseline scenario. Compared to the Aggressive scenario, the Aggressive-Dynamic scenario sees a slightly lower incremental planning cost due to optimal charging of the PEVs. The trend in electricity prices is also similar to that of the system planning costs under all the scenarios. Though it should be noted that the increase in electricity prices in all the PEV scenarios compared to the Baseline scenario is very low, ranging from 0.2% to 1.2%, and is about 3.4% for the low carbon grid scenario (of which about ~1.2% happens under Baseline-Low Carbon scenario without any PEV integration). As discussed in recommendations for future work, a grid simulation approach more capable of capturing the dynamic capability of PEV charging may result in net reductions in electricity system costs.

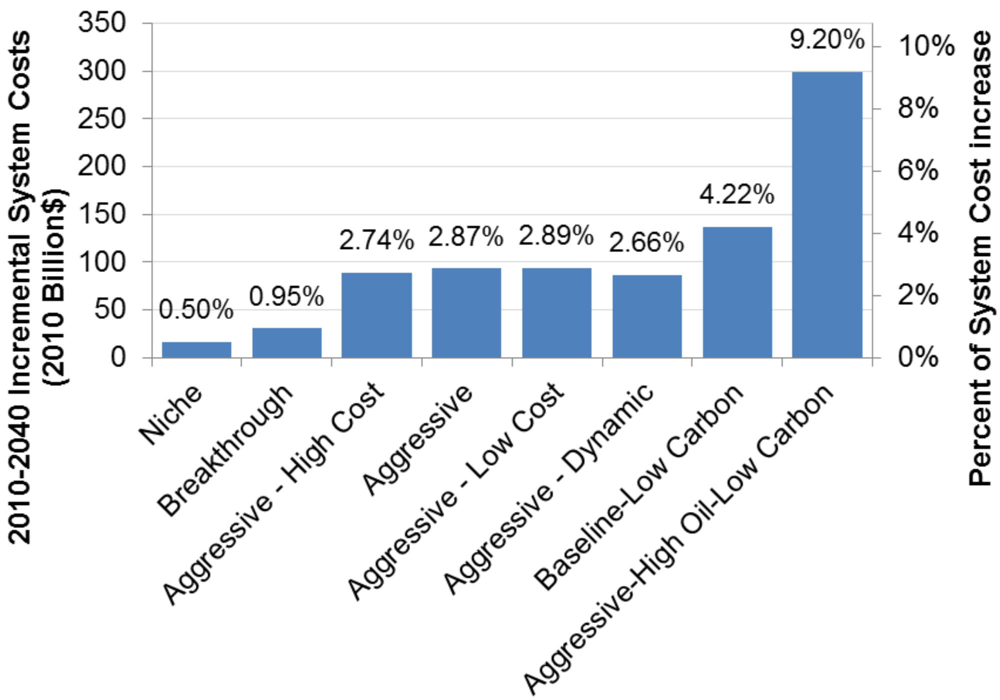


Figure 45. Incremental net present value (2010–2040, 3% discount rate) electric system expenditures compared to the Baseline scenario

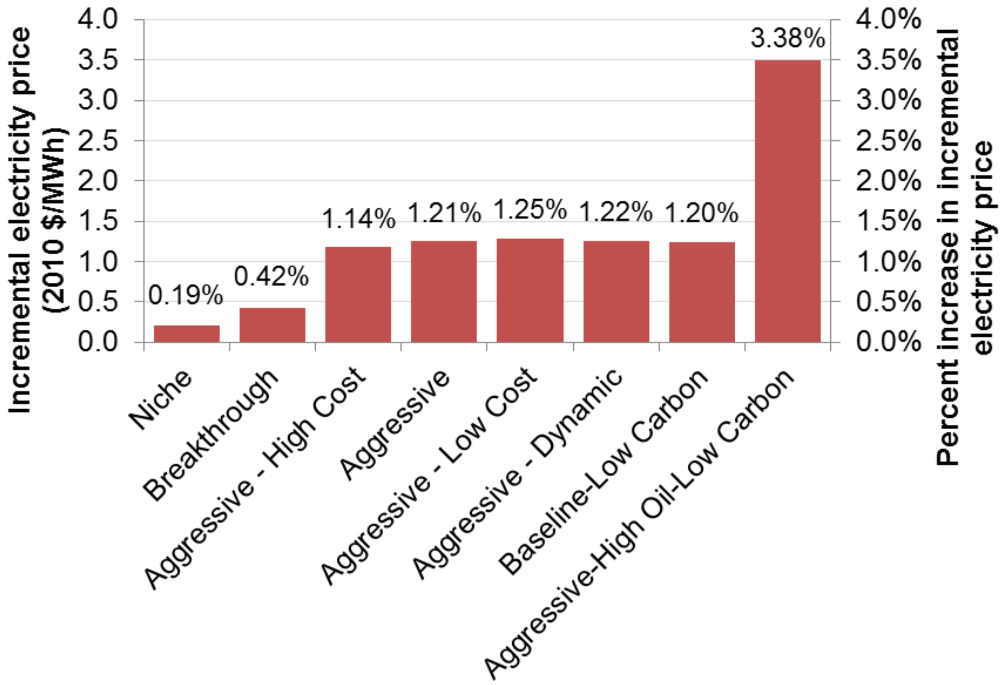


Figure 46. Year 2035: Incremental change in national average electricity prices compared to the Baseline scenario

3.4.3 Vehicle Charging Emissions from Grid

Figure 47 provides the 2035 national total CO_2 emissions from the power sector in billion metric tons and the national average CO_2 intensity in metric tons/MWh. The figure does not show the low carbon grid scenarios because the scale is very different. Under the Baseline scenario, the grid sees close to 1.52 billion metric tons of CO_2 emissions in 2035, while the Baseline-Low Carbon grid scenario has close to 0.97 billion metric tons of CO_2 emissions in 2035 (~36% decrease in 2035). Due to increased generation under PEV penetration scenarios, total grid CO_2 emissions increase under all the scenarios shown, though the increase is very mild (~0.4% under the Aggressive scenario compared to Baseline in 2035). The average CO_2 intensity, however, decreases with the increase in electricity demand (due to PEV charging) and therefore is lower under all PEV integration scenarios compared to the Baseline. This is because the additional generation in 2035 is primarily coming from renewable resources.

Under a low carbon grid scenario a similar trend of decreasing average system CO_2 intensity with increasing PEV penetration is observed. Comparing Aggressive and Aggressive-Dynamic scenarios, we observe that though the PEV penetration is same under both the scenarios, both the total CO_2 emissions and the average intensity slightly increase under the Aggressive-Dynamic scenario due to increased utilization of existing low-cost fossil plants as a consequence of optimal charging. However, an increase in emissions need not always occur. The change in emissions depends on the grid mixture and the structure that encourages vehicle behavior. The Dynamic scenario focuses on achieving the lowest cost, which as shown here can oppose a reduction in emissions. Changing the utility charging rate structures or other incentives to encourage a co-optimization of both low system cost and low emissions can result in a combination that falls between the Aggressive scenario and the Aggressive-Dynamic scenario.

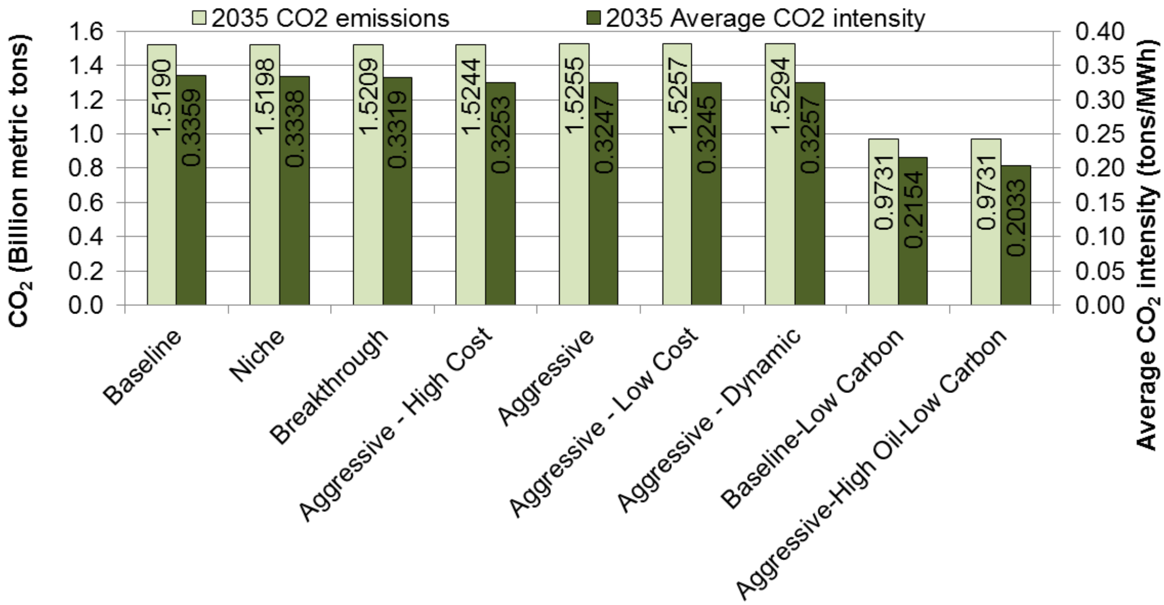


Figure 47. Year 2035 CO_2 emissions (left axis) and average CO_2 intensity (right axis)

In addition to changing for each scenario, carbon dioxide emission intensities change by region based on the grid mixture. Figure 48 shows variations in average carbon intensities across the country. The highest emissions are in the East North Central census division, and the lowest emissions are in the Pacific census division.

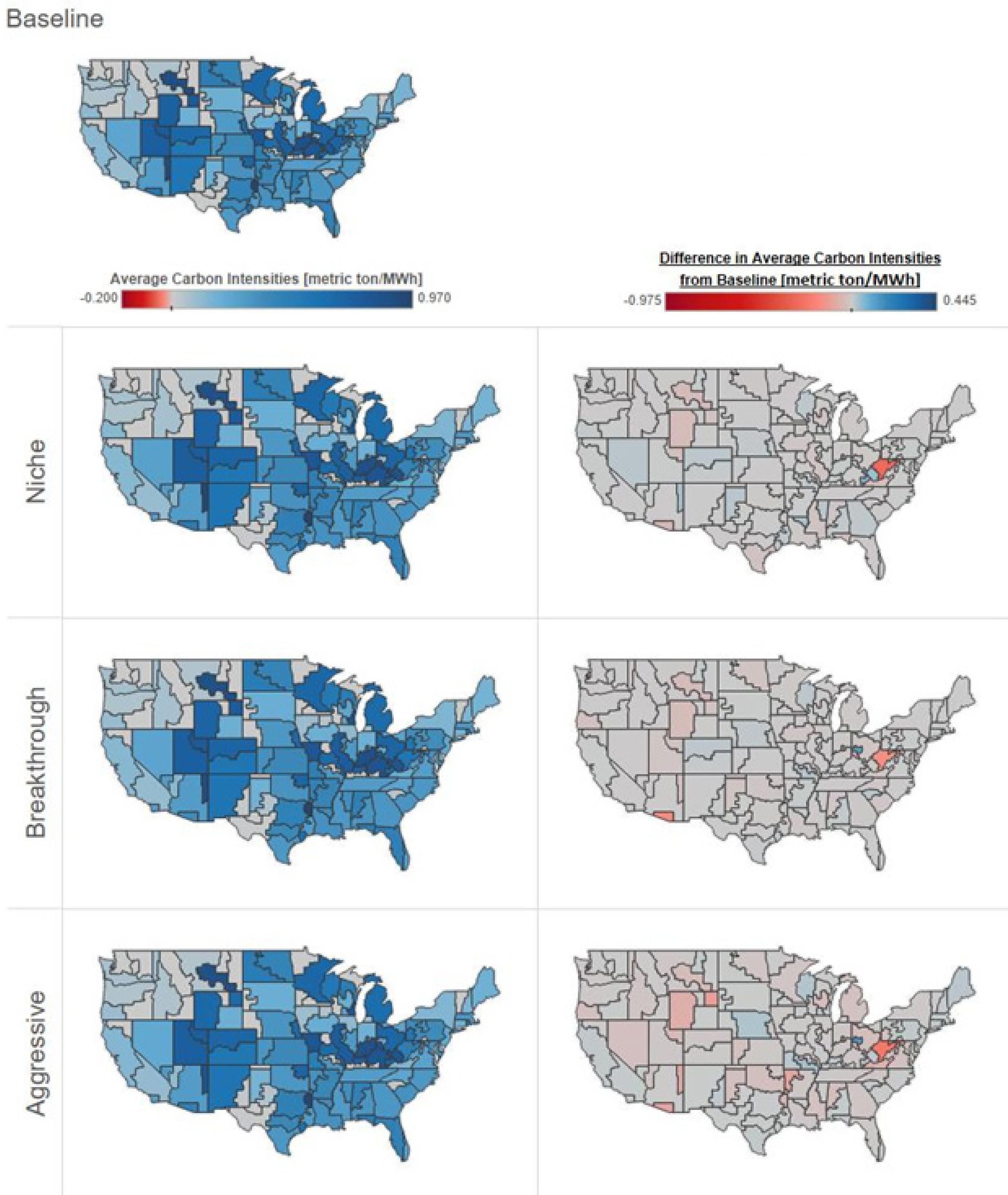


Figure 48. Average electricity grid carbon intensities and differences by balancing areas

3.4.4 Criteria Pollutant Emissions Impacts

This report identifies and quantifies many of the costs and benefits associated with the implementation of electric vehicles. Criteria pollutant emissions by upstream fuel supply, vehicles, or electric power generation represent a social cost that can result in damage of property and premature mortality. This report does not estimate the social cost of criteria pollutants. Several other studies have explored assessing the associated social cost of criteria pollutant emissions (Weis et al. 2015; Michalek et al. 2011; Holland et al. 2015). Those studies show that the environmental cost of PHEVs and BEVs is dependent on the fuel source for the electricity from which they charge. Weis et al. (2015) demonstrated that on the current PJM grid, GHG and criteria pollutant emissions could be greater than that of hybrid electric and even conventional vehicles; however, for the future 2018 PJM grid with coal retirements vehicles show a reduction for most of the emissions types. Michalek et al. (2011) demonstrated a similar finding for the entire United States, while Holland et al. (2015) showed that the current environmental benefit in the United States varies by state and can be positive or negative.

While those studies explore the emission damage costs, they also look at only current and near-term grid configurations. The available sources for emissions damage estimates do not consider pollutant concentrations out to 2035 and are not representative of the 2035 grid and vehicle mix developed for the current study. Without running an air quality simulation that is more representative of the assumptions in this study, the accuracy of the resulting marginal damages cannot be determined. To understand the relative order of emissions for long-term grid expansion and policy rollout we can compare the current study to the 2015 EPRI-NRDC study. That study explored the source emission and air quality impacts of vehicle electrification out to 2030 for two scenarios. The first scenario involved a minimal implementation of electric vehicles and the second incorporated eVMT for 17% of light-duty vehicles, 8% of heavy-duty vehicles, and a variety of electrified non-road vehicles.

In terms of pollutant impact, vehicle electrification will reduce total vehicle emissions and, depending on when and where electric vehicles charge, can have a positive impact or negative impact on the electric sector emissions. For example, a PEV that charges in the afternoon in a state with high solar penetration could result in a very low emissions rate while a PEV that charges in a region where electricity is provided predominantly by coal and gas will have a higher emissions rate.

In the 2015 EPRI-NRDC study, electrification was shown to reduce vehicle pollutant emissions for the United States between 4% and 16% for a variety of pollutants including volatile organic compounds (VOCs), carbon monoxide (CO), oxides of nitrogen (NOx), sulfur dioxide (SO_2), ammonia (NH_3), and particulate matter (10 µm and 2.5µm). In addition to reducing emissions from the vehicles there is a reduction in the upstream fuel supply emissions including from refining, refueling, and marine. Lastly, EPRI found that based on the mixture of generation in the United States and the assumed charging pattern, electrification caused a minimal impact on SO_2 and NOx emissions in the electricity sector.

Pollutant emissions from electricity generation are calculated for each of the scenarios explored in this study (Figure 49 and Figure 50). The scenarios that introduce a carbon cap see a more significant reduction in criteria pollutant emissions. This results from greater economic incentives to shift from carbon-based fuels to renewable sources, which will reduce criteria pollutants. Similar to the EPRI study, SO_2 and NOx emissions change slightly with the addition of electric vehicles. From 2016 to 2022, in the Aggressive scenario, there is a slight increase in emissions: 1.7% for SO_2 and 1.25% for NOx for the aggressive cases. Then there is a reduction from 2024 to 2040 with a maximum of 2.75% for SO_2 and 3% for NOx.

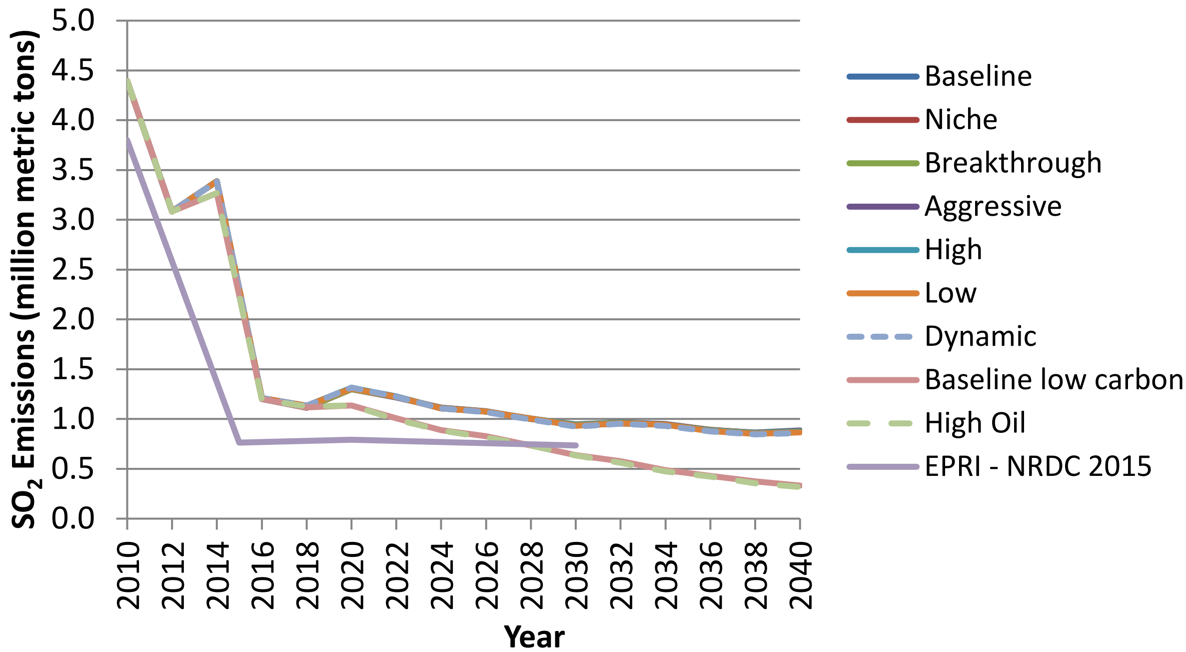


Figure 49. SO_2 emissions for the U.S. electric sector for each scenario of vehicle electrification

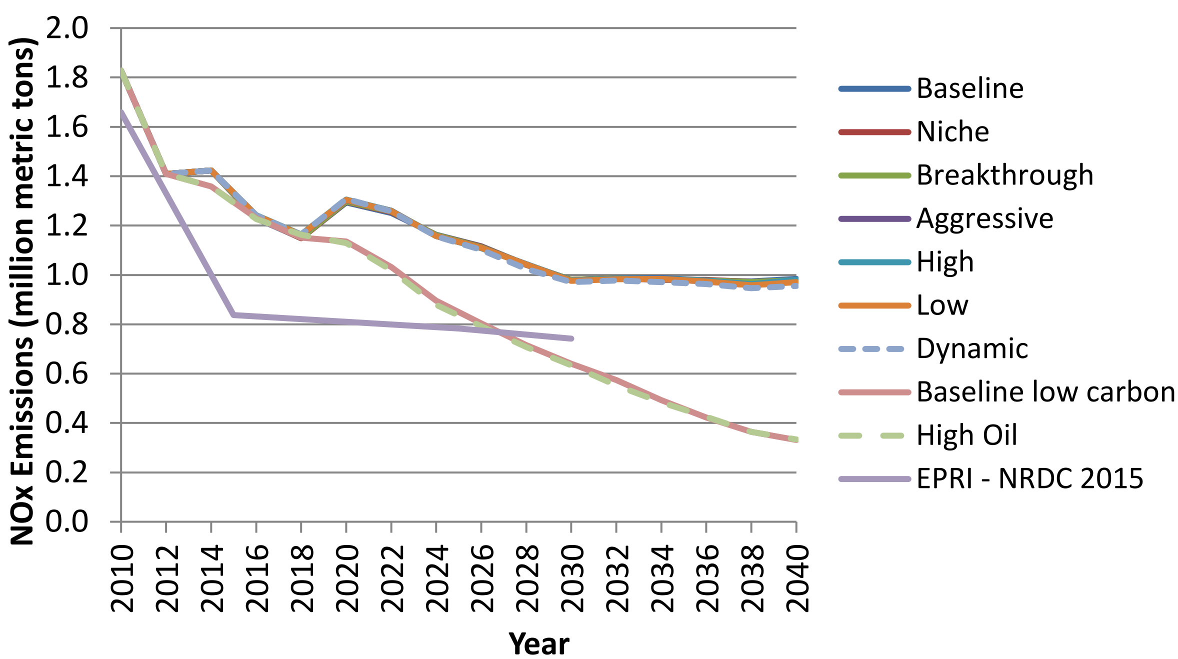


Figure 50. NOx emissions for the U.S. electric sector for each scenario of vehicle electrification

3.5 Macroeconomic Impacts

3.5.1 Interpreting Results and Limitations

There are limitations to this methodology. Material presented in section 2.5 reviews the I-O model used in this study, terminology, and assumptions. The I-O model is static and assumes fixed relationships between sectors and fixed household expenditure patterns. This assumes that prices and taxes do not change. In other words, businesses always use the same portions of inputs and households always consume the same basket of goods. The proportions are always the same regardless of the level of expenditures modeled. Wages are also constant and fixed. If $100,000 in expenditures supports one job, then the model will show $500,000 as supporting five jobs. All inputs, including labor, are assumed to be available. The model does not estimate whether inputs needed for production are available, nor does it estimate whether or not workers with necessary skills and education are available.

The version of the model used in this study is also based on IMPLAN 2012 economic data. Model results show impacts that could be supported based on the 2012 economy. It is not an estimate of how the economy could change in the future. Results, then, should be interpreted as a general estimate of impacts that would reasonably be supported within the framework of the current economy based on average prices (including wages) as well as average producer and consumer behavior.

3.5.2 Macroeconomic Results

Impacts of modeled scenarios are typically positive compared to baseline, even when considering both costs and benefits of their implementation (Table 17). There are two exceptions to this: (1) the High Cost scenario, which results in a net increase in earnings, GDP and gross output, and a decrease in jobs, and (2) the average annual output for the niche scenario. Table 17 shows the annual impacts averaged over the entire range of years from 2015 to 2040. Scenarios begin with a limited numbers of plug-in vehicles and grow each year. Similarly, the impacts grow each year, but the value represents the average of the entire range of 26 years.

Table 17. Average Annual Impacts for Each Scenario

Economic Metrics (2013 dollars)	Jobs (number of jobs/yr)	Income ($million/yr)	GDP ($million/yr)	Output ($million/yr)
Niche	111,000	3,855	5,571	(619)
Breakthrough	99,000	3,707	5,804	1,723
Aggressive	52,000	3,016	6,592	11,003
High Cost	(30,000)	176	2,528	11,994
Low Cost	198,000	5,104	9,913	11,201
High Oil	147,000	6,990	12,505	20,196
Low Oil	1,000	1,046	3,732	8,444

The totals shown in Table 17 represent a combination of increases and decreases stemming from direct, indirect and induced effects. Table 18 through Table 21 show a breakdown of each of these items for jobs, earnings, output and GDP, respectively.

Direct and indirect effects are largely negative across jobs, income, output, and GDP. These types of impacts are pushed up by increased domestic expenditures on vehicles, chargers, and electricity while pushed down by decreased expenditures on petroleum. The induced impacts are largely positive and more significant than negative direct and indirect impacts. Increases in disposable household income, driven by cost savings compared to baseline, increase the amount that households spend. This increased spending causes net total increases across all metrics for most scenarios.

The induced effect for job creation caused by the introduction of electric vehicles strongly outweighs the direct and indirect impacts of electrification except for the high cost and low oil scenarios. For these scenarios, the high cost of electric vehicles or the low cost of oil reduces the benefit of electrification resulting in a low average annual impact.

Table 18. Average Annual Job Impacts by Type for Each Scenario

Economic Metrics (number of jobs/yr)	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Niche	(37,000)	(50,000)	199,000	110,000
Breakthrough	(37,000)	(43,000)	180,000	99,000
Aggressive	(37,000)	(12,000)	102,000	52,000
High Cost	(10,000)	27,000	(46,000)	(30,000)
Low Cost	(57,000)	(38,000)	205,000	109,000
High Oil	(88,000)	(44,000)	279,000	147,000
Low Oil	(15,000)	8,000	9,000	1,000

Table 19. Average Annual Household Income Impacts by Type for Each Scenario

Economic Metrics ($million/yr, 2013)	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Niche	(2,293)	(3,511)	9,659	3,855
Breakthrough	(2,087)	(2,988)	8,781	3,707
Aggressive	(1,198)	(814)	5,028	3,016
High Cost	500	1,849	(2,173)	176
Low Cost	(2,351)	(2,589)	10,044	5,104
High Oil	(3,655)	(3,017)	13,662	6,990
Low Oil	15	568	463	1,046

Table 20. Average Annual Output Impacts by Type for Each Scenario

Economic Metrics ($million/yr, 2013)	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Niche	(15,542)	(14,521)	29,443	(619)
Breakthrough	(12,974)	(12,078)	26,775	1,723
Aggressive	(2,350)	(2,003)	15,357	11,003
High Cost	9,487	9,102	(6,595)	11,994
Low Cost	(10,081)	(9,369)	30,651	11,201
High Oil	(12,386)	(9,099)	41,681	20,196
Low Oil	3,900	3,105	1,439	8,444

Table 21. Average Annual GDP Impacts by Type for Each Scenario

Economic Metrics ($million/yr, 2013)	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Niche	(4,987)	(6,348)	16,906	5,571
Breakthrough	(4,213)	(5,346)	15,363	5,804
Aggressive	(973)	(1,198)	8,763	6,592
High Cost	2,739	3,633	(3,843)	2,528
Low Cost	(3,218)	(4,405)	17,537	9,913
High Oil	(6,541)	(4,820)	23,867	12,505
Low Oil	1,766	1,192	774	3,732

4 Results: National Economic Value of PEVs

The sections below review economic valuation results for each of the seven main scenarios: Niche, Breakthrough, Aggressive, High Cost, Low Cost, Low Oil, and High Oil. Changes in fuel supply, GHG emissions, and carbon intensities per mile are compared to the Baseline scenario in section 4.1. Summary results for private economic value and public or common economic value are reviewed in sections 4.2 and 4.3, respectively. Results for the sum of private and public economic value, referred to as total social economic value, are reviewed in section 4.4. Regional variations in the total social economic value results are reviewed in section 4.5, and results for jobs and GDP are reviewed in section 4.6. Though they are not modeled in a comprehensive manner, section 4.7 discussed anticipated trends in criteria pollutant emissions resulting from PEV market growth. Finally, section 4.8 reviews sensitivities around key input variables.

As discussed in previous sections, the private economic value results account for two major trends: (1) fuel saving measured as total fuel costs in 2035 with PEV market shares increases compared to gasoline fuel costs in the Baseline scenario with no PEV adoption, and (2) the rolling sum of the additional capital cost of EVSE infrastructure and the incremental cost to consumers of PEVs compared to CV and HEVs, divided by nominal lifetimes of 11.68 years. The results therefore show a snapshot of costs and benefits in 2035: there is no "spillover" from earlier years or discounting of future years.

Folding the prior or later year impacts into 2035 would have been misleading because PEV market shares are not static; PEV adoption rapidly changes over time in all scenarios. In other words, the net cost of PEVs to consumers in 2035 includes approximately one-twelfth of the incremental cost of PEVs over (or below, in the case of short-range BEVs) CVs or HEVs for all PEVs purchased over the previous 11.68 years. At the same time, the fuel savings from previous PEV sales are also taken into account. This approach allows for a consistent accounting over time of the incremental cost of PEVs and resulting fuel savings (see section 2.3 for discussion). Public or common economic values are estimated as GHG emission reductions multiplied by a social cost of carbon and gasoline consumption reductions multiplied by a petroleum import premium.

This approach does not account for any additional transition costs incurred or policy incentives required to achieve strong market growth between 2016 and 2035. It does, however, account for time constraints on the rate at which improvements in LDV technologies occur over time, new vehicle sales and change the performance of the overall LDV fleet, and rates at which regional electricity grids change over time. These are primarily reflected by temporal trends in new vehicle costs and performance attributes (e.g., fuel economy) and temporal and regional trends in vehicle operation, gasoline prices, and the price and carbon intensity of electricity. Because the incremental cost of PEVs is relatively stable by around 2030–2035, most of the net PEV costs incurred by 2035 reflect the long-term cost reduction potential reflected in the trends reported by Moawad et al. (2016), which are used as external inputs to the NEVA framework (see Figure ES-1, section ES.2.2, and section 2.2.1).

4.1 Scenario Supply and Demand Results Overview

This section reviews the scenario demand results based upon PEV market growth, electricity supply and gasoline displacement, and resulting GHG emission reductions. A brief summary of major inputs and outputs associated with the national economic value calculations for each scenario is provided in Table 22. The stock of BEVs, PHEVs, and total PEVs is shown for 2035, broken out as results for CV, HEV, PHEV, and BEV. Given assumptions about VMT limitations for BEVs, climate impacts on e-miles, and regional variations in market shares, the average VMT per day (including gasoline and e-miles for PHEVs) decreases slightly for the more aggressive scenarios. The resulting gallons of gasoline displaced, additional kWh of electricity used, and net reductions in GHG emissions are also shown. These values provide some context for the relative scale of results across each scenario by PEV type.

Table 22. Summary of Key Demand Inputs, Fuel Results, and GHG Emission Reductions

Scenario	2035 LDV Fleet (10^6 vehicles)				Gasoline Use (10^6 gal/yr)		Electricity Use (10^6 kWh/yr)	GHG Emissions (10^6 tonne CO_2e/yr)	
	CV	HEV	PHEV	BEV	All LDV	% Red.	All LDV	All LDV	% Red.
Niche	136.2	120.8	9.2	3.0	66,506	23%	16,942	841	22%
Breakthrough	130.0	114.8	18.5	5.9	64,665	25%	33,726	825	24%
Aggressive	105.1	90.9	55.4	17.7	57,471	34%	99,337	761	30%
Low Cost	111.9	88.2	54.8	14.2	58,750	32%	90,178	774	28%
High Cost	99.1	90.6	53.9	25.6	55,949	35%	115,292	749	31%
Low Oil	114.3	89.2	50.3	15.3	59,824	31%	86,514	785	27%
High Oil	83.8	93.4	67.6	24.4	51,948	40%	133,512	694	36%
Baseline Scenarios	2035 LDV Fleet (10^6 vehicles)				Gasoline Use (10^6 gal/yr)		Electricity Use (10^6 kWh/yr)	GHG Emissions (10^6 tonne CO_2e/yr)	
	CV	HEV	PHEV	BEV	All LDV		All LDV	All LDV	
Baseline	259	10.0	0	0	86,735		0	1,080	
Base: Low Oil	259	10.0	0	0	86,684		0	1,080	
Base: High Oil	259	10.0	0	0	86,713		0	1,080	

In addition to vehicle specific results by type, the introduction of electric vehicles also has an impact on the electric system and its operation. Table 23 presents summary results concerning how the price of electricity, electricity grid carbon intensity and vehicle fleet carbon intensity are impacted by different electric vehicle implementation scenarios. Changes in electricity price are relatively minor (i.e., less than approximately 2%) and the carbon intensities of electricity produced (metric tons CO_2e per MWh) and the total carbon intensity for the entire LDV fleet (grams CO_2e per mile) are reduced by varying degrees for each scenario. The fleet scenarios are calculated for 2035 and include both the gasoline and electricity contributions to emissions for all vehicles. The largest reductions in the carbon intensity of LDV miles are achieved in the Aggressive and High Cost scenarios, at 90 and 94 g CO_2e/mile, respectively. All of the scenarios represent a range of reductions from 67 to 94 g CO_2e/mile (23%–32% reduction), compared to the respective baseline scenarios. Note that the high price of oil influences the evolving grid mix in the High Oil Baseline and Aggressive scenarios.

Table 23. Electricity and Carbon Intensity Results for Main Scenarios in 2035

Scenario	Average U.S. Electricity Price Increase (percent from BAU)	Electric System Carbon Intensity (metric tons CO_2e/MWh)	Total Vehicle Carbon Intensity (grams CO_2e/mile)[a]
Baseline	0.0%	0.336	294
Niche	0.2%	0.334	227
Breakthrough	0.4%	0.332	222
Aggressive	1.2%	0.325	204
High Cost	1.1%	0.325	200
Low Cost	1.2%	0.325	208
Baseline High Oil	1.2%	0.215	294
Aggressive High Oil	3.4%	0.203	210

[a] Includes emissions from gasoline and electricity associated with plug-in electric, conventional, and hybrid-electric vehicles.

4.2 Private Economic Value

Private economic valuation involves costs and benefits directly associated with the vehicle owner or household. Private benefits primarily include fuel savings resulting from switching from gasoline to electricity. Private costs include any additional costs for purchasing a PEV compared to a CV or HEV, the cost of electricity used to charge PEVs, and the cost of any home charging equipment (i.e., Level 1 or Level 2 EVSE). The difference in private costs between the Baseline scenario and the Niche, Breakthrough, Aggressive, and Low Cost scenarios by 2035 is shown in Figure 51. Costs are shown as stacked negative bars to the left of zero, and the fuel savings benefit is shown as positive bars to the right of zero. Results are shown in billions of dollars per year in the top panel, and economic values per vehicle are shown as dollars per PEV per year in the bottom panel. For both sets of values the net balance of costs and benefits is denoted by a black vertical line; when the black vertical line is positive total benefits are greater than total costs. The dollar values shown in each row, following the name of each scenario, indicate the net private economic values for each scenario. These are positive for each of the four scenarios, with gasoline savings more than sufficient to offset the incremental or net PEV costs, electricity cost, and home charger costs.

Total net positive social benefits increase in proportion to the number of PEVs deployed in the Niche, Breakthrough, and Aggressive scenarios, and then increase further in response to lower net PEV costs in the Low Cost scenario. A close examination reveals that the slight decline in per-vehicle benefits moving from the Niche to Breakthrough to Aggressive scenarios is due to a slight decline in the fuel savings benefit. This suggests that PEVs have mostly saturated households that achieve strong economic advantage by switching from CVs or HEVs to PEVs in the Niche scenario, and that these economic advantages only decline slightly, on average, as an increasing number of households adopt PEVs in the Breakthrough and Aggressive scenarios (see section 2.2). In other words, due to household travel requirements, PEVs on average tend to displace less gasoline moving from the Niche to the Breakthrough and Aggressive scenarios. However, this effect is very small, suggesting that all households where PEVs are a good fit in terms of travel requirements have received PEVs in the Niche scenario, and expanding PEV markets further into additional households results in only slightly less gasoline displacement per PEV while still maintaining net positive benefits.

The increased benefits in the Low Cost scenario are due to a combination of effects including more PEVs being deployed in general, different types of PEVs being deployed, and more gasoline being displaced in absolute terms. The lower panel with per-PEV benefits shows that fuel savings per PEV are similar to those in the other scenarios, while lower net vehicle cost per PEV is the major contributor to the shift toward more positive benefits on a per PEV basis. As discussed in section 2.2, vehicle prices are lower across all LDV types in the Low Cost scenario. The reduction in net vehicle costs therefore indicates that the net cost of the PEVs deployed relative to the CVs and HEVs they displace is smaller in the Low Cost scenario compared to the Aggressive Scenario. Additional details on the differences between the Aggressive and Low Cost scenario results are discussed below.

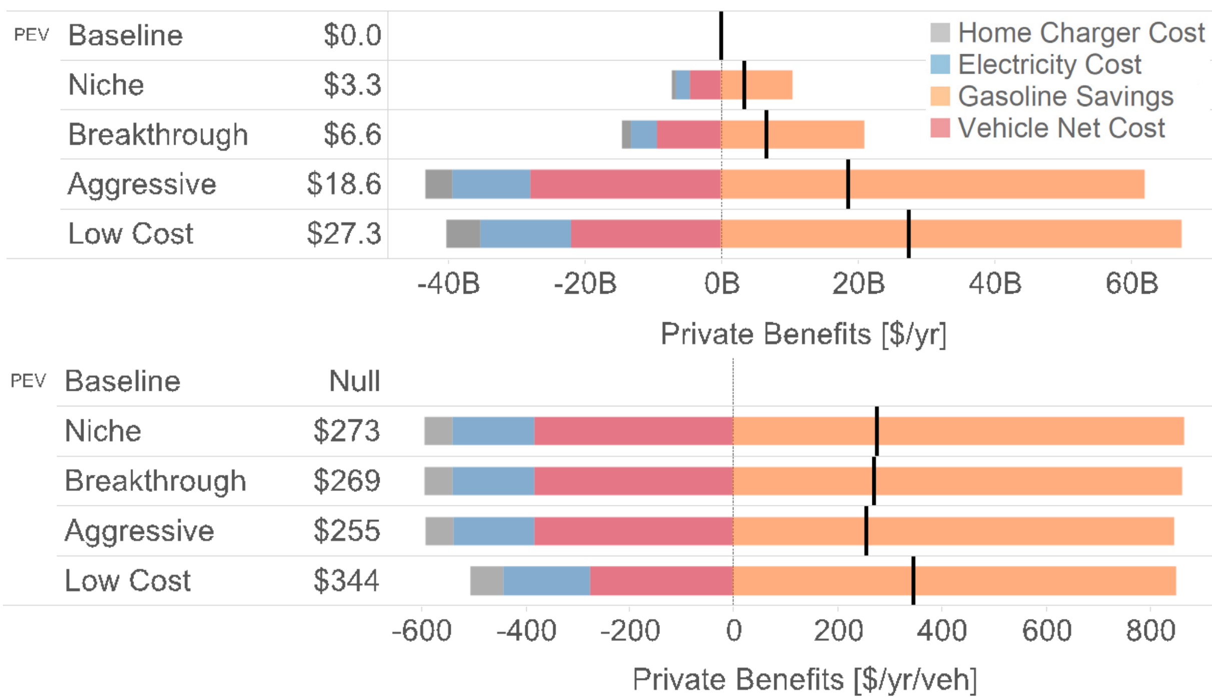


Figure 51. Private benefits for Niche, Breakthrough, Aggressive, and Low Cost scenarios in 2035

The private economic value results for three additional variations on the Aggressive scenario are shown in Figure 52 for comparison with the Aggressive and Low Cost scenarios. The High Cost scenario involves less optimistic assumptions about future LDV cost reductions (though identical fuel economy improvement as in the Aggressive scenario) and somewhat greater EVSE costs. Gasoline price trends are higher than the Aggressive scenario in the High Oil scenario and lower in the Low Oil scenario. As in the previous figures, net economic values are indicated visually by the vertical black bars and numerically by the values shown next to each scenario name.

Comparing these results to the net private benefits of the Aggressive scenario emphasizes the importance of gasoline prices for the future potential economic value of PEVs: net benefits increase approximately four-fold in the High Oil scenario (increasing from $18.6 billion to $72.7 billion per year) and fall to close to zero in the Low Oil scenario ($0.2 billion per year). As indicated by relative changes in the stacked bars, these shifts are primarily due to changes in gasoline savings. However, there are also shifts in the total number of PEVs sold. The cost per vehicle and fuel economy of all LDVs deployed is identical in the Aggressive, High Oil, and Low Oil scenarios, but higher or lower future gasoline prices does change the total number and type of PEVs sold (see Figure 32). The High Cost scenario has reduced gasoline savings due to lower total PEV sales, as well as sales of different types of PEVs, but higher incremental PEV costs still result in larger vehicle net costs compared to the Aggressive Scenario, resulting in a net private benefit that is approximately half that achieved in the Aggressive scenario ($10 billion per year compared to $18.6 billion per year). The per PEV per year results show that this reduction in total benefits is due to higher incremental vehicle costs rather than changes in gasoline consumption per vehicle.

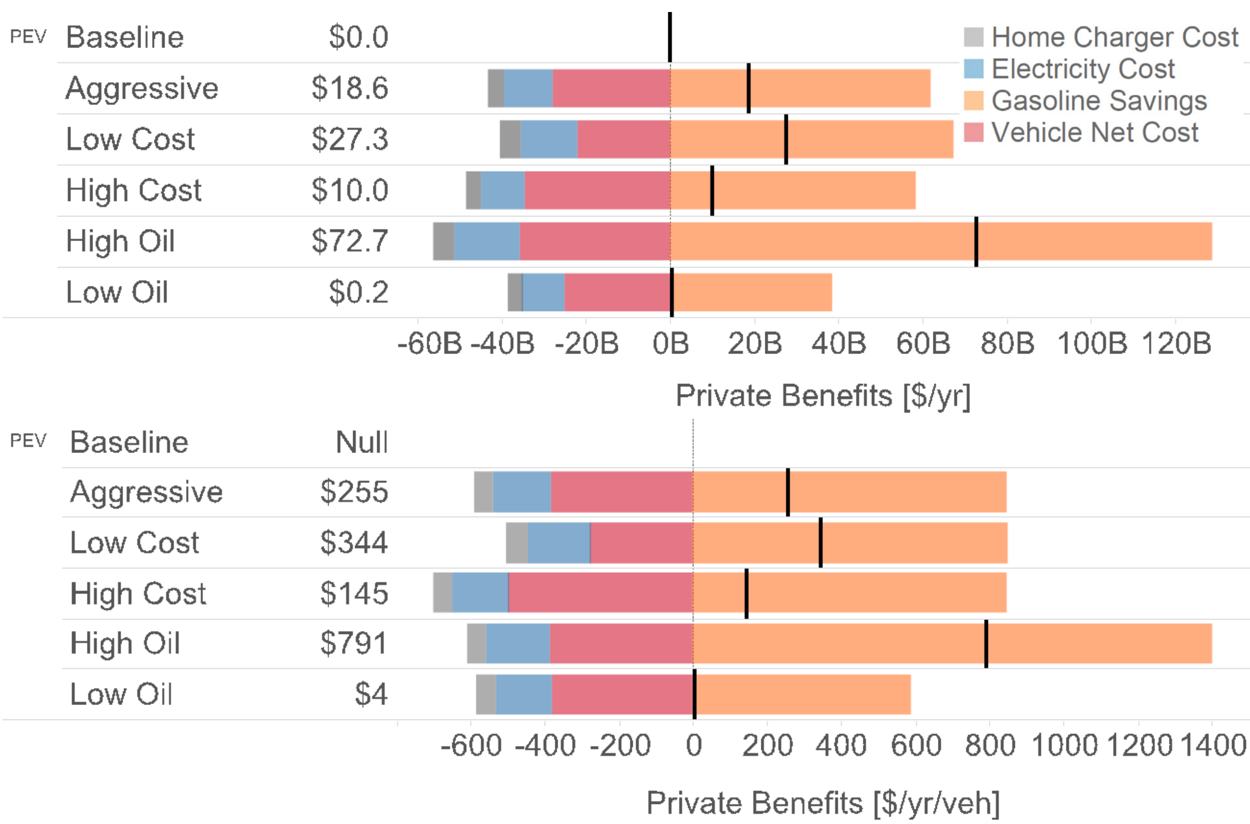


Figure 52. Private benefits for the Aggressive scenario compared to the main scenarios in 2035

Another perspective on private economic value is by PEV type. While the allocation of PEVs by type is somewhat formalized in the present study, as discussion in section 2.3, the underlying cost structure and performance of PEVs by type provides insights into the economic value when allocated across U.S. households. The valuation results based upon this economic allocation are shown by PEV type for the Aggressive and Low Cost scenarios in Figure 53. Net private benefits range from $213 to $314 per PHEV per year in the Aggressive scenario, and $307 to $395 per

PHEV per year in the Low Cost scenario. The patterns in both scenarios are similar, with the PHEV15 offering relatively high net benefits, and net benefits for the other three PHEVs increasing with increasing all-electric range. In contrast, the BEV70 has the greatest net benefit across all PEV types, and net benefits decrease with increasing BEV all-electric range. Net benefits are negative for BEV210 and BEV280 vehicles in the Aggressive scenario, while BEV210 vehicles shift to positive net benefits in the Low Cost scenario. These trends are revisited below when public benefits are added to private benefits in the total social valuation results.

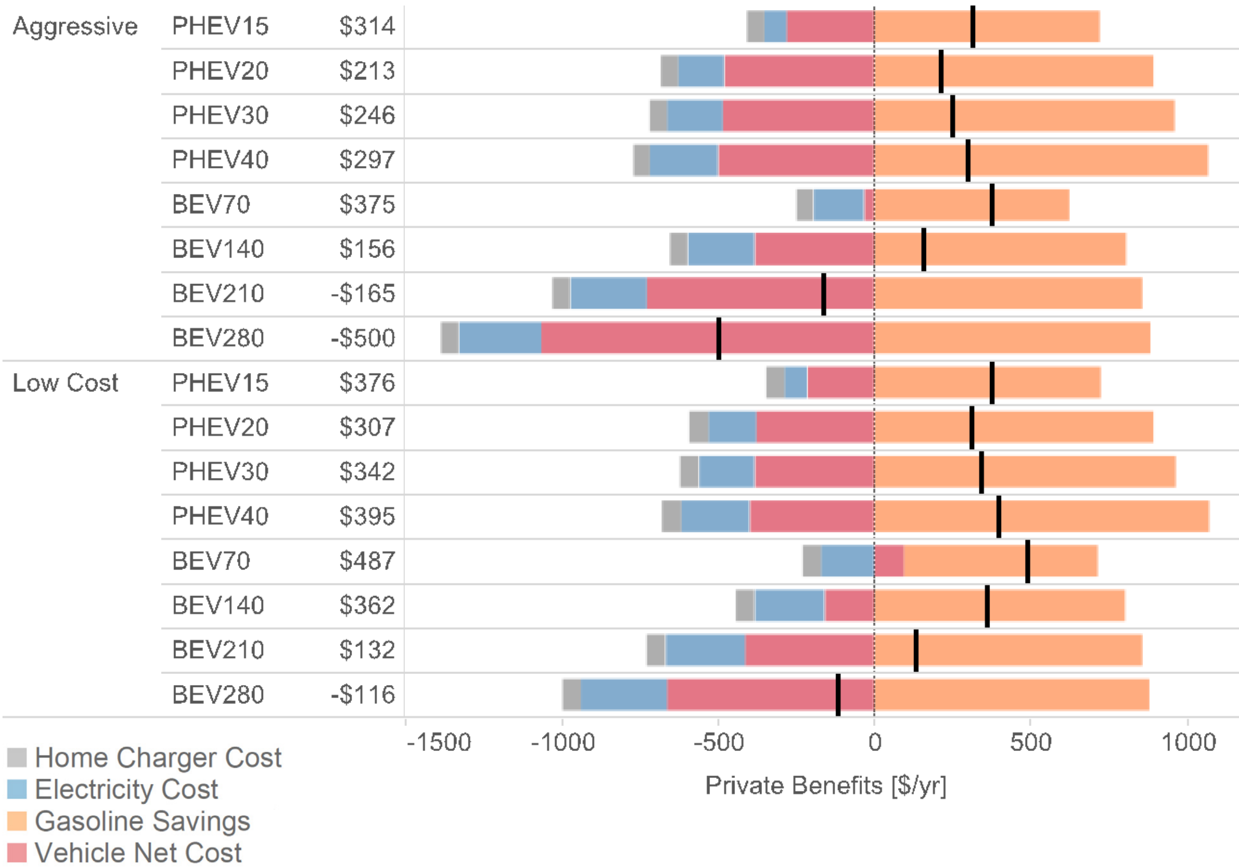


Figure 53. Private economic valuation by PEV type for Aggressive and Low Cost scenarios

4.3 Public Economic Value

Public benefits include the social value of reductions in GHG emissions and petroleum utilization. These public benefits are considered externalities, as they are traditionally not included in market prices but represent positive benefits to society. In this section these social or externality benefits are discussed alongside the cost of workplace and public charging infrastructure, even though these costs would be internal to markets and would be paid by some mix of public and private entities, such as workplace employers, retail establishments, or utilities. A characteristic of these assets is that they would tend to be used by the general PEV fleet and are therefore common or public in their utilization.

Total public economic values are shown for the Aggressive and Low Cost scenarios in Figure 54 with net positive public benefits (black vertical lines) for each scenario. The top panel indicates absolute values in billions of dollars per year and the bottom panel indicates values per PEV per year. GHG benefits are roughly three times greater than petroleum reduction benefits, and the costs of public charging infrastructure are roughly half the sum of GHG and petroleum reduction benefits. The Low Cost scenario involves a greater number of PEVs as well as a shift toward a greater fraction of BEVs compared to the Aggressive scenario, resulting in larger costs for public charging infrastructure in absolute terms (due to the larger PEV fleet and more BEVs) and per PEV (due to more BEVs). However, the per-PEV benefits of GHG and petroleum reductions are similar between the two scenarios, and the net benefit per PEV in the Low Cost scenario is about 18% lower than in the Aggressive scenario due to higher public charging infrastructure costs.

Results for three additional variations on the Aggressive scenario are also indicated. With comparison to the Aggressive scenario, the High Cost scenario involves decreased per-unit public EVSE costs and similar per-unit GHG and petroleum reduction benefits. The smaller total PEV fleet translates to reductions in absolute costs and benefits, resulting in net social benefits comparable to those in the Aggressive scenario. The variations in total public EVSE costs in the High Oil and Low Oil scenarios are due to higher and lower levels of PEV market share, respectively. The somewhat higher GHG reduction benefits per PEV in the High Oil case are due to the lower carbon intensity of the electricity grid in that scenario compared to the Baseline scenario. These relative costs and benefits are placed into perspective in the next section by comparing all private and public valuation results.

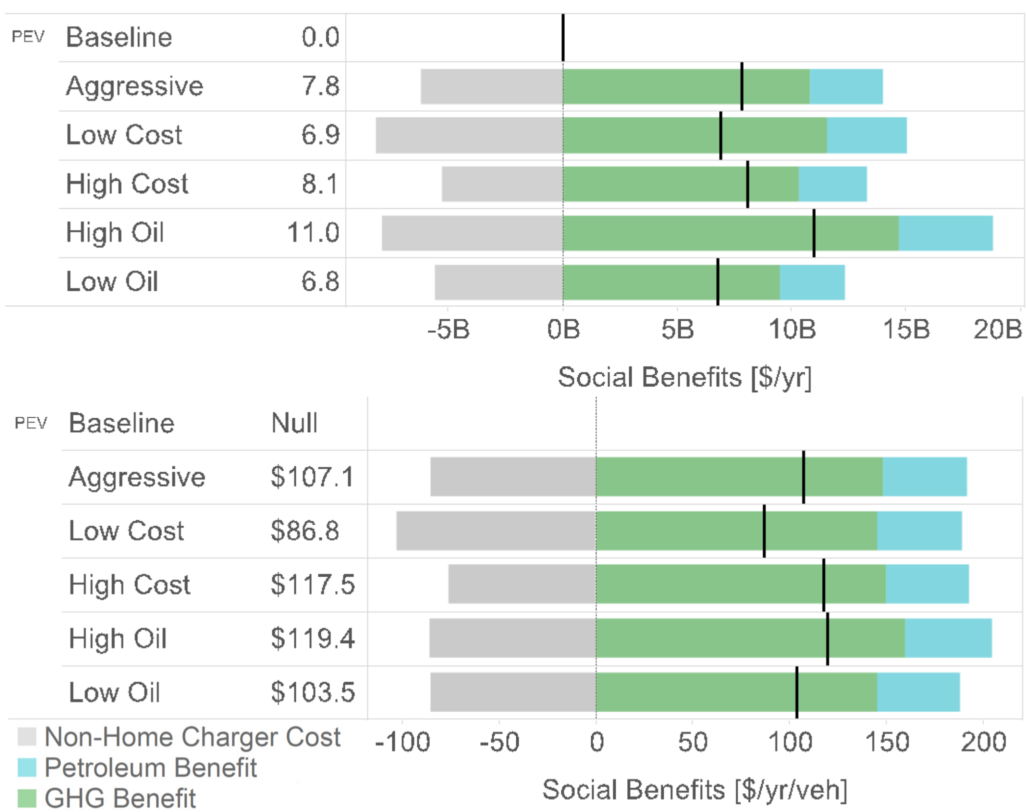


Figure 54. Breakdown of public costs and benefits in 2035

4.4 Total Social Economic Value

Combining private and public costs provides a measure of the total social economic value associated with increased PEV adoption. Figure 55 shows these total social benefits and costs for each of the seven main scenarios over the Baseline scenario, which is shown as zero. Absolute economic values are indicated in the top panel in billions of dollars per year, and economic value per PEV is shown in the bottom panel in units of dollars per PEV per year. Positive benefits are driven largely by gasoline savings (orange bars), along with benefits from GHG reductions (green bars) and petroleum reductions (light blue bars). These benefits are counterbalanced by additional electricity costs (blue bars), incremental vehicle costs (red bars), and private and public charging infrastructure costs (dark and light grey bars, respectively). Net benefits (indicated by vertical black bars, and numerically next to each scenario name) are positive in each scenario.

The addition of social or public valuation results to the private valuation results does not significantly change the relative costs, benefits, and net benefits across scenarios compared to the private costs reviewed in section 4.2. Niche and Breakthrough scenarios scale up to the Aggressive scenario according to the number of PEVs deployed. Both total and per-PEV results for the Aggressive scenario fall between the Low Cost and High Cost scenario results, and the High Oil scenario still provides the largest net positive benefit of all scenarios. With the addition of social valuations, the Low Oil scenario is well above zero, at $7 billion per year and $107 per PEV per year.

Building on the results shown in Figure 53, Figure 56 indicates total social valuation results on a per-PEV basis nationally and by PEV type for the Aggressive and Low Cost scenarios. Net positive benefits are comparable for each PHEV type, with the PHEV40 providing slightly greater benefit than the smaller-battery PHEVs ($455 and $536 per PHEV40 in the Aggressive and Low Cost scenarios, respectively). In contrast, results for the BEV70 are significantly different than those for the other BEV types. As indicated in the private benefits in Figure 53, the BEV70 has slightly negative vehicle net costs in the Aggressive scenario and positive vehicle net costs in the Low Cost scenario (see cost input assumptions in section 2.2), as well as lower fuel savings than other BEVs due to range limitations. After accounting for social benefits the BEV70 is comparable to but slightly lower than the PHEV40 ($417 to $511 per BEV70 per year in the Aggressive and Low Cost scenarios, respectively). Net benefits for the BEV140 are about half those of the BEV70 in the Aggressive scenario but are comparable to the BEV70 and PHEVs in the Low Cost scenario.

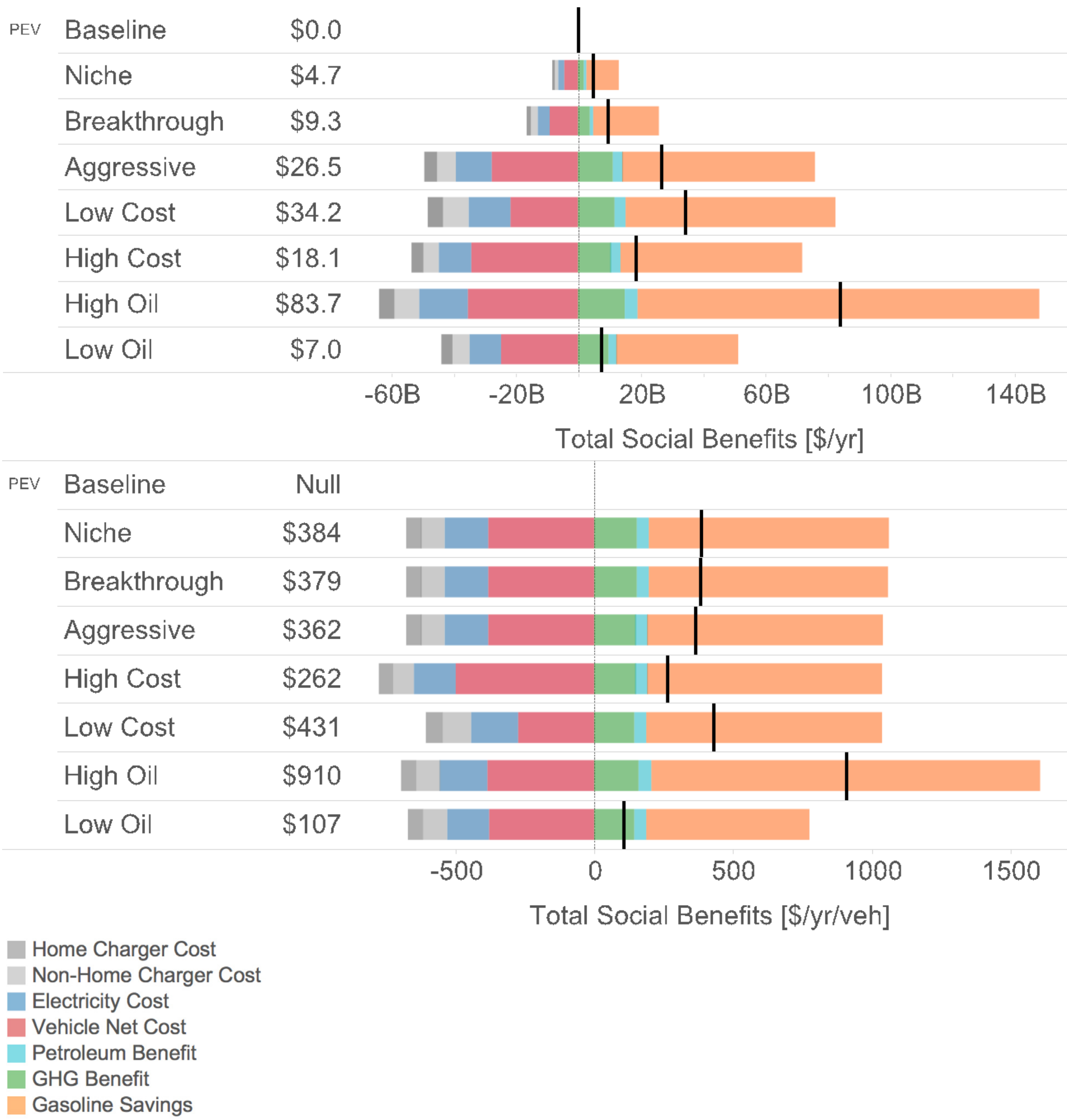


Figure 55. Breakdown of total social costs and benefits for each scenario in 2035

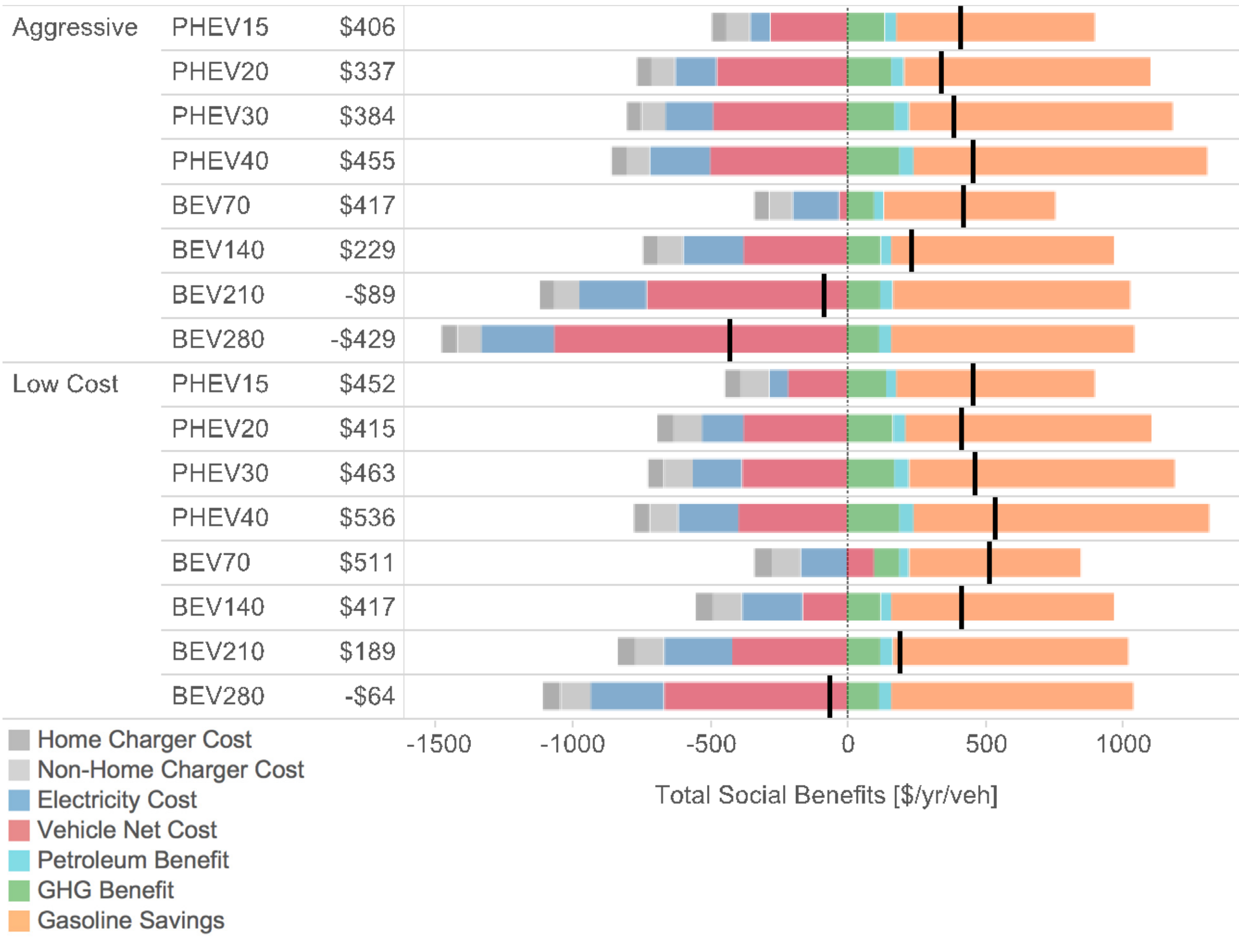


Figure 56. Total social benefits by PEV type in the Aggressive and Low Cost scenarios

The high incremental costs of the BEV 210 and BEV280 reduce total social benefits significantly. Both vehicles have net negative social benefits in the Aggressive scenario. The BEV210 falls to -$89 per vehicle per year in the Aggressive scenario but maintains a positive $189 per vehicle per year in the Low Cost scenario. The BEV280 is strongly negative in the Aggressive scenario (-$429 per BEV280 per year) but is close to zero in the Low Cost scenario. In terms of the probability of PEV cost projections being realized in either scenario, it should be kept in mind that PEV costs have been declining rapidly and that price signals seen today suggest either trajectory may be realized the long term, as discussed in section ES.2.2.

As a reminder, the cost structure underlying each PEV type used as an external input to the present analysis is a relatively static set of assumptions about vehicle costs and performance. While this cost structure may be accurate on average in terms of the costs of electrification per e-mile driven, the variability in market adoption across different types of PEVs would likely depend on many additional vehicle attributes and consumer preference factors beyond the vehicle upfront purchase price, fuel savings, and range. Taking into account heterogeneity in consumer preferences may also contribute to significant deviations from the relative market shares resulting from the allocation approach described in section 2.3. With these factors in mind, the results for total social benefits for PEVs in aggregate, such as those shown in Figure 55, should be considered the most robust. The variations across different PEV types indicated in Figure 56 provide only limited insight into the overall social benefit result. A more complete and dynamic modeling of consumer preferences would be required to more fully understand the relative benefits across different PEV types and drivetrains. These types of models have been developed by DOE and continue to be refined and improved as new market data on consumer preferences for advanced LDVs and PEVs becomes available (NRC 2013; Stephens et al. 2016; Brooker et al. 2015). The framework established in the present study to account for household travel patterns, climate, and regional variations in gasoline prices and grid simulations would still prove valuable in the implementation of a more sophisticated vehicle choice modeling approach.

4.5 Regional Variability of Economic Value Results

The benefit of electric vehicles varies across the country. Factors that affect regional variations are sales by PEV type, gasoline prices, average annual ambient temperature, and electricity prices and grid mixture. While data on these trends have been incorporated at a relatively high geographic resolution, the most detailed level at which the results can be reported with a high degree of consistency is at the census division level.[10] A map indicating states within each of the nine census divisions is shown in Figure 57.

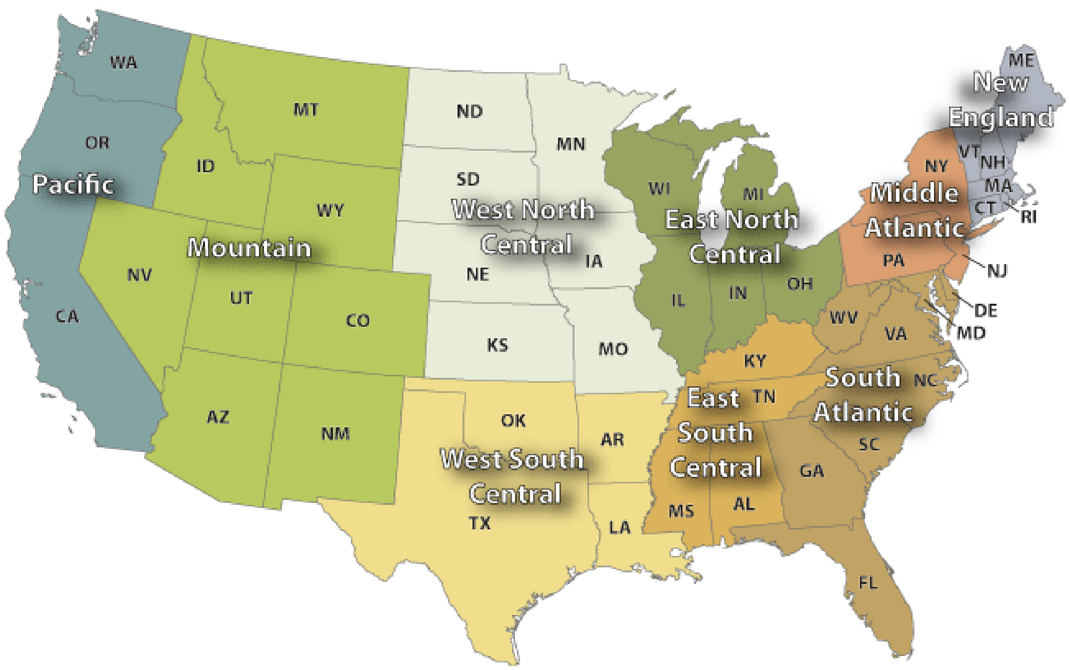


Figure 57. U.S. states and census divisions

Figure 58 depicts the same breakdown of total social benefits as shown in Figure 55 but for the Aggressive and Low Cost scenario results by census division. The sum over all regions for each cost and benefit indicated results in the same totals discussed earlier: net benefits of $26.5 billion per year for the Aggressive scenario and $34.2 billion per year for the Low Cost scenario. The results by region are ranked by the total net benefits, indicated visually by black vertical lines

[10] The limiting factor here is the price of electricity results generated by the ReEDS model. While prices can be estimated at higher levels of detail by the ReEDS model, the aggregate prices at the census division level are considered the most robust for the present analysis.

and numerically by the values next to each region name. Interestingly, this ranking also tends to follow the total costs and total benefits for each region, which tend to be proportional to total market size. The exception to this trend is the Middle Atlantic region, where higher electricity costs result in total costs (bars stacked to the left of zero) being larger than those in the West South Central division.

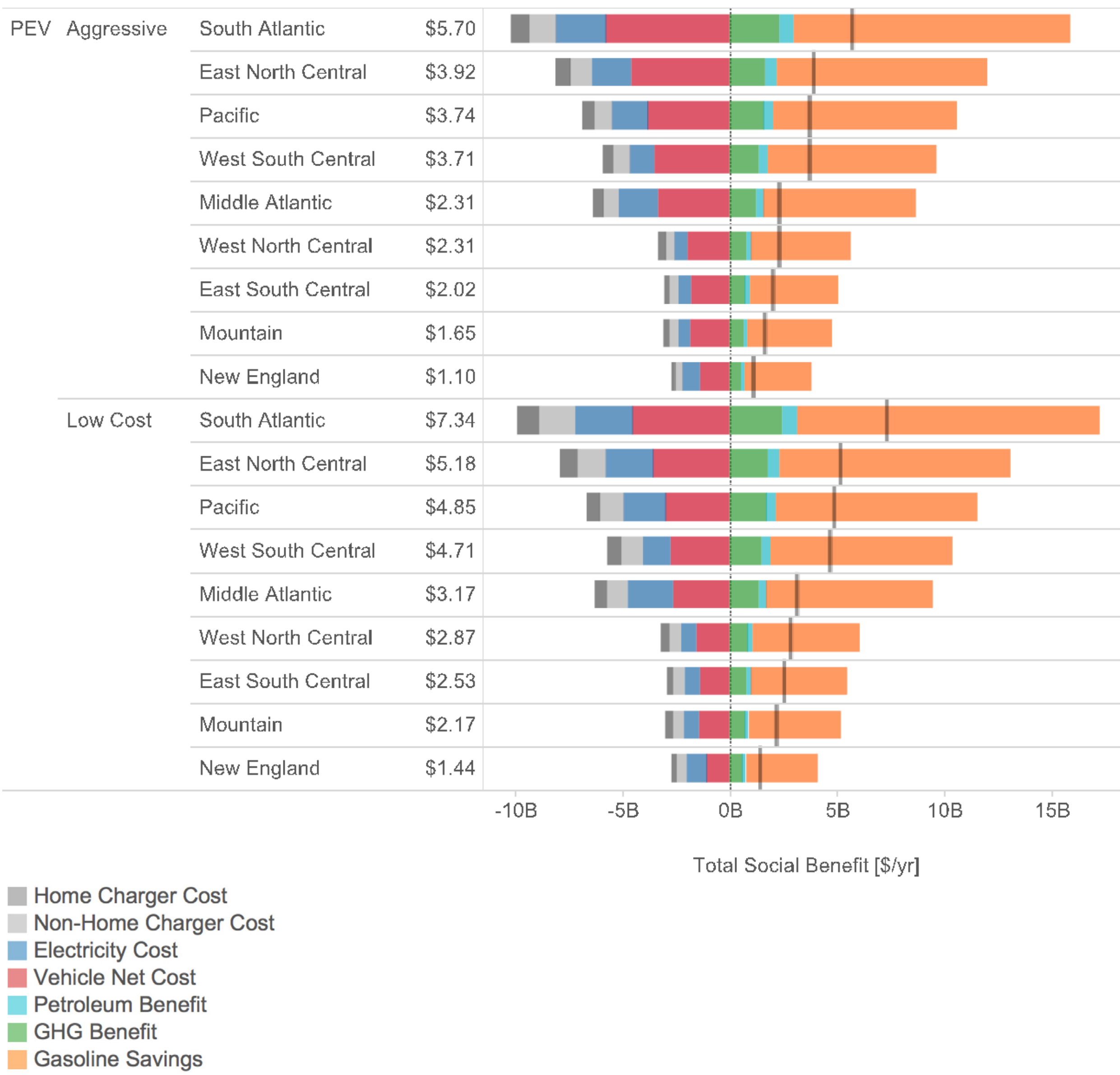


Figure 58. Regional breakdown of total social costs per year in 2035

Another way of viewing these regional results is on a per-vehicle basis, as shown in Figure 59. Again the ranking of divisions is done by total net social benefit, but now the order differs slightly from the order in Figure 58. Considering the proximity of divisions to one another geographically, we can consider three related groups. The first group consists of the first four divisions with the highest net benefit per PEV: West North Central, East South Central, West

South Central, and South Atlantic. These divisions are, generally, the middle of the country and the southeast. The second group consists of the next two divisions with the highest net benefit per PEV: Pacific and Mountain. The third group consists of the three divisions with the lowest total social benefit per PEV: East North Central, New England, and Middle Atlantic.

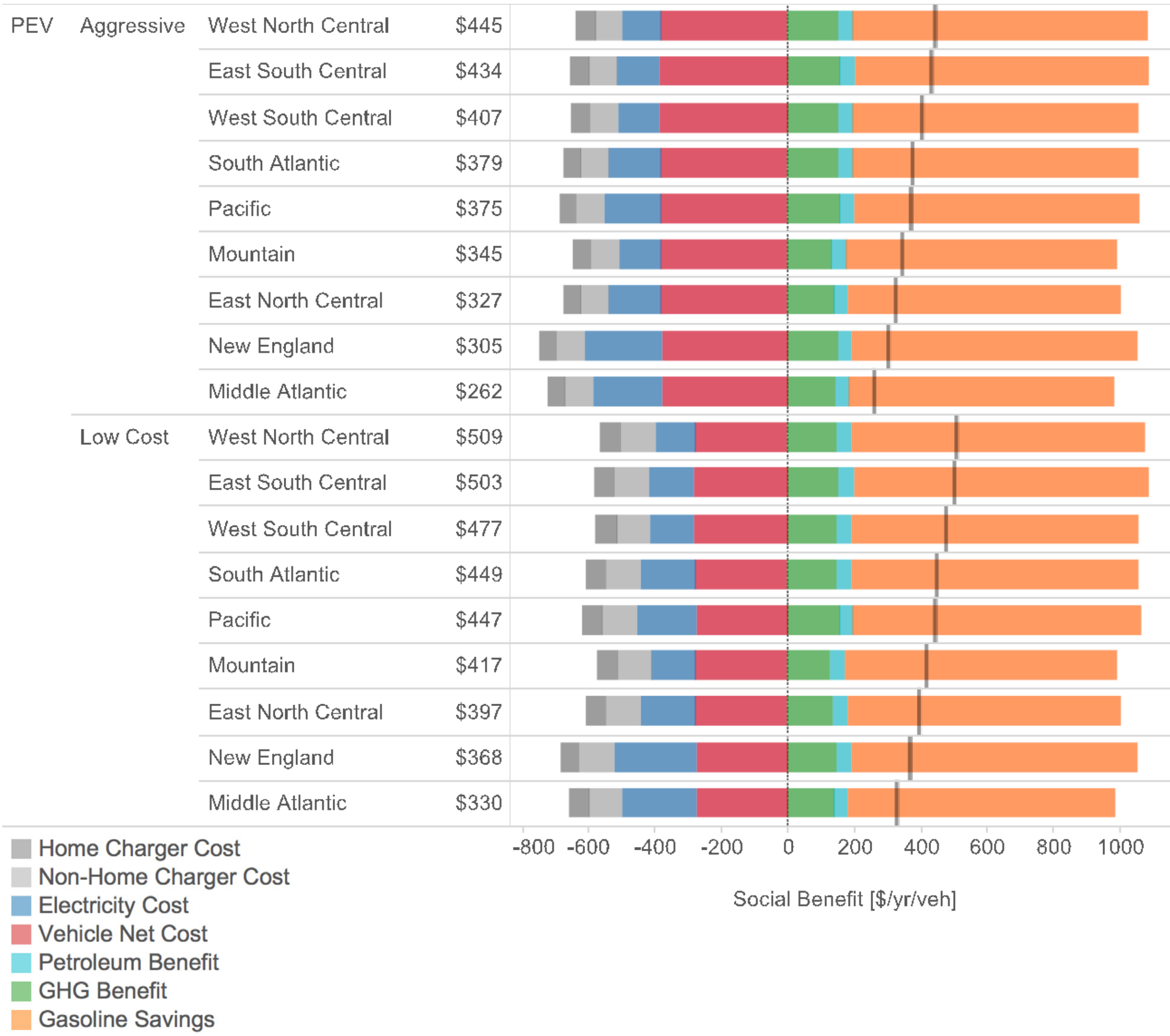


Figure 59. Regional breakdown of social benefit per year per vehicle for Aggressive and Low Cost scenarios

Given the breakdown of costs and benefits indicated in Figure 59, it is difficult to identify the underlying trends that are distinct between regions. The main variations appear to be in electricity and fuel savings, but these components themselves are a result of a number of combined factors that vary by region.

The extent to which different underlying factors contribute to variations in total social benefits can be examined by disaggregating the influence of each factor on the final results. One approach to visualizing these influences in a disaggregated manner is shown in Figure 60. The aggregated national average net benefit of $362 per PEV per year is shown as the first data point on the left-hand side of the figure and is labeled as “U.S. Fleet” on the horizontal axis.

Deviations from this national average result are then tracked in succession, showing the influence of each individual factor for each division. The factors are introduced in order of least effect to largest effect in terms of broadening total regional variation. The first factor is the change in PEV market share due to the PEV allocation algorithm. This has a very small effect on regional variability. As discussed above, the influence of this factor is derived from relatively static vehicle cost and performance inputs and the simplified allocation algorithm used to represent consumer choice. The next factor is climate, which influences vehicle efficiency. The effect is a tendency to improve the total social benefit for temperate regions (such as the Pacific region) while reducing the benefit for less temperate, colder regions (such as the West North Central, Mountain, and East North Central regions).

The third factor is the carbon intensity (CI) of electricity. This provides an increase for the Pacific division as well as increases to the East South Central, South Atlantic, and West Central divisions. Again, this is not due to just the average carbon intensity in each region but rather the alignment of the most prevalent charging profiles with the time period resolutions inherent to the ReEDS model (see section 2.4). The fourth factor is the price of gasoline, with higher gasoline prices increasing total social benefits for the Pacific, New England, Middle Atlantic, and Mountain divisions. Lower gasoline prices tend to decrease the total social value for PEVs in all other divisions. Electricity price is the fifth factor taken into account. The strongest influences are reductions in total social benefit due to the high electricity prices in the Pacific, New England, and Middle Atlantic divisions. Modest positive increases are seen for the South Atlantic and East North Central divisions, while all other divisions experience relatively large increases in total social value due to lower electricity prices.

The final factor is variations in social costs due to household travel patterns, labeled as VMT in the figure but taking into account both average VMT per year and the influence of long-distance trip frequency on the adoption of BEVs vs PHEVs. Significant reductions in total social benefits are seen for the Pacific, Mountain, New England, East North Central, and Middle Atlantic divisions, while all other divisions see strong increases.

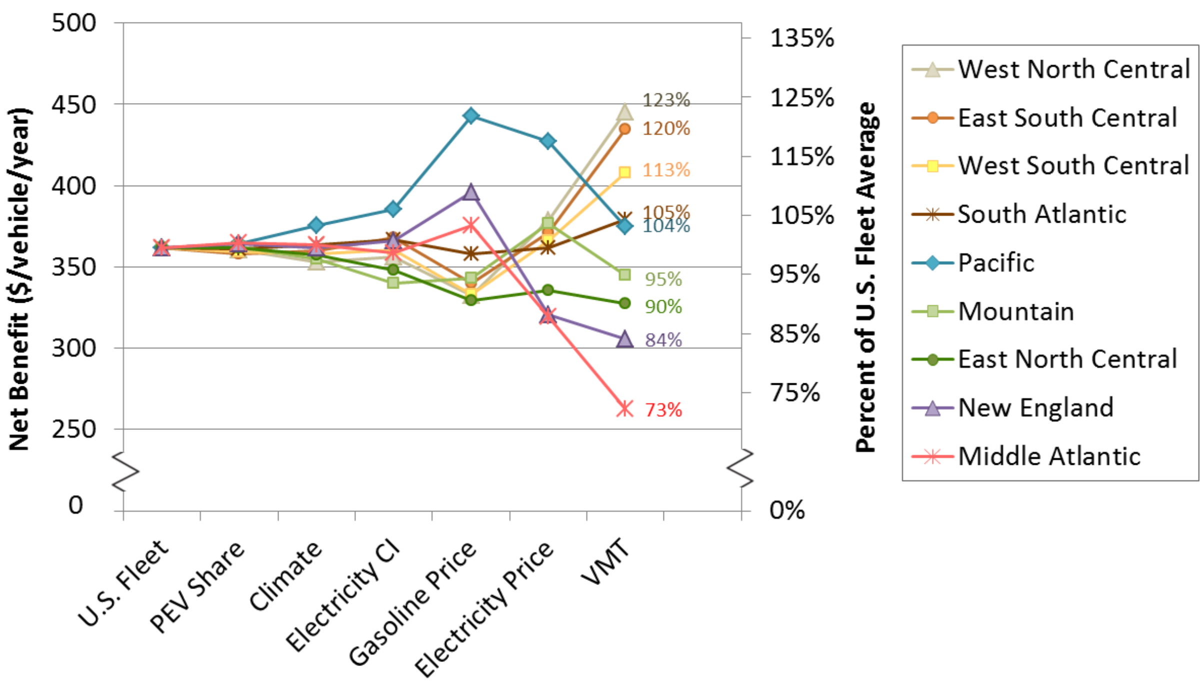


Figure 60. Progressive revisions to net benefit per vehicle per year by assumption

These combined trends suggest two general and distinct combinations of factors. PEVs in the Pacific, New England, and Middle Atlantic regions have increases in social benefits due to higher gasoline prices and reductions due to higher electricity prices and VMT. However, unlike PEVs in the New England and Middle Atlantic divisions, PEVs in the Pacific division also benefit from mild climate and the lower carbon intensity of electricity provided to PEVs. PEVs in the other six divisions experience a different general trend. With some exceptions, gasoline prices tend to reduce total social benefits, and lower electricity prices and VMT tend to increase total social benefits.

The percent deviation from the national average for each division is indicated numerically in the figure after the final VMT factor is taken into account. The variation is the same as indicated in Figure 59, with West North Central being 123% of the national average and the Middle Atlantic being 73% of the national average.

Another interesting result by region is variations in total social costs per vehicle by PEV type. This level of disaggregation of the national results is presented for PHEVs in Figure 61, using the Low Cost scenario as an example. Regions are shown in order of the net benefits for PHEV40 vehicles, and this order holds for all PHEVs and regions with the exception of the order of PHEV15 vehicles in the New England and Mountain regions. In general the trends across regions are very regular and consistent and mirror the trends for PHEVs by type nationally.

The same trends for BEVs are shown in Figure 62 with the order of regions following net economic value results for the BEV280 vehicles. For most of the regions the negative economic value results for BEV280 vehicles are quite small, less than $50. The largest negative values are in the Middle Atlantic and New England regions and are on the order of $180 per year per vehicle. As is the case with the national average results, all other BEV types have positive net total social benefits in each region.

Absolute total social valuation results for the two main scenarios of interest, the Aggressive and Low Cost scenarios, are summarized by region in Figure 63. Regions with the largest total net benefits are indicated first, starting with the South Atlantic, and are shown increasing cumulatively toward the national totals at the bottom of the graph. Aggressive scenario results are shown as orange bars and Low Cost scenario results are shown as blue bars. The cumulative results sum to the national total for each scenario, suggesting a range of benefits between $26.5 and $34.3 billion per year (see section ES.2.2 for a discussion of comparing vehicle costs in the Aggressive and Low Cost scenarios).

This sequence of benefits from largest to smallest by division only accounts for absolute results and does not address the relative value of adopting PEVs within each division. Results for total net social benefits per PEV are shown as a range between Aggressive (orange) and Low Cost (blue) scenarios by census division in Figure 64. The largest benefits (ranging from $434 to $509 per PEV per year) are seen in the West North Central and East South Central divisions, while the smallest benefits (ranging from $262 to $368 per PEV per year) are seen in the New England and Middle Atlantic divisions. The range of $362 to $431 per PEV per year for the national average falls more or less in the middle of these higher and lower division ranges. While all divisions see a net positive benefit for these two scenarios, results suggest a variation between roughly $250 and $500 per PEV per year, or about 200%, across all census divisions.

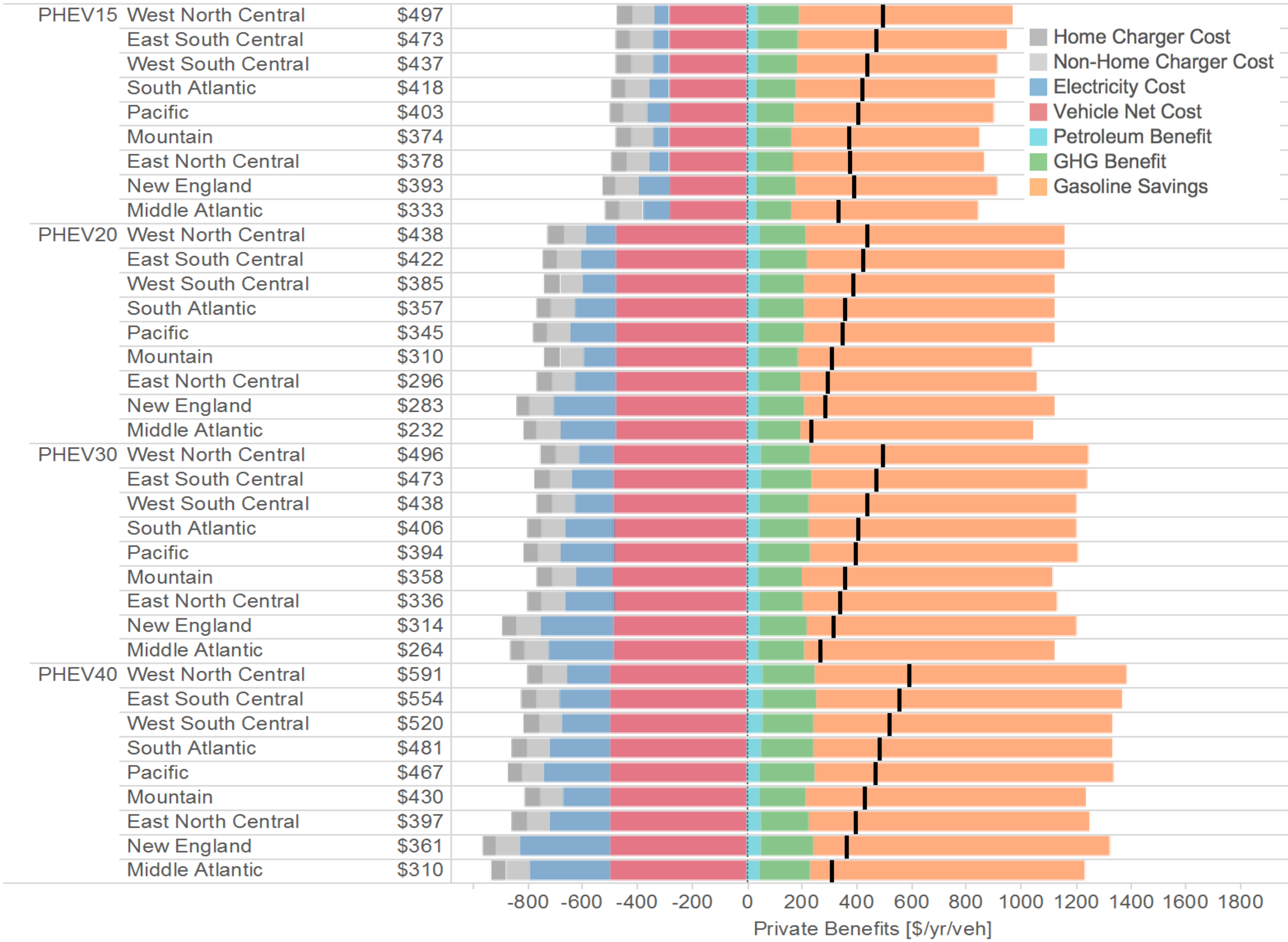


Figure 61. Social costs and benefits per PHEV type by region in the Low Cost scenario

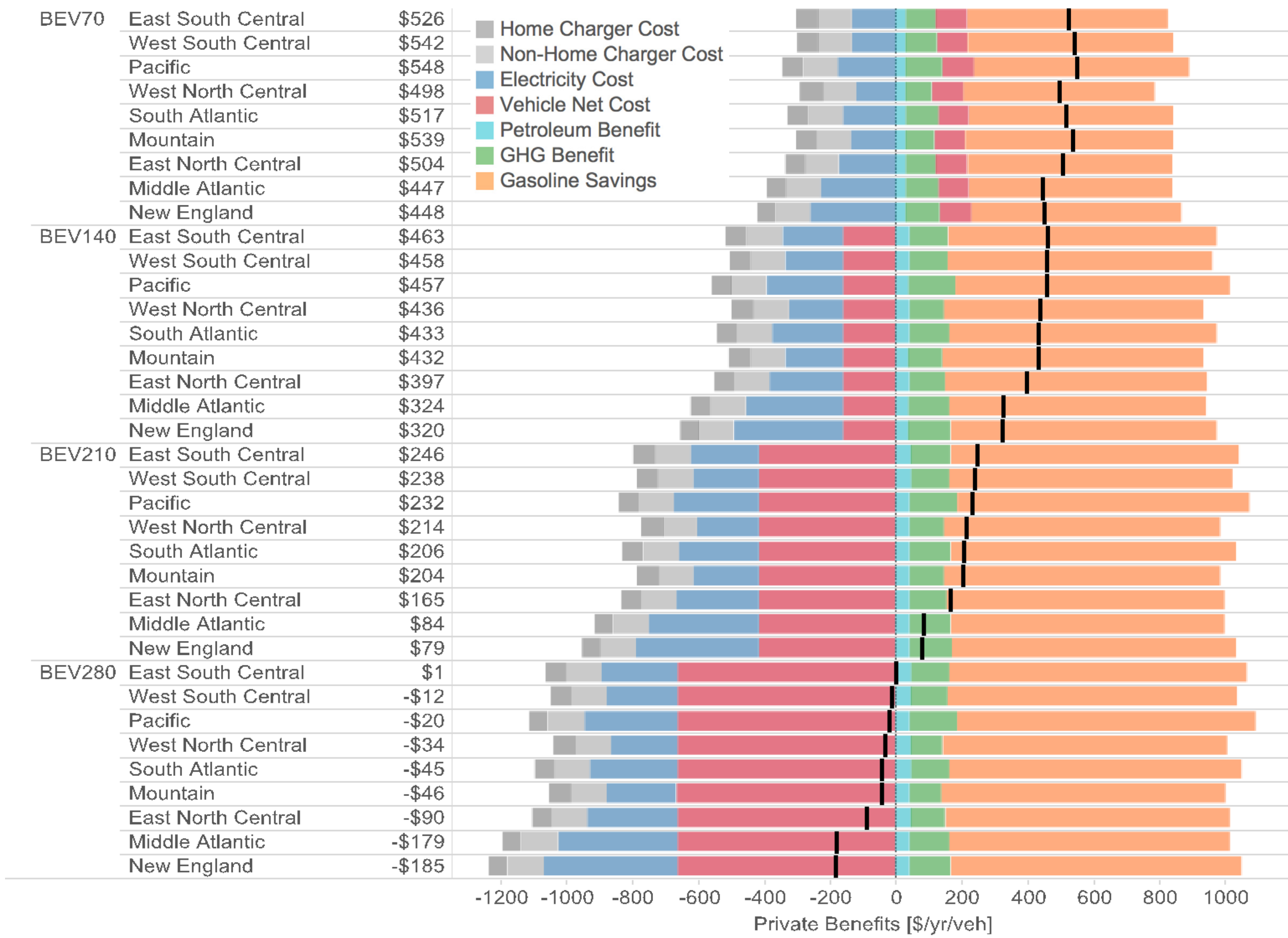


Figure 62. Social costs and benefits by BEV type and region in the Low Cost scenario

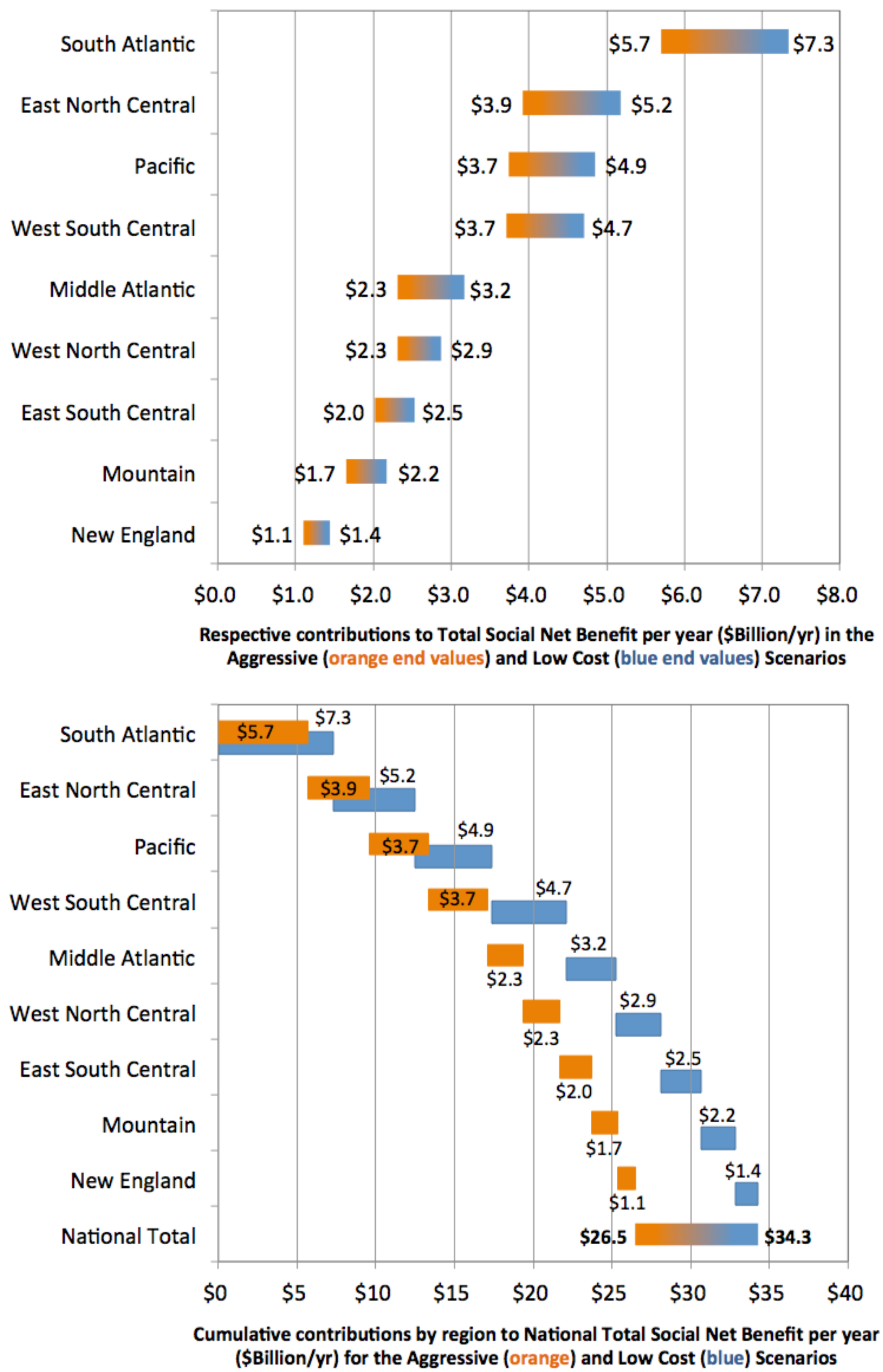


Figure 63. Respective (top) and cumulative (bottom) contributions to total social net benefit by region for the Aggressive and Low Cost scenarios

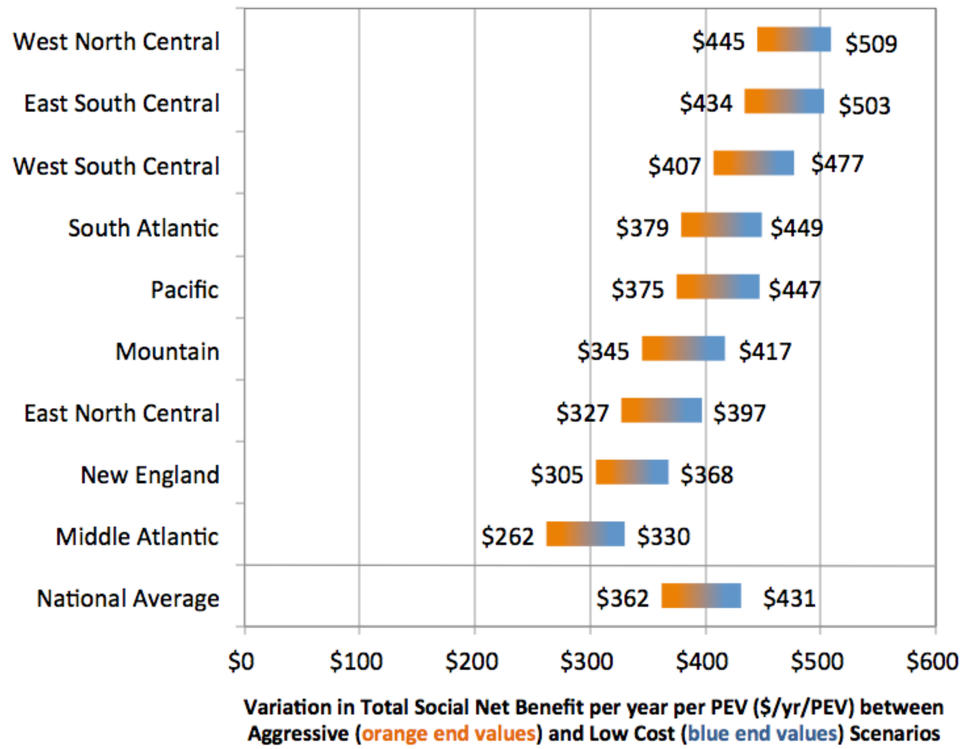


Figure 64. Range of total social net benefit per year per PEV by region for the Aggressive and Low Cost scenarios

4.6 Jobs, Earnings, GDP, and Output Impacts

Overall, the introduction of electric vehicles has positive impacts for all of the scenarios except for the number of jobs with high cost vehicles and the total output for the niche scenario. Table 24 shows the average annual impacts over the entire range of years explored (2015–2040). Macroeconomic impacts are described in greater detail in Section 3.5.2.

Table 24. Average Annual Impacts for Each Major Scenario

Economic Metrics (2013 dollars)	Jobs (number of jobs/yr)	Income ($million/yr)	GDP ($million/yr)	Output ($million/yr)
Niche	110,000	3,855	5,571	(619)
Breakthrough	99,000	3,707	5,804	1,723
Aggressive	52,000	3,016	6,592	11,003
High Cost	(30,000)	176	2,528	11,994
Low Cost	109,000	5,104	9,913	11,201
High Oil	147,000	6,990	12,505	20,196
Low Oil	1,000	1,046	3,732	8,444

4.7 Anticipated Trend for Criteria Emissions

In addition to social costs for greenhouse gas emission reductions (i.e., \$39.6–\$60.5/tonne CO_2e [2013\$]) and petroleum reduction (\$0.18/gallon gasoline reduced) there is also a social cost for the release of criteria pollutants. Quantification of criteria pollutants and resulting public health and other damages is beyond the scope of this study. However, other studies have shown that introducing electric vehicles reduces the total source emissions from the transportation sector, though pollutant emissions are shifted to the electric sector. Depending on the policies included and the resulting grid mixture, total pollutant emissions most often decrease (EPRI 2015). There are occasions where high emitting power plants could cause a slight increase in emissions, but with the reduction of conventional coal power generation this is not likely to occur (Michalek et al. 2011).

Based upon ReEDS simulations, total source pollutant emissions from the electric sector can be calculated for scenarios with and without electric vehicles. Largely on account of Mercury and Air Toxic Standards, the Cross-State Air Pollution Rule, and other regulations, the SO_2 and NOx emissions drop dramatically through 2018 and then the reduction slows (see Figure 49 and Figure 50). With the addition of electric vehicles, SO_2 and NOx emissions experience very minimal changes through 2035, which is similar to results from a recent EPRI-NRDC study (2015). These results strongly depend on achieving a cleaner and more renewable grid. Weis et al. has shown that with retirements of power plants as prescribed by the EPA and the introduction of wind power, even an area with high levels of coal generation (PJM) can reduce the life cycle criteria pollutant emissions levels for PEVs below that of CVs in all categories except for SO_2 (Weis et al. 2015). This result will vary regionally based on the grid mixture and vehicle charging patterns and will improve for regions less reliant on coal generation. More complete regional assessments of public health damages can provide greater insights into the social benefits associated with criteria pollutant emissions.

4.8 Scenario Sensitivity Results

A number of input parameters have been examined through sensitivity analyses to better understand how and to what degree they influence the analysis results. While this section examines key input assumptions, a broader set of sensitivities will be explored in Volume II of the NEVA study. Figure 65 indicates changes in the percent of PEVs on the road in 2035 in the Aggressive scenario as a result of varying the percent reduction in the BEV range penalty discuss in section 2.3.1. The results are shown for each of the four BEV and PHEV types. The Aggressive scenario assumes a 40% reduction in the BEV range penalty, which is indicated as the third column of stacked bars for different PEV types. The 0% reduction, where the full range penalty is applied within the PEV allocation algorithm, has very few BEVs on the road by 2035. Reducing the range penalty more than 40% results in a significant increase in BEVs, and in the number of BEV70 vehicles on the road in particular. This is due to the BEV70 being more competitive with CVs and HEVs in terms of capital cost than the other BEVs are. As indicated, BEV70 market share increases at the expense of all types of PHEVs. Reducing the range penalty also increases the number of BEV140 vehicles but has relatively little influence on the longer range BEVs, which were not significantly dampened by the range penalty in the Aggressive scenario.

The net social benefits associated with these variations on the percent reduction of the BEV range penalty are indicated in Figure 66. The Aggressive scenario is indicated first, with total net social benefits of $26.5 billion per year in 2035. Reductions in the range penalty less than that assumed in the Aggressive scenario, the 0% and 20% reductions, indicate reduced total net social benefits. Larger reductions result in higher net social benefits, with an 80% reduction resulting in $31.2 billion per year and removal of the range penalty (100% reduction) resulting in $35.2 billion per year. As discussed previously, the relationship between increased public charging availability and the range penalty for BEVs is poorly understood. The 40% reduction assumed for the Aggressive scenario is a highly uncertain input assumption. These sensitivities suggest the degree to which an improved and more precise understanding of consumer perceived range penalties and the availability of public charging infrastructure might influence estimates of the net social benefits associated with increased PEV adoption. Moreover, a more precise understanding would allow for a more robust cost-benefit assessment of options for investment in public infrastructure with the goal of increasing PEV market growth or the benefits accrued from PEV market growth.

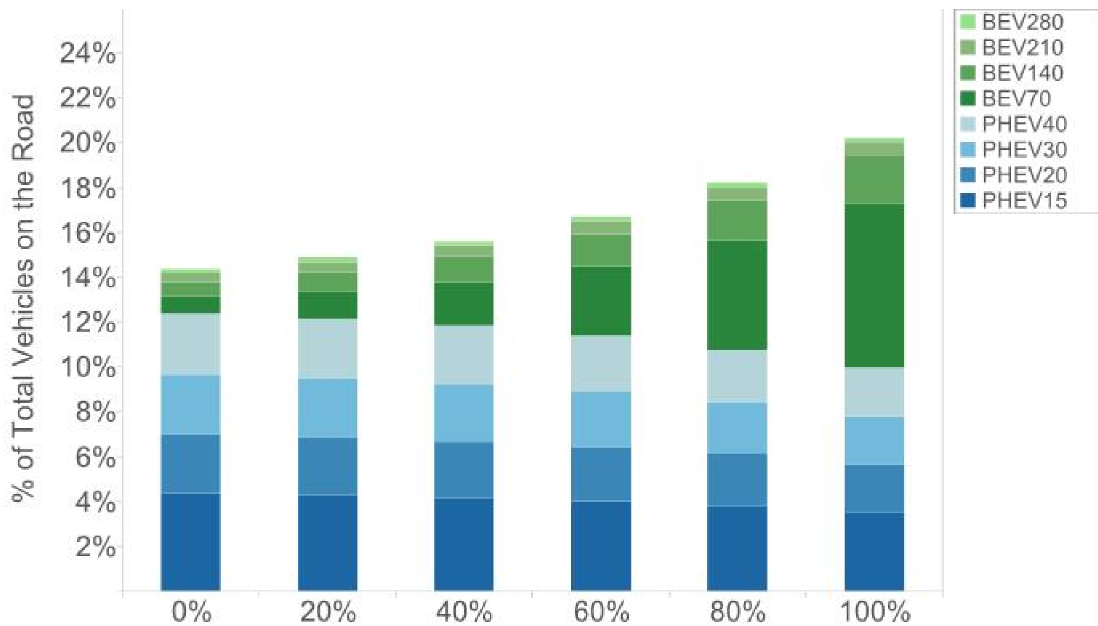


Figure 65. Sensitivity on BEV range penalty reduction (0%, 20%, and 40% reduction results)

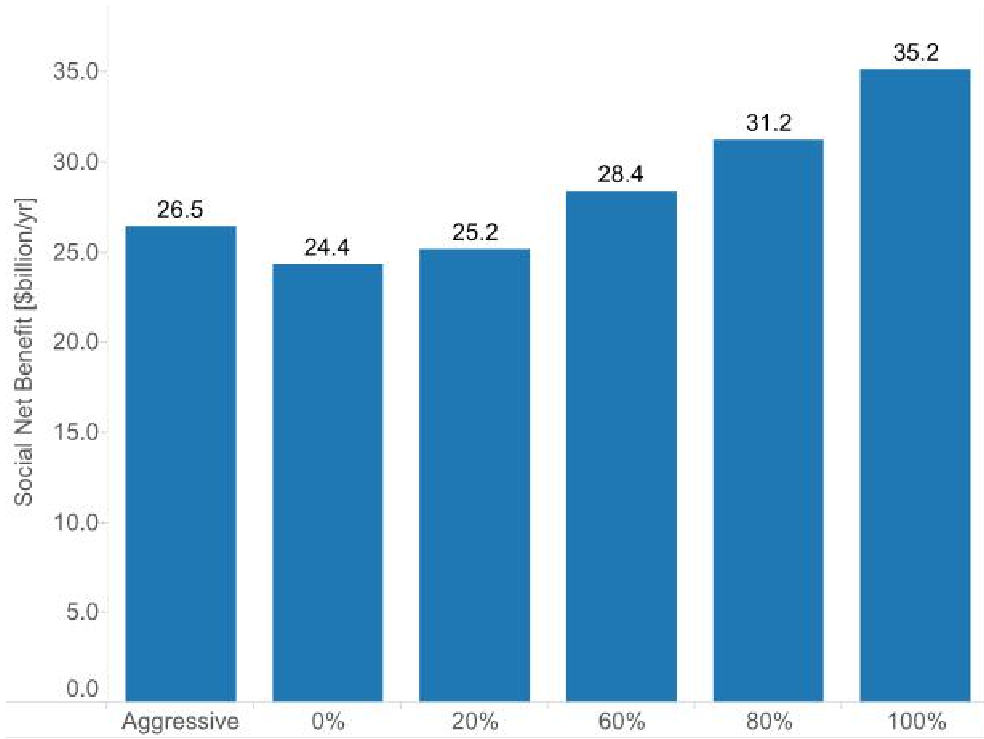


Figure 66. Net social benefits in 2035 for the Aggressive scenario with a range of reductions in the BEV range penalty (Aggressive scenario has a 40% reduction)

5 Summary, Conclusions, and Future Work

A scenario approach is employed to provide insights into the long-term economic value of increased future PEV market growth. The analytic methods applied do not predict future PEV market growth or future fuel prices; instead they estimate fundamental costs and benefits associated with an economic allocation of PEVs across households based upon household driving patterns, projected vehicle cost and performance attributes, and electricity grid simulations. Multiple PEV market growth scenarios are explored, with the greatest attention placed upon a hypothetical Aggressive scenario with 73 million PEVs on the road by 2035. Variations on the Aggressive scenario provide insights into a variety of key issues.

As is the case with any techno-economic study of future technology trends, results are highly dependent upon input assumptions and modeling limitations. Major input assumptions and modeling limitations are therefore reviewed below, followed by an overview of conclusions and recommendations for future research. As noted earlier, a subsequent Volume II report will examine a broader range of sensitivities around modeling input assumptions.

5.1 Summary of Inputs and Modeling Limitations

The modeling approach relied upon in this study has been reviewed briefly in section ES.2 and presented in significant detail in section 2. Major aspects of the techno-economic scenario approach that place conclusions in appropriate context are the following:

- **PEVs are adopted in households where they provide the greatest economic value.** Given the high upfront costs of most PEVs, combined with fuel cost savings with respect to gasoline, the most economically efficient use of these vehicles is in households with high VMT. Higher annual mileage per vehicle results in greater household fuel savings as electricity is substituted for gasoline. For the same reasons, high-VMT households also tend to adopt HEVs instead of CVs. This study assumes an economically efficient allocation of PHEVs and HEVs into high-VMT households while accounting for the range limitations of BEVs as a barrier into households with a high frequency of long-distance trips. This approach is favorable to PEVs in assuming that future consumers make purchase decisions based upon information about relative vehicle and fuel economics, while actual consumers base purchase decisions on a wide range of household requirements and vehicle attributes.
- **Relatively high prices and limited range are barriers to the widespread allocation of BEVs across mainstream households.** A relatively small share of U.S. households have both a high annual VMT and a small number of long-distance trips. With an allocation algorithm based upon economic efficiency, these cost and behavior input assumptions tend to limit the sales of BEVs compared to PHEVs and HEVs. This limitation is captured by a range penalty assumption used in determining the economic allocation of BEVs vs. PHEVs in meeting the scenario design target of 14% of all VMT being eVMT in the Aggressive scenario (see section 2.1.2). This tendency could shift more in favor of BEVs as additional mainstream consumer preference data are collected—such as a more robust quantification of consumer preferences for the all-electric drive experience, the relative preference for BEVs as a “green” alternative, or the influence of public charging availability on sales.

- **Electricity prices and carbon intensities vary significantly by region, and electricity prices increase only modestly (<~3%) with increased PEV electricity demand, given the limitations of the grid simulation methodology.** Charging PEVs in regions that have greater renewable penetration or low carbon intensity increases the reduction in GHG emissions resulting from switching to PEVs. Similarly, regions that have lower electricity prices have increased household fuel savings as a result of reduced expenditures on gasoline due to switching to PEVs. These regional trends are captured through a simulation of the future electricity grid, which estimates an increase in electricity prices in response to PEV electricity demands as well as a decline in carbon intensities based on the relative cost of generation equipment rather than unique attributes of PEV demand patterns (see section 2.4). However, this analytic approach may not fully capture the future value of flexible demand from PEVs or the capacity to provide storage capability and ancillary services (see recommendations for future work below).
- **Some base level of workplace and public charging infrastructure is required for robust PEV market growth.** Given the very aggressive eVMT target used as a scenario input assumption, a significant amount of workplace and public charging availability is assumed to be required to support strong PEV market growth trends: 333,400 workplace and 4,800 public L1 and L2 chargers are required for every million PEVs deployed. These results are based upon fixed input assumptions. In addition, it is assumed that 1% of all electricity is provided to BEVs through 8,320 DCFC stations, or 470 DCFC stations per one million PEVs. The analytic approach does not estimate the cost-benefit balance of providing greater or lesser charging infrastructure with respect to PEV market growth. If future mainstream consumers place less value on away-from-home charging infrastructure than implied by this relatively conservative assumption, similar PEV benefits could be attained while incurring lower charging infrastructure costs by reducing the number of workplace or public chargers. The collection of additional empirical market data can help to inform these projections of future relationships between PEV market growth and the availability of workplace and public charging.

5.2 Major Conclusions

Intermediary results from the analysis are reviewed in section 3 and final economic valuation results are reviewed in section 4. Key scenario insights and economic valuation results include the following:

- **Increased PEV market growth is correlated with positive private household benefits.** In most future scenarios, private household fuel savings tend to outweigh two major costs of PEV market growth: (1) the additional cost of PEVs relative to conventional and hybrid vehicles, and (2) the costs of charging infrastructure. The only scenarios with low or negative household benefits are the High Cost scenario, with relatively high electric-drive vehicle component costs and low PEV efficiencies (see section 2.2), and the Low Oil scenario, with low gasoline price projections. Fuel savings are the most significant positive benefit, so all economic valuation results are heavily dependent on future gasoline prices. A long-term trend of low gasoline prices would tend to both suppress PEV sales and diminish fuel savings, which is inconsistent with the very high market growth assumed in the Aggressive scenario. Results across multiple PEV market success scenarios suggest average net private benefits ranging from $255 to $791 per PEV per year by 2035. In total, the private benefits for the main Aggressive and Low Cost scenarios range from $18.6 billion to $27.3 billion per year by 2035, corresponding to average benefits of $255 and $344 per PEV per year, respectively. Private benefits from the less aggressive and more likely PEV market growth trends in the Niche and Breakthrough scenarios range from $3.3 billion to $6.6 billion per year by 2035, corresponding to average benefits of $273 and $269 per PEV per year, respectively.

- **Increased PEV market growth tends to result in positive social benefits.** With declining carbon intensity on the electricity grid as more renewables are installed, and with constant gasoline carbon intensities, increased PEV adoption results in net GHG emission reductions in most U.S. regions by 2035. The resulting national net social benefits for the Aggressive and Low Cost scenarios are $26.5 billion and $34.2 billion per year by 2035, corresponding to average benefits of $362 and $431 per PEV per year, respectively. This includes the private benefits discussed above, the additional cost of workplace and commercial charging infrastructure, and social benefits associated with reduced GHG emissions and petroleum imports. Public health benefits from improved air quality over the long term, which warrant future research but are beyond the scope of the present analysis, would likely result in additional positive social benefits. In the present analysis, the electricity sector experiences minimal changes to criteria pollutant emissions in response to increased demand from PEVs, largely due to the incremental installation of low-cost renewable generation technologies to meet any additional future electricity demand.
- **PEV market growth increases economic activity, while net job and GDP growth is highly dependent upon gasoline prices, PEV costs, and fuel economies.** Household fuel savings, reductions in petroleum imports, and increased domestic electricity consumption tend to stimulate GDP and create U.S. jobs. However, these trends tend to be counterbalanced by reduced household disposable income resulting from purchasing more expensive PEVs and charging infrastructure. Positive job growth results range from 52,000 and 109,000 net jobs per year (average from 2015 to 2040) for the Aggressive and Low Cost scenarios, respectively. However, the higher PEV costs in the High Cost scenario result in a net reduction of 30,000 jobs. All scenarios see positive net GDP, with a low of $2.5 billion per year in the Aggressive High Cost scenario, and a range of $6.6 to $9.9 billion per year in the Aggressive and Low Cost scenarios, respectively.
- **BEVs economically satisfy the driving needs of a relatively small market.** In comparison to PHEVs, BEVs are less attractive economically due to either their high upfront costs compared to alternatives or their limited range, or both. While increased public charging will make BEVs more attractive, it is unclear to what degree this may provide a market advantage over the purchase of PHEVs. The economically efficient allocation approach in this study, which only captures a portion of all consumer preferences for vehicles, results in PHEVs dominating future PEV markets. In addition to the modeling limitations and input assumptions discussed above, future trends that may influence BEV market shares and have not been accounted for in this analysis include changes in urban form and transportation systems, changes in vehicle ownership and car sharing, and the introduction of connected and automated vehicles.

- **PEV electricity demands are small in comparison to the total installed electric capacity and resulting generation, and the majority of incremental capacity and generation are projected to come from renewable sources by 2035.** The electricity demand from 73 million PEVs deployed by 2035 increases the installed capacity by less than 5% and the required electric generation by less than 4%. Grid capacity expansion simulations, subject to future technology costs and policies, tend to project increasing installation of renewable generation by 2035 in response to any increased marginal demands, whether from PEVs or other sources of demand. For the main Aggressive scenario and the Aggressive High Oil scenario in 2035, compared to their respective baseline simulations without PEVs, these simulations indicate electricity price increases of 1.3% and 3.4%, carbon intensity reductions of 3.4% and 5.6%, and renewable penetration increases of 1.7% and 2.6% respectively.
- **Changing the charging times for PEVs to better complement the grid can reduce the incremental system cost, but may also result in modestly increased GHG emissions, depending on the regional grid mixture.** Avoiding charging vehicles during peak electric demand periods, as done in the Dynamic scenario, enables existing generation to support much of the incremental PEV demand, thereby reducing the need for additional capacity. At the same time, reducing additional capacity reduces the incremental system cost. Adding PEVs increases the system costs by 2.9% for the main Aggressive scenario compared to the Baseline. Smart charging in the Dynamic scenario reduces the increase in system costs for the Aggressive scenario from 2.9% to 2.7%. Several utilities already offer special electric vehicle rates to encourage delayed or off-peak charging.
- **The cost of providing sufficient public charging infrastructure to support PEV markets is on the same scale as the social benefits of GHG emission and petroleum reductions.** While PEV market responsiveness to public charging is still uncertain, an estimation of workplace and public charging infrastructure required to support large PEV market growth suggests costs ranging from \$7.8 billion to \$8.1 billion per year in the Aggressive and Low Cost scenarios by 2035. In comparison, the positive social benefits of GHG emission and petroleum reductions in the same two scenarios range from \$14.1 billion to \$15.1 billion per year by 2035.

5.3 Recommendations for Future Work

The following items are suggested for future work to improve upon the economic valuation results in the present report.

- **More detailed treatment of PEV interactions with the electricity grid and tailored rate structures.** The present analysis relies upon grid simulations at the generation and transmission levels with hourly demand profiles for PEV charging. More detailed grid and charging profile simulations could take into account specific rate structures that include utility incentives to promote PEVs and programs tailored for the integration of large, distributed, and perhaps controlled PEV fleets. These more detailed simulations could result in significant changes in the balance of costs and benefits associated with PEV market adoption and would help to inform ongoing utility efforts to support PEV market adoption.

- **Grid simulations to examine the operational impacts of PEV demands on the electric system are warranted and may reveal additional trends not captured in the approach used in this study.** For this report, a capacity planning tool (ReEDS) is used to understand the least-cost rollout of electrical equipment (e.g., generation, transmission, and storage) to satisfy the system demand with electric vehicles. However, to understand operational impacts that extend beyond planning decisions, a grid operations simulation must be used (e.g., PLEXOS, Grid View). An operations simulation includes the ability to better resolve individual generator and storage operation, reserve provision, generator startup, and shutdown, all at higher time resolution. Use of an operation model can more accurately reflect vehicle charging impacts and advise on preferred charging strategies to better support the grid. In addition, an operation model can be used in combination with a planning tool to examine impacts of PEVs on future grids. Accounting for consumer behavior and responsiveness to pricing mechanisms, a more robust operations simulation approach could improve estimated fuel savings and the value of PEVs to the electricity grid.
- **Incorporate updated electric drivetrain component costs as new empirical data become available.** The present analysis is an approximate assessment of the Vehicle Technologies Office's goal to produce PEVs that are "as affordable and convenient as today's gasoline powered vehicles by 2022" (DOE 2014). Incorporating updated and near-term cost reductions for components such as batteries could improve estimates of the costs and benefits associated with increased PEV market growth.
- **Greater integration of evolving techno-economic estimates, market dynamics, and policy mechanisms.** The exogenous vehicle cost and performance metrics used for LDVs in this study provide a consistent representation of relative cost improvements and technology potential across multiple powertrains. However, a more integrated modeling approach could simulate changes in market adoption trends in response to evolving battery cost estimates, regulations such as CAFE, market support policy mechanisms such as the ZEV Mandate and state purchase incentives, and changes in consumer preferences and awareness. A more dynamic modeling approach could estimate transition costs as new electric drivetrain technologies are introduced over time and in different regional markets, and could provide insights into reinforced or restricted market adoption trends for different types of PEVs. While the underlying cost structure of electric-drive components may be very similar, a more dynamic simulation framework could evaluate the costs and benefits associated with specific policy mechanisms.
- **Better travel data regionally and by metro area; more longitudinal data on the frequency of long-distance trips.** This study develops utilization of PEVs by type using NHTS data for average VMT per year by household and applies a BEV range penalty based upon a parameterization of the frequency of long-distance trips by household. These input assumptions modified the utility of PEVs and their household economics with respect to utility, operation, fuel use, and perceived value. Additional and improved data on consumer driving patterns, and in particular additional or improved longitudinal data, could result in more realistic and robust vehicle simulation and economic valuation results.

- **Improved treatment of market segmentation and consumer choice.** The present analysis assumes rather static assumptions about total e-miles driven by PEVs in each census division and allocates PEVs by type according to a limited set of economic attributes and consumer preferences. A more complete treatment of additional LDV attributes, a broader set of consumer preferences (e.g., MA3T, ADOPT), and a more nuanced approach to market segmentation could result in a more realistic representation of both the allocation of LDVs to different households and the relative costs and benefits of increased PEV adoption. Stated preference surveys are one method of collecting data on consumer preferences, and additional empirical data on revealed preferences will become available as PEV and LDV markets evolve over time. In particular, more empirical market data on consumer preferences with respect to the electric-drive experience and limited BEV range as vehicle attributes should become available as PEVs continue to be adopted into more and broader market segments.
- **More detailed air quality simulations with respect to public health damage costs, PEV operation, and upstream fuel cycle emissions.** The present report includes a limited assessment of criteria pollutants from the electricity sector. The conventional vehicle emissions are not compared directly to a case with a higher number of PEVs. Damages to human health and the environment are an important consideration for scenarios with increased electric vehicles. Previous studies have found that the overall impact of converting to PEVs depends on the vehicle selection, grid mixture, and analysis timeframe. Future work should include an assessment of not only the amount and location of emissions across the United States but also the damages associated with these emissions as the electricity grid evolves in response to various policy and technology drivers. This will provide insight into the additional value that PEVs could potentially provide to the transportation system, particularly for high renewable and low carbon scenarios.

6 References

AEO. 2015. *Annual Energy Outlook 2015 with projections to 2040*. DOE/EIA-0383(2015). Office of Integrated and International Energy Analysis, U.S. Department of Energy.

AFDC. 2016. Electric Vehicle Charging Stations, Alternative Fuels Data Center, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available online: http://www.afdc.energy.gov/fuels/electricity_stations.html.

Anair, D., and A. Mahmassani. 2012. *State of Charge: Electric Vehicles' Global Warming Emissions and Fuel-Cost Savings across the United States*, Union of Concerned Scientists. Available online: http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/electric-car-global-warming-emissions-report.pdf.

Axsen, J., and K. Kurani. 2013. "Hybrid, Plug-in Hybrid, or Electric—What Do Car Buyers Want?" *Energy Policy* 61: 532–43. doi: http://dx.doi.org/10.1016/j.enpol.2013.05.122.

Axsen, J., and K. Kurani. 2012. "Interpersonal Influence Within Car Buyers' Social Networks: Applying Five Perspectives to Plug-in Hybrid Vehicle Drivers." *Environment and Planning A* 44 (December): 1047–65.

Börjeson, L., M. Hojer, K-H. Dreborg, T. Ekvall, and G. Finnveden. 2006. "Scenario types and techniques: Towards a user's guide." *Futures* 38 (7): 723-739.

Brooker, Aaron, Jeffrey Gonder, Sean Lopp, and Jacob Ward. 2015. "ADOPT: a Historically Validated Light Duty Vehicle Consumer Choice Model." Society of Automotive Engineers World Congress, Detroit Michigan, 21-23 April, 2015, NREL Report: NREL/CP-5400-63608.

Bush B., M. Melaina, M. Penev, W. Daniel. 2013. *SERA Scenarios of Early Market Fuel Cell Electric Vehicle Introductions: Modeling Framework, Regional Markets, and Station Clustering* (NREL Internal Use Only). NREL/TP-5400-56588. Golden, CO: National Renewable Energy Laboratory.

CalETC. 2014a. *California Transportation Electrification Assessment Phase 1: Final Report.* ICF International and Energy and Environmental Economics, Inc., 2014.

CalETC. 2014b. *California Transportation Electrification Assessment Phase 2: Grid Impacts.* Energy and Environmental Economics, Inc., 2014.

CAPEVC. 2016. PEV Sales Dashboard, California Plug-in Electric Vehicle Collaborative, available online: http://www.pevcollaborative.org.

Craig, P., A. Gadgil, and J. Koomey. 2002. "What Can History Teach Us? a Retrospective Examination of Long-Term Energy Forecasts for the United States." *Annual Review of Energy and the Environment* 27: 83–118.

DeShazo, J.R., CC Song, M. Sin, T. Gariffo. 2015. *State of the States' Plug-in Electric Vehicle Policies*. UCLA Luskin School of Public Affairs.

DOE. 2015. *Wind Vision: A New Era for Wind Power in the United States*. DOE/GO-102015-4557.

DOE. 2014. *EV Everywhere Grand Challenge Road to Success*. U.S. Department of Energy, report number DOE/EE-1024, January, available online: http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_road_to_success.pdf.

DOE. 2013. *EV Everywhere Grand Challenge Blueprint*. U.S. Department of Energy, January, available online: http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_blueprint.pdf

DOE. 2012. *SunShot Vision Study*. U.S. Department of Energy, DOE/GO-102012-3037.

EERE. 2015. *Costs Associated With Non-Residential Electric Vehicle Supply Equipment*. Prepared by New West Technologies, LLC, Englewood, Colorado, for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, available online: http://www.afdc.energy.gov/uploads/publication/evse_cost_report_2015.pdf.

EIA. 2015. "Electric Power Monthly," May 2015. Available online: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

Elgowainy, A., A. Rousseau, M. Wang, M. Ruth, D. Andress, J. Ward, F. Joseck, T. Nguyen, and S. Das. 2013. "Cost of ownership and well-to-wheels carbon emissions/oil use of alternative fuels and advanced light-duty vehicle technologies." *Energy for Sustainable Development* 17: 626-641.

Eppstein, M., D. Grover, J. Marshall, and D. Rizzo. 2011. "An Agent-Based Model to Study Market Penetration of Plug-in Hybrid Electric Vehicles." *Energy Policy* 39 (6): 3789–3802. doi:10.1016/j.enpol.2011.04.007.

EPRI. 2015. *Environmental Assessment of a Full Electric Transportation Portfolio*. EPRI, Palo Alto, CA. Available online: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=3002006881.

EPRI, 2007a. *Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions.* EPRI, Palo Alto, CA: 1015325.

EPRI, 2007b. *Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030*. EPRI, Palo Alto, CA: 1015326.

EPRI. 2001. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Electric Power Research Institute, Palo Alto, CA: 1000349.

Faguy, P. 2015. *Overview of the DOE Advanced Battery R&D Program*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Annual Merit Review Meeting, Available online: http://energy.gov/eere/vehicles/vehicle-technologies-office-annual-merit-review-presentations.

GCC. 2016a. "Tesla Model 3 reservations top 325,000; Tesla projects average price ~$43,000." Green Car Congress: Energy, technologies, issues and policies for sustainable mobility, available online: http://www.greencarcongress.com/2016/04/tesla-model-3-reservations-top-325000-tesla-projects-average-price-43000.html.

GCC. 2016b. "Topics: Plug-ins." Green Car Congress: Energy, technologies, issues and policies for sustainable mobility, available online: http://www.greencarcongress.com/plugins/.

Greene, David L. 2016. "Analysis of Incentives and Policy Impacts on the Market for Alternative Fuels and Vehicles." U.S. Department of Energy's Annual Merit Review Meeting, Washington, DC, June 8.

Greene, David. 2001. *TAFV Alternative Fuels and Vehicles Choice Model Documentation*. Oak Ridge National Laboratory, Report number ORNL/TM-2001/134.

Greene, David L., Sangsoo Park, and Changzheng Liu. 2013. "Analyzing the Transition to Electric Drive in California." White Paper 4.13, Howard H. Baker J. Center for Public Policy, University of Tennessee, Report to the International Council on Clean Transportation, April, 1–52.

Helveston, John Paul, Yimin Liu, Elea McDonnell Feit, Erica Fuchs, Erica Klampfl, and Jeremy J Michalek. 2015. "Will Subsidies Drive Electric Vehicle Adoption? Measuring Consumer Preferences in the U.S. and China." *Transportation Research Part A: Policy and Practice* 73: 96–112. doi: http://dx.doi.org/10.1016/j.tra.2015.01.002.

Holland, S., E. Mansur, N. Muller and A. Yates. 2015. *Environmental Benefits from Driving Electric Vehicles?* National Bureau of Economic Research, Working Paper 21291. Available online: http://www.nber.org/papers/w21291.

IAWG. 2015. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. Interagency Working Group on Social Cost of Carbon, United States Government, Washington, DC.

INL. 2015. "Plugged-In: How Americans Charge Their Electric Vehicles." Idaho National Laboratory. Available online: http://avt.inl.gov/pdf/arra/SummaryReport.pdf

Jenn, A., I. Azeveo, J. Michalek. 2016. "Alternative fuel vehicle adoption increases fleet gasoline consumption and greenhouse gas emissions under United States corporate average fuel economy policy and greenhouse gas emissions standards." *Environmental Science & Technology* 50: 2165-2174.

Jin, Lingzhi, Stephanie Searle, and Nic Lutsey. 2014. "Evaluation of State-Level U.S. Electric Vehicle Incentives," December, 1–49.

Laitner, J.A., S. J. DeCanio, J. G. Koomey, and A. H. Sanstad. 2003. "Room for improvement: increasing the value of energy modeling for policy analysis" *Utilities Policy* 11 (2): 87-94.

Leiby, Paul N. 2012. *Approach to Estimating the U.S. Oil Security Premium for the 2017-2025 Light -Duty Vehicle GHG/Fuel Economy Rule*. Supporting Doc for EPA Cafe Rules, 1–12.

Lin, Zhenhong, J. Dong, C. Liu, and D. Greene. 2012. "Estimation of Energy Use by Plug-In Hybrid Electric Vehicles: Validating Gamma Distribution for Representing Random Daily Driving Distance." *Transportation Research Record: Journal of the Transportation Research Board* 2287: 37-43.

Lutsey, N., S. Searle, S. Chambliss, A. Bandivadekar. 2015. *Assessment of leading electric vehicle promotion activities in United States Cities*. International Council on Clean Transportation and the 11th Hour Project of the Schmidt Family Foundation.

Mai, T., R. Wiser, D. Sandor, G. Brinkman, G. Heath, P. Denholm, D. J. Hostick, N. Darghouth, A. Schlosser and K. Strzepek. 2012. "Exploration of High-Penetration Renewable Electricity Futures." Vol. 1 of *Renewable Electricity Futures Study*, NREL/TP-6A20-52409-1.

Massiani, Jérôme. 2015. "Cost-Benefit Analysis of policies for the development of electric vehicles in Germany: Methods and results." *Transport Policy* 38:19–26. doi:10.1016/j.tranpol.2014.10.005.

McNutt, B., and D. Rogers. 2004. *Lessons Learned from 15 Years of Alternative Fuels Experience - 1988 to 2003*. In The Hydrogen Energy Transition: Moving Toward the Post Petroleum Age in Transportation. D. Sperling and J. Cannon, eds. Burlington, MA: Elsevier.

Melaina, M.W. and J. Bremson, 2006. Regularities in early hydrogen station size distributions. Energy in a World of Changing Costs and Technologies, 26th North American Conference, International Association of Energy Economics. Ann Arbor, Michigan, September 24-27.

Melaina, M., and M. Helwig. 2014. *California Statewide Plug-In Electric Vehicle Infrastructure Assessment*. Prepared for the California Energy Commission by the National Renewable Energy Laboratory. Publication Number: CEC-600-2014-003.

Michalek, J., M. Chester, P. Jaramillo, C. Samaras, C-S Shaiu, and L. Lave. 2011. "Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits." *Proceedings of the National Academy of Sciences* October 4 108 (40): 16554-16558.

Moawad, A., N. Kim, N. Shidore, and A. Rousseau. 2016. *Assessment of vehicle sizing, energy consumption, and cost through large-scale simulation of advanced vehicle technologies*. Argonne National Laboratory, Report Number ANL/ESD-15/28, available online: http://www.autonomie.net/publications/fuel_economy_report.html.

NHTS. 2009. National Household Travel Survey, U.S. Department of Transportation, Federal Highway Administration. Available online: http://nhts.ornl.gov.

NRC. 2015. *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*. The National Academies Press, Washington DC: National Academy of Sciences. Available online: http://www.nap.edu.

NRC, 2013. *Transitions to Alternative Vehicles and Fuels*. The National Academies Press, Washington DC: National Academy of Sciences and the U.S. Department of Energy. Available online: http://www.nap.edu.

Neubauer, J., A. Pesaran, A. Brooker, E. Wood, K. Smith, C. Johnson, and M. Mendelsohn. 2012. "Applying the Battery Ownership Model in Pursuit of Optimal Battery Use Strategies," presented at Vehicle Technologies Program (VTP) Annual Merit Review (AMR), May 14-18 2012, Washington, DC. NREL/PR-5400-54424. Available online: http://www.nrel.gov/transportation/energystorage/pdfs/54424.pdf.

Neubauer, J. and E. Wood. 2014. "Thru-life impacts of driver aggression, climate, cabin thermal management, and battery thermal management on battery electric vehicle utility." *Journal of Power Sources* 259: 262-275. http://dx.doi.org/10.1016/j.jpowsour.2014.02.083.

NREL. 2015. National Solar Radiation Data Base of Typical Meteorological Years, third edition, TMY3. Available online: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

Nykvist, B., and M. Nilsson, 2015. "Rapidly falling costs of battery packs for electric vehicles." *Nature Climate Change* 5 (March): 329-332. doi: 10.1038/NCLIMATE2564.

Ogden, J., L. Fulton, D. Sperling. 2016. "Making the Transition to Light-duty Electric-drive Vehicles in the U.S.: Costs in Perspective, Sustainable Transportation Energy Pathways," University of California at Davis, Institute for Transportation Studies, *forthcoming*.

Ottman, J.A., E.R. Stafford and C.L. Hartman. 2006. "Avoiding Green Marketing Myopia: Ways to Improve Consumer Appeal for Environmentally Preferable Products." *Environment: Science and Policy for Sustainable Development* 48 (5): 22-36. doi: 10.3200/ENVT.48.5.22-36.

Paltsev, Sergey. 2016. *Energy Scenarios: The Value and Limits of Scenario Analysis*. MIT Center for Energy and Environmental Policy Research, report number CEEPR WP 2016-007, April, available online: http://ceepr.mit.edu/files/papers/2016-007.pdf.

RMI. 2014. "Pulling Back the Veil on EV Charging Station Costs." Outlet: Plug Into New Ideas, Rocky Mountain Institute, April 29, available online: http://blog.rmi.org/blog_2014_04_29_pulling_back_the_veil_on_ev_charging_station_costs.

SAE J2841. 2010. Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data. Available online: http://standards.sae.org/j2841_201009/.

Shepherd, A., P. Bonsall, and G. Harrison. 2012. "Factors Affecting Future Demand for Electric Vehicles: a Model Based Study." *Transport Policy* 20: 62–74. doi:10.1016/j.tranpol.2011.12.006.

Short, W., P. Sullivan, T. Mai, M. Mowers, C. Uriarte, N. Blair, D. Heimiller, and A. Martinez. 2011. *Regional Energy Deployment System (ReEDS)*, NREL/TP-6A20-46534, Golden, CO: National Renewable Energy Laboratory.

Sigrin B., M. Gleason, R. Preus, I. Baring-Gould, and R. Margolis. 2016. *The Distributed Generation Market Demand Model (dGen): Documentation*. NREL/TP-6A20-65231. Golden, CO: National Renewable Energy Laboratory.

Singer, Mark. 2016. *Consumer Views on Plug-in Electric Vehicles - National Benchmark Report*. NREL/TP-5400-65279. National Renewable Energy Laboratory.

Small, K. and K.V. Dender, 2007. "If Cars Were More Efficient Would We Use Less Fuel?" Access, University of California Transportation Center, University of California, October 1, available online: https://escholarship.org/uc/item/88b6n96c.

Smart, J., T. Bradley, and S. Salisbury. 2015. "Actual Versus Estimated Utility Factor of a Large Set of Privately Owned Chevrolet Volts." Idaho National Lab and Colorado State University. Available online: http://avt.inel.gov/pdf/EVProj/EVProjectUtilityFactorVolt.pdf.

Stephens, T.S, et al. 2016. Comparison of Vehicle Choice Models, Argonne National Laboratory, forthcoming.

Struben, J. and J. Sterman. 2008. "Transition Challenges for Alternative Fuel Vehicle and Transportation Systems." *Environment and Planning B: Planning and Design* 35 (6): 1070-1097.

Sullivan P., W. Cole, N. Blair, E. Lantz, V. Krishnan, T. Mai, D. Mulcahy and G. Porro. 2015. *2015 Standard Scenarios Annual Report: U.S. Electric Sector Scenario Exploration*. NREL/TP-6A20-64072. Golden, CO: National Renewable Energy Laboratory.

Vlasic, B. 2016. "Automakers Go Electric, Even if Gas is Cheap." New York Times, Jan 11, 2016. Available online: http://www.nytimes.com/2016/01/12/business/going-electric-even-if-gas-is-cheap.html.

Wack, Pierre. 1985. "Scenarios: uncharted waters ahead." Harvard Business Review, September-October. Available online: https://hbr.org/1985/09/scenarios-uncharted-waters-ahead.

Ward, J. 2008. "VISION 2008 User's Guide." ANL-08/34. Argonne National Laboratory, Energy Systems Division. Available online: http://www.npc.org/LDV/VISION_2008_Users_Guide.pdf.

Weis, A., J. Michalek, P. Jaramillo, and R. Lueken. 2015. "Emissions and Cost Implications of Controlled Electric Vehicle Charging in the U.S. PJM Interconnection." *Environmental Science and Technology* 49: 5813-5819.

WHOPS. 2016. "FACT SHEET: Obama Administration Announces Federal and Private Sector Actions to Accelerate Electric Vehicle Adoption in the United States." White House, Office of the Press Secretary, July 21. Available online: https://www.whitehouse.gov/the-press-office/2016/07/21/fact-sheet-obama-administration-announces-federal-and-private-sector.

Wood, E., J. Gonder, S. Lopp and F. Jehlik. 2015. "Simulated Real-World Energy Impacts of a Thermally Sensitive Powertrain Considering Viscous Losses and Enrichment." Presented at the Society of Automotive Engineering World Congress and Exhibition, Detroit, Michigan, April 21-23. Available online: http://www.nrel.gov/docs/fy15osti/63255.pdf.

Yuksel, T. and J. Michalek. 2015. "Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States." *Environmental Science & Technology* 49 (6): 3974-3980.

Zhou, Y. and A. Vyas. 2014. *Vision Model description and users guide*. ANL/ESD-14/1. Oak Ridge, TN: Argonne National Lab. Available online: https://anl.app.box.com/s/1d14ylnk6ywxc3g7k3qz8qjocts2lx8x.