ELECTRIC POWER RESEARCH INSTITUTE

NRDC
THE EARTH'S BEST DEFENSE

Environmental Assessment of Plug-In Hybrid Electric Vehicles

Volume 1: Nationwide Greenhouse Gas Emissions

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Environmental Assessment of Plug-In Hybrid Electric Vehicles

Volume 1: Nationwide Greenhouse Gas Emissions

1015325

Final Report, July 2007

"Each of the ... scenarios showed significant Greenhouse Gas reductions due to PHEV fleet penetration ...

... PHEVs adoption results in significant reduction in the consumption of petroleum fuels."

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electric Power Research Institute
Natural Resources Defense Council
Charles Clark Group

NOTE

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ELECTRIC POWER RESEARCH INSTITUTE

NRDC
THE EARTH'S BEST DEFENSE

Executive Summary

Environmental Assessment of Plug-In Hybrid Electric Vehicles

Volume 1: Nationwide Greenhouse Gas Emissions

Environmental Assessment of Plug-in Hybrid Electric Vehicles

In the most comprehensive environmental assessment of electric transportation to date, the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) are examining the greenhouse gas emissions and air quality impacts of plug-in hybrid electric vehicles (PHEV). The purpose of the program is to evaluate the nationwide environmental impacts of potentially large numbers of PHEVs over a time period of 2010 to 2050. The year 2010 is assumed to be the first year PHEVs would become available in the U.S. market, while 2050 would allow the technology sufficient time to fully penetrate the U.S. vehicle fleet.

A Collaborative Study

The objectives of this study are the following:

- Understand the impact of widespread PHEV adoption on full fuel-cycle greenhouse gas emissions from the nationwide vehicle fleet.
- Model the impact of a high level of PHEV adoption on nationwide air quality.
- Develop a consistent analysis methodology for scientific determination of the environmental impact of future vehicle technology and electric sector scenarios.

NRDC and EPRI collaborated to conduct this eighteen-month study. The scenarios and key study parameters were generated, analyzed, and approved by both organizations. NRDC contributed its substantial experience in wide-ranging environmental studies, EPRI its operating knowledge of the electric sector and prior simulation and modeling work on plug-in hybrids[1]. Both organizations analyzed, reviewed, and approved of the resulting data and report findings.

Two Study Components, Two Reports

Phase 1 of the study, completed in July 2007, has two major components. The first is a scenario-based modeling analysis to determine the greenhouse gas emissions impacts of PHEVs over a timeframe of 2010 to 2050. The second component is a nationwide air quality analysis for the year 2030 that assumes an aggressive market penetration of PHEVs.

The methodology and findings of these two analyses are presented separately in two technical reports:

- Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions (1015325)

[1] Initial study data on PHEV performance characteristics and on future power plant technology availability and performance were drawn from prior EPRI work.

- Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030 (1015326)

PHEV Impact on Nationwide Greenhouse Gas Emissions

Overview of Study and Results

This report describes the first detailed, nationwide analysis of greenhouse gas (GHG) impacts of plug-in hybrid electric vehicles. The "well-to-wheels" analysis accounted for emissions from the generation of electricity to charge PHEV batteries and from the production, distribution and consumption of gasoline and diesel motor fuels.

Researchers used detailed models of the U.S. electric and transportation sectors and created a series of scenarios to examine assumed changes in both sectors over the 2010 to 2050 timeframe of the study.

- Three scenarios represent high, medium, and low levels of both CO_2 and total GHG[2] emissions intensity for the electric sector as determined by the mix of generating technologies and other factors.
- Three scenarios represent high, medium, and low penetration of PHEVs in the 2010 to 2050 timeframe.

From these two sets of scenarios emerge nine different outcomes spanning the potential long-term GHG emissions impacts of PHEVs, as shown in the following table.

Annual greenhouse gas emissions reductions from PHEVs in the year 2050.

2050 Annual GHG Reduction (million metric tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

Researchers drew the following conclusions from the modeling exercises:

- Annual and cumulative GHG emissions are reduced significantly across each of the nine scenario combinations.
- Annual GHG emissions reductions were significant in every scenario combination of the study, reaching a maximum reduction of 612 million metric tons in 2050 (High PHEV fleet penetration, Low electric sector CO_2 intensity case).
- Cumulative GHG emissions reductions from 2010 to 2050 can range from 3.4 to 10.3 billion metric tons.
- Each region of the country will yield reductions in GHG emissions.

More detailed results are presented below and in Chapter 5 of this report.

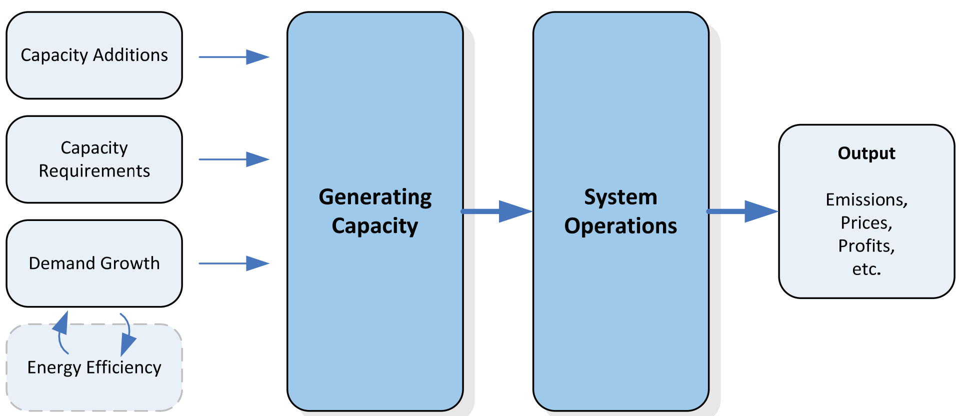
2 CO_2 is the dominant greenhouse gas resulting from operation of natural gas and coal-fired power plants. Full fuel cycle GHG emissions include N_2O and CH_4, primarily from upstream processes related to the production and transport of the fuel source.

Study Methodology

The project team developed detailed and comprehensive models of the U.S. electric and transportation sectors that simulated the evolution of both sectors over the 2010 to 2050 study timeframe. The researchers also developed a series of scenarios to assess the impact of PHEVs over a range of different possible futures depending on the evolution of the energy and transportation sectors.

Electric Sector Model

To determine the GHG emissions from the electricity generated to charge PHEV batteries, EPRI developed a modeling framework that provides a detailed simulation of the electric sector. The EPRI framework integrates two sophisticated computer models. The first model, the Energy Information Agency's National Energy Modeling System (NEMS) covers the entire U.S. energy-economy system and calculates energy supply and demand nationwide. NEMS outputs—prices and electric loads—are the inputs to the second model, the EPRI National Electric System Simulation Integrated Evaluator (NESSIE). The NESSIE model represents the U.S. electricity sector from 2010 to 2050.



Structure of U.S. Electric Sector Model (NESSIE)

The model simulates decisions to add new capacity and to retire existing capacity. This component is extremely important for tracking the evolution of the generation capacity over time as it serves existing load and new load from PHEV charging. New generating capacity is generally lower in GHG emissions than existing capacity. Capacity retirements increase the rate at which newer, lower emitting capacity is created. In addition, NESSIE simulates how technologies change over time, including gradual performance improvements for commercially available technologies such as combustion turbines or the emergence of advanced technologies such as Integrated Gasification Combined Cycle (IGCC) coal plants. Technology improvement is an important factor for reducing the GHG intensity of the future electric grid.

After simulating capacity additions and retirements, the model operates this capacity to meet electricity demand. Electric sector analysts call this a "production simulation" or "dispatch." The load varies across the year. Each generating technology has a bid price for energy that it offers to the market based on its variable cost of production. The market selects the lowest possible bids. The price for all operating generators is set by the technology with the highest bid price that is operating at the time. This production simulation identifies the load served by every technology, cost of electricity, and emissions of SO_2, NOx, Hg, and GHG.

The electric sector model of the United States is divided into 13 distinct study regions based on the North American Electric Reliability Corporation (NERC) Regional Reliability Councils and Federal Energy Regulatory Commission (FERC) regions. The representation of these regions allows a careful accounting of how different regional capacity mixes affect GHG emissions.

Electric Sector Scenarios

The future of the U.S. electric sector may follow different paths, depending on the evolution of environmental policies, electricity demand, and available technologies. Rather than trying to develop a single consensus view, the team created three scenarios to span the impact of PHEVs over different possible futures.

The scenarios represent different levels of CO_2 intensity for the sector.

1. High CO_2 intensity scenario: There is limited availability of higher efficiency and non-emitting generation technologies and a low cost associated with allowances to emit CO_2 and other GHGs in this scenario. Total annual electric sector GHG emissions increase by 25% from 2010 to 2050.
2. Medium CO_2 intensity scenario: Advanced renewable and non-emitting generation technologies, such as biomass and IGCC with carbon capture and storage, are available in this scenario. There is a moderate cost associated with allowances to emit CO_2 and other GHGs. Total annual electric sector emissions decline by 41% between 2010 and 2050.
3. Low CO_2 scenario: Carbon capture and storage retrofit technology for existing coal plants are available in this scenario. In addition, there is significantly slower load growth indicative of a nationwide adoption of energy efficiency, or other demand reduction, and a high cost to emit CO_2 and other GHGs. Total electric sector emissions decline by 85% in this scenario from 2010 to 2050.

The NESSIE model was used to model each of the above scenarios and to output the detailed results. Each scenario used a different set of input data and was run through the entire model to produce the measures of interest. The following table shows the key differences among electric sector scenarios.

Key parameters of the High, Medium, and Low CO_2 Intensity electric scenarios.

Scenario Definition	High CO_2 Intensity	Medium CO_2 Intensity	Low CO_2 Intensity
Price of Greenhouse Gas Emission Allowances	Low	Moderate	High
Power Plant Retirements	Slower	Normal	Faster
New Generation Technologies	Unavailable: Coal with CCS New Nuclear New Biomass	Available: IGCC Coal with CCS New Nuclear New Biomass Advanced Renewables	Available: Retrofit of CCS to Existing IGCC and PC Plants
	Lower Performance: SCPC, CCNG, GT, Wind, and Solar	Nominal EPRI Performance Assumptions	Higher Performance: Wind and Solar
Annual Electricity Demand Growth	1.56% per year on average	1.56% per year on average	2010-2025: 0.45% 2025-2050: None

PC – Pulverized Coal
SCPC – Supercritical Pulverized Coal
CCNG – Combined Cycle Natural Gas
GT – Gas Turbine (Natural Gas)
CCS – Carbon Capture and Storage

Vehicle Emissions Model

The vehicle emissions model represents the energy consumption and other performance attributes of three vehicle types: PHEVs, hybrid electric vehicles (HEVs), and conventional vehicles (CV) powered by internal combustion engines. The model also represents the penetration rate of each configuration across multiple vehicle categories (passenger cars to light trucks) throughout the 48 continental United States over the 2010-2050 timeframe.

The study assumes that PHEVs will be available in vehicles up to 19,500 lb gross vehicle weight (Class 5 Heavy Duty Vehicles). PHEVs will also be available in configurations offering different levels of electric range—the number of miles a vehicle can travel on the energy in its battery for a single charge. A vehicle's electric range is denoted by attaching the electric range after the term PHEV. For example, a PHEV 10 is a plug-in hybrid with 10 miles of electric range.

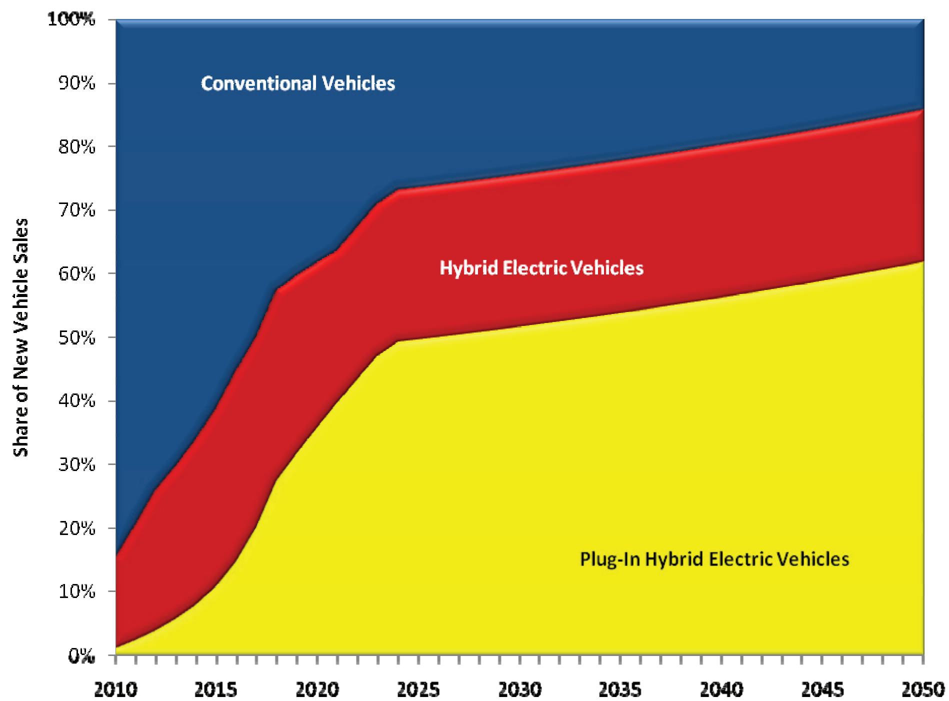
The use of electricity is an important attribute of PHEVs. Use of electricity reduces both gasoline consumption and emissions—starting emissions, refueling emissions, running emissions and even upstream refinery emissions.

Market Adoption

The project team developed three distinct market adoption scenarios, each based on PHEVs entering the market in 2010 and achieving maximum new vehicle market share in 2050. As shown in the following table, PHEVs reach a maximum of 20% new vehicle market share in the Low PHEV scenario, 62% in the Medium PHEV scenario, and 80% in the High PHEV scenario.

Peak new vehicle market share in 2050 for the three PHEV adoption scenarios

2050 New Vehicle Market Share by Scenario		Vehicle Type		
		Conventional	Hybrid	Plug-In Hybrid
PHEV Fleet Penetration Scenario	Low PHEV Fleet Penetration	56%	24%	20%
	Medium PHEV Fleet Penetration	14%	24%	62%
	High PHEV Fleet Penetration	5%	15%	80%

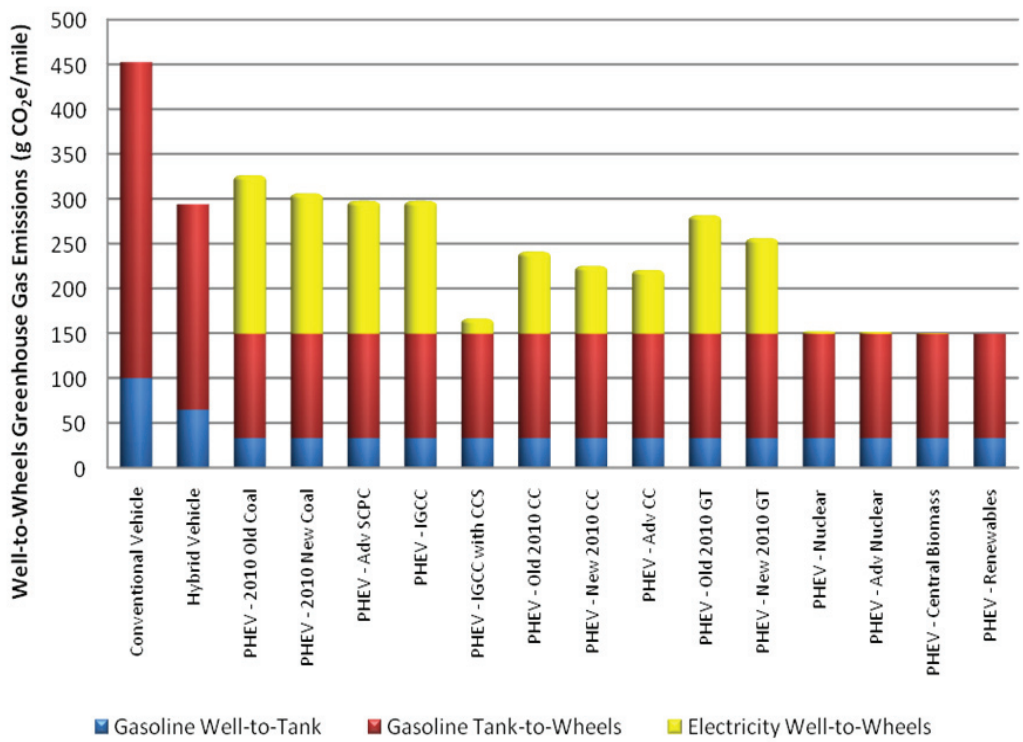


Assumed new car market share for the Medium PHEV scenario for conventional vehicles, hybrid electric vehicles, and plug-in hybrid electric vehicles for each vehicle category

Results

Emissions Decline as Electric and Transportation Sectors Evolve

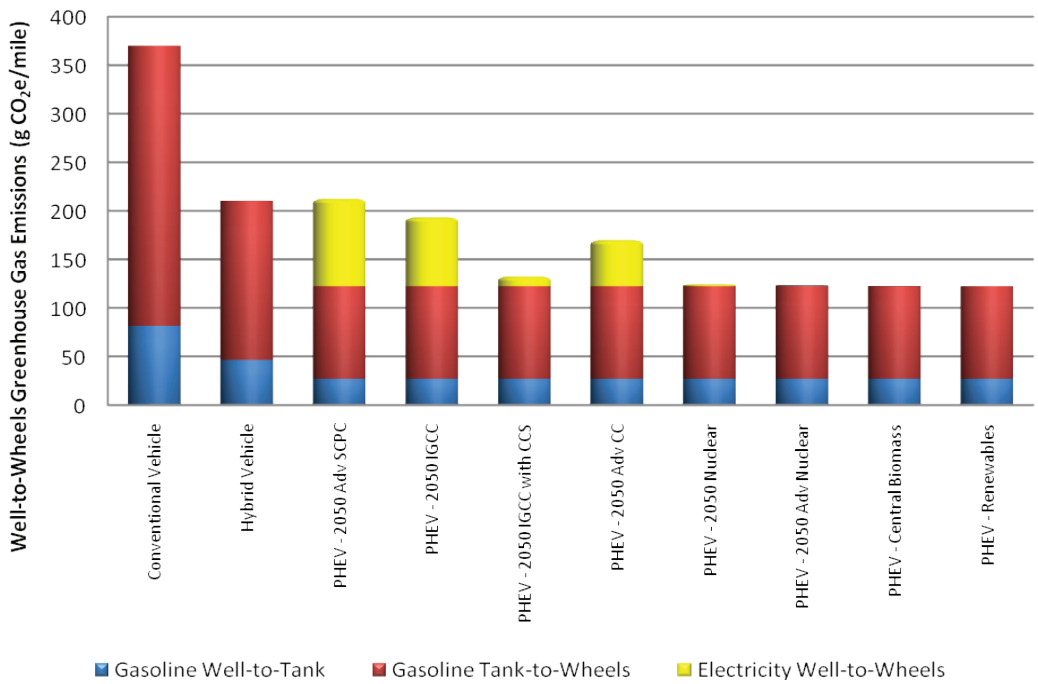
The study generated a wealth of information that enables researchers to examine the GHG emissions impacts of different vehicle categories and generating technologies over time. The following figure is a year 2010 comparison of total GHG emissions from conventional vehicles, hybrid electric vehicles, and a PHEV with 20 miles of all-electric range for a typical case of 12,000 miles driven per year. For PHEVs, the figure includes GHG emissions associated with all-electric and hybrid-electric operation.



Year 2010 comparison of PHEV 20 GHG emissions when charged entirely with electricity from specific power plant technologies (12,000 miles driven per year).

From this figure, it is clear that the carbon intensity of the generation technology plays a significant role in the total GHG emissions from PHEVs. In 2010, current coal technologies result in 28% to 34% lower GHG emissions compared to the conventional vehicle and 1% to 11% higher GHG emissions compared to the hybrid electric vehicle.

In year 2050, however, GHG emissions fall as higher emitting technologies are assumed to phase out of the electric generating fleet. In 2050, vehicle efficiency has improved, so all three components of well-to-wheel GHG emissions are lower. The PHEV 20 produces approximately the same GHG emissions as an HEV if powered by electricity from coal-fired power plants that do not capture CO_2, and has 37% lower GHG emissions than the HEV if powered by coal-fired power plants with CO_2 capture and storage.



Year 2050 comparison of PHEV 20 GHG emissions charged entirely with electricity from specific power plant technologies (12,000 miles driven per year)

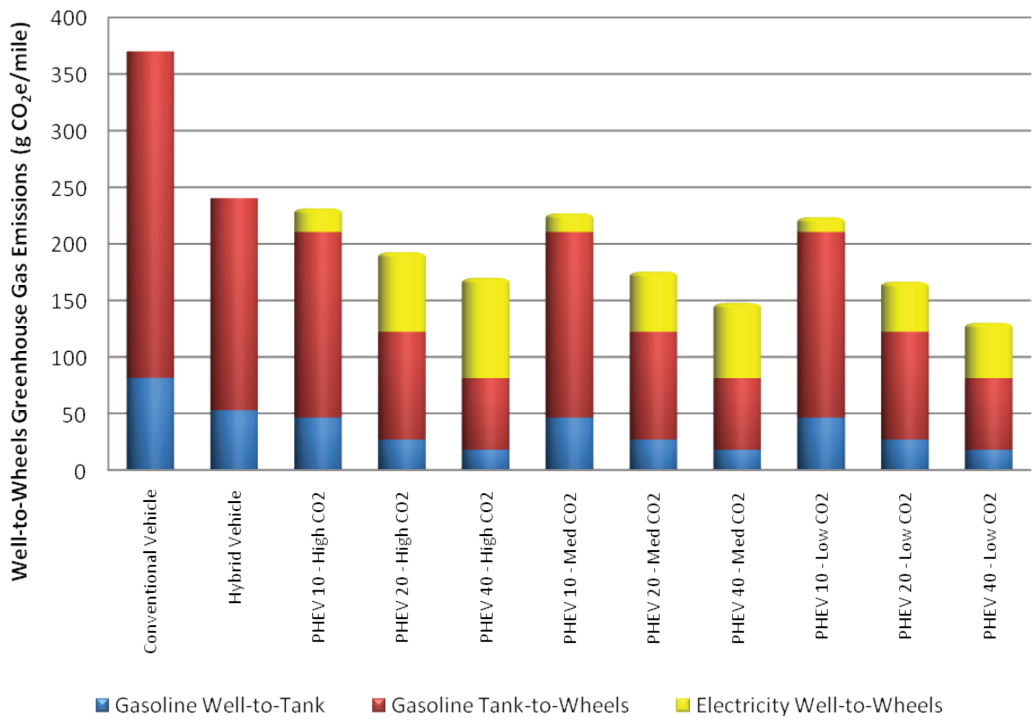
Electric Sector Simulation Results

The preceding examples show the strong dependence of PHEV GHG emissions on the source of electricity. In reality, PHEVs will not be drawing power solely from individual generating technologies but rather from a mix of resources that include fossil, nuclear, hydroelectric and renewable technologies.

Total system emissions from a given level of PHEV use will be determined by a combination of the vehicle type (PHEV with a 10, 20 or 40 miles of electric range), annual vehicle miles traveled by vehicle type, and the types of generating resources that are built and dispatched to serve the electrical load from grid-connected PHEVs.

The following figure compares GHG emissions of model year 2050 conventional and hybrid vehicles to the three PHEV types (10, 20 and 40 miles of electric range) in each of the three electric sector scenarios (High CO_2, Medium CO_2, and Low CO_2 Intensity).

PHEVs have lower GHG emissions in all nine cases than either the conventional or the hybrid vehicles, ranging from a 40% to 65% improvement over the conventional vehicle to a 7% to 46% improvement over the hybrid electric vehicle.



Year 2050 comparison of PHEV GHG emissions from within the High CO_2, Medium CO_2, and Low CO_2 Intensity electric sector scenarios (12,000 miles driven per year)

EPRI Perspective

This report describes a study to explore the air quality impacts of large numbers of plug-in hybrid electric vehicles (PHEVs) in year 2030 using a combination of transportation-sector, electric-sector and atmospheric (air quality) models.

PHEVs represent an important technical step toward increased fuel efficiency, decreased emissions, and greater energy independence. EPRI has supported the development of PHEV technology and continues to support its deployment with collaborative R&D and analyses.

Policymakers, technology developers, and utility and environmental planners need objective and accurate information to make sound decisions about developing and deploying PHEVs in support of national energy and environmental policy. PHEVs offer the potential for reducing both emissions and fuel consumption, simultaneously addressing the issues of global warming and the nation's dependence on imported oil. Quantifying these benefits has proved challenging, however, and misinformation has circulated about the environmental performance of PHEVs.

The objective of this study was to evaluate the impact of PHEVs on key air quality parameters for a future-year scenario with substantial penetration of PHEVs in the U.S. light-duty vehicle fleet (passenger cars and light-trucks).

This study is one component of a comprehensive environmental assessment of PHEVs conducted in collaboration with the Natural Resources Defense Council (NRDC). A second component is a nationwide analysis of the nationwide impacts on air quality of a large PHEV fleet in the year 2030. Results of the air quality analysis are presented in an EPRI technical report, Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030 (1015326).

Study findings will help support informed decision-making regarding PHEV development and deployment in support of national energy and environmental policy. Study results will also dispel misunderstandings about PHEVs and emissions—such as the common misunderstanding that PHEVs would worsen air quality due to emissions from electricity generation for battery charging.

NRDC Perspective

The Natural Resources Defense Council's purpose is to safeguard the Earth: its people, its plants and animals and the natural systems on which all life depends. The organization uses law, science, and the support of its members to promote solutions to our environmental challenges.

- Participation in this study does not imply NRDC endorses the power plant emission control assumptions in the air quality report. The study's air quality modeling and analysis are based on an assumption that regulatory caps govern NOx, SO_2 and mercury emissions during the study period, and that EPA rules do not change during the study time horizon. However, the actual situation is more complex—for example, a number of states have declined to participate in EPA's model cap-and-trade rule for mercury in favor of more stringent approaches. In addition, EPA's Clean Air Mercury Rule and Clean Air Interstate Rule (resulting in tighter NOx and SO_2 caps in the eastern U.S.) are currently being challenged in court. NRDC firmly believes that stronger emissions controls are necessary to protect human health. This study does not attempt to determine the adequate level of power plant controls or adequate levels of ambient air pollution and strives only to determine the specific impacts of large-scale PHEV penetration given the assumptions of the study.
- NRDC does not support trading off pollution benefits in some regions for pollution increases in others regions. NRDC believes that no areas or populations should be allowed to experience increases in air pollution exposures and that further emission controls from all sources are needed in order to protect public health. Consequently, NRDC supports more stringent emissions control requirements for the electric and transportation sectors, as well as other economic sectors.
- NRDC does believe that with sufficient emissions controls in place PHEVs have the potential to improve air quality and to substantially contribute to meeting our long term GHG reduction goals of 80% below 1990 levels by 2050.
- NRDC supports the introduction of PHEVs accompanied by substantial additional improvements in power plant emission rates. In areas where there are potential adverse impacts from air pollution as a result of PHEV charging, NRDC believes it is not appropriate to promote introduction until the public can be assured that air pollution will not increase.

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Contents

List of Figures

ELECTRIC POWER RESEARCH INSTITUTE

List of Tables

1 Introduction

National interest in electric transportation, particularly plug-in hybrid electric vehicles (PHEVs), has increased dramatically. In addition to near-daily media exposure and the strong support of scientists, politicians, and other prominent figures, PHEVs are now receiving very strong support from the federal government. The Energy Policy Act of 2005 contained language supporting PHEVs and directed the Department of Energy to initiate the formation of PHEV research and development effort under the FreedomCAR and Vehicle Technologies Program. PHEVs were also featured prominently as one of four strategic technologies for the reduction of U.S. petroleum dependence in the Advanced Energy Initiative developed by the National Economic Council. Major automobile manufacturers have earmarked PHEV development as part of a strategy to develop alternate fuel vehicle options.

Much of this interest is based on the potential societal benefits of electrifying transportation in general, and PHEVs in particular, including:

- A reduction in petroleum consumption leading to reduced dependence on imported oil and increased energy security;
- A net reduction in greenhouse gas emissions due to the electrification of transportation; and
- The potential to improve air quality, particularly in urban areas with high levels of vehicle-related pollution.

Environmental Assessment of Plug-In Hybrid Electric Vehicles

This study was conducted by the Natural Resources Defense Council (NRDC) and the Electric Power Research Institute (EPRI). The motivation for this study is to address critical and persistent knowledge gaps regarding the environmental impacts from the use of electricity as a transportation fuel, specifically:

- Net effect of PHEVs on vehicle fleet greenhouse gas emissions
- Impact of widespread use of electricity as a transportation fuel on air quality

These issues are separately addressed by two distinct reports:

Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions (1015325)

Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030 (1015326)

The objectives of this study are the following:

- Understand the impact of widespread PHEV adoption on full fuel-cycle greenhouse gas emissions from the nationwide vehicle fleet.
- Model the impact of a high level of PHEV adoption on nationwide air quality.
- Develop a consistent analysis methodology for scientific determination of the environmental impact of future vehicle technology and electric sector scenarios.

NRDC and EPRI collaborated to conduct this eighteen-month study. The scenarios and key study parameters were generated, analyzed, and approved by both organizations. NRDC contributed its substantial experience in wide-ranging environmental studies, EPRI its operating knowledge of the electric sector and prior simulation and modeling work on plug-in hybrids[1]. Both organizations analyzed, reviewed, and approved of the resulting data and report findings.

Plug-In Hybrid Electric Vehicles

Plug-in hybrid electric vehicles combine operational aspects of both battery electric vehicles (BEVs) and power-assist hybrid electric vehicles (HEVs). A PHEV, like a BEV, can be recharged from the electric grid, stores significant energy in an onboard battery, and then uses this energy, depleting the battery, during daily driving. Unlike a BEV, a PHEV has an internal combustion engine that is also used for propulsion, therefore never suffering from a "dead" battery. Due to this versatility, a PHEV can serve as a direct replacement for a conventional internal combustion engine vehicle (ICEV or CV) or HEV.

The potential of PHEV technology is primarily due to their close technological kinship with hybrid vehicles. Hybrid vehicles with sophisticated, high-power traction drive systems, power electronics, and high-voltage systems are already in the marketplace. PHEVs leverage much of this existing technology foundation—the primary difference is the incorporation of an "energy" battery that allows the PHEV to directly use grid electricity for propulsion.

A number of significant environmental benefits accompany the use of grid electricity in a plug-in hybrid. Electricity is produced largely from diverse domestic resources, in contrast to the high level of dependence on imported petroleum in the transportation sector. PHEVs can reduce direct emissions at the vehicle, with positive implications for transportation-dense urban areas that suffer from poor air quality due to mobile-source emissions. PHEVs recharged by electricity produced by efficient combustion, non-emitting, or renewable generation technologies will emit significantly lower fuel-cycle greenhouse gas emissions than either conventional or hybrid vehicles.

Definition of Greenhouse Gas Emissions

Carbon dioxide (CO_2) is the dominant greenhouse gas emitted by the combustion of fossil fuels in electric generating units (EGUs) or internal combustion engines in automobiles. CO_2 is a stable product of combustion (along with water). There are two other components common in fuel combustion emissions that also exhibit a global warming potential: methane (CH_4) and nitrous oxide (N_2O). While typically emitted in trace amounts, both demonstrate many times the global warming potential of CO_2—a given mass of CH_4 has approximately 23 times the global warming impact as the equivalent mass of CO_2. For N_2O, the multiple is 296[2]. In this study, greenhouse gas emissions are always shown as "carbon dioxide equivalents", or CO_2e using the following formula:

$$CO_2e = CO_2 + 23 \times CH_4 + 296 \times N_2O$$

In this study, the terms *"greenhouse gas (GHG) emissions"* and *"CO_2e emissions"* are used interchangeably.

[1]Initial study data on PHEV performance characteristics and future power plant technology availability and performance were derived from EPRI based on prior studies.

[2]Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

2 Electric Sector Model

A detailed simulation of the electric sector is necessary to determine the emissions associated with the electricity used to charge PHEVs. This simulation must take into account the location and time of the increased load on the electric grid. EPRI has developed an electric sector model to calculate the GHG emissions of PHEV charging electricity (for a given fleet penetration timeline) in five year time steps on a 2010 to 2050 timeframe. This timeframe was chosen since PHEVs — as with any new automotive technology — would require several years to achieve significant fleet penetration.

Modeling Framework

Figure 2-1 shows a top level depiction of the models used to study GHG emissions from the electric sector. The modeling framework starts by running the Energy Information Agency's (EIA) National Energy Modeling System (NEMS)[3]. This model covers the economics of the entire U.S. energy system and calculates a supply and demand based on its inputs.

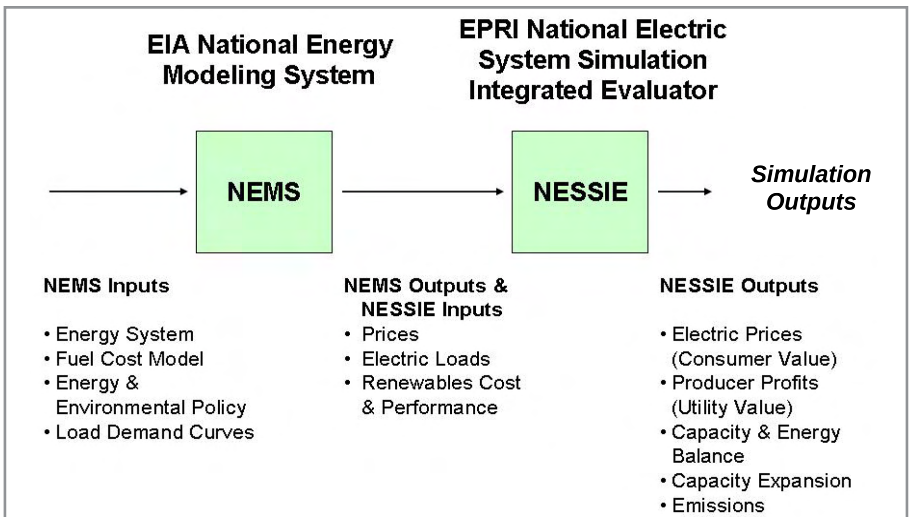

Figure 2-1
Input and Outputs of the Models Used to Calculate Grid CO_2e Impacts

The role of NEMS is to incorporate nationwide information on the U.S. energy system and to output relevant data required for electric sector modeling. This includes estimating the future prices of fuels and emissions allowances, based on demand as well as energy and environmental policies. Electricity load demand curves dictate the quantity of electrical energy required for delivery by the electric sector over time.

[3] *The National Energy Modeling System: An Overview 2003.* Energy Information Administration, Washington D.C., DOE/EIA-0581 (2003).

The EPRI National Electric System Simulation Integrated Evaluator (NESSIE) modeling framework used is a representation of the U.S. electric sector.[4, 5,6] In this study, both NEMS and NESSIE are run in five-year time steps from 2010 to 2050.

The basic model structure is shown below in **Figure 2-2**. The analysis tracks the evolution of the electric system over time, particularly important for the PHEV technology that will take a significant amount of time to alter the on-the-road fleet through new vehicle sales.

Varying Electrical Demand

The model requires an estimate of the demand for electricity as an input, which is supplied by NEMS. The demand received from NEMS can be altered by changes in customer loads. This is denoted by the energy efficiency box in Figure 2-2.

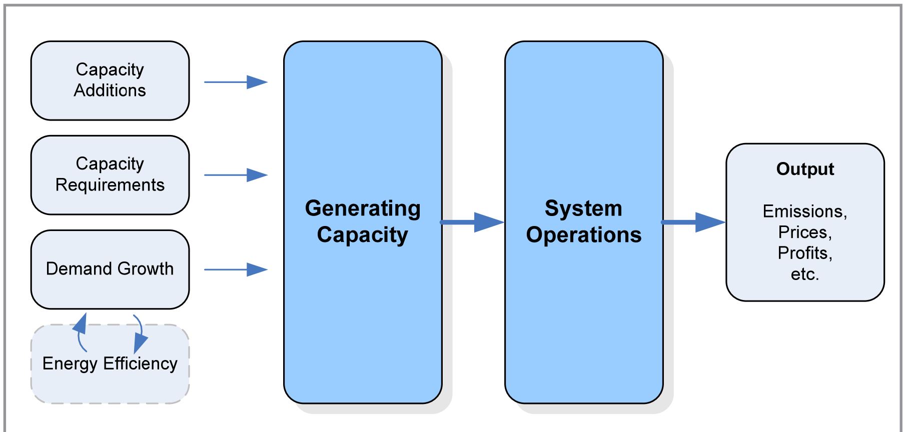

Figure 2-2
Structure of U.S. Electric Sector Model (NESSIE)

Modeling different PHEV market penetration scenarios has the effect of altering demand by increasing customer loads. This incremental load requires a specification of its timing so that it can augment the NEMS load. This allows the NESSIE model to track the impact of the new load on system energy and capacity needs as well as allowing delineation of the generating units that will serve the loads.

Marginal Modeling

A "marginal" or incremental modeling approach is used to forecast the GHG emissions that result from the PHEV scenarios. The purpose of this modeling is to determine specific changes that occur in both the evolution of electric sector capacity and how this capacity is dispatched to serve the new load represented by the charging of PHEVs. The marginal results from NESSIE output are more useful in determining the specific impacts of PHEV charging to the electric grid.

[4] *Evaluating the Potential Effects of Environmental Regulation and Other Variables on Future Non-Emitting Generation Profitability.* Palo Alto, CA: 1007732.
[5] *Preliminary Analysis of the Role of Nuclear Power in Achieving a Sustainable Electric System.* Palo Alto, CA: 1011513.
[6] *Program on Technology Innovation: Analysis of the Role of Nuclear Power in Achieving a Sustainable Electric System.* Palo Alto, CA: 1011772.

Capacity Retirement and Expansion

The model simulates decision-making within the electric sector to add new capacity and to retire existing capacity. This component is extremely important for tracking the evolution of the generation capacity over time as it serves existing load and new load from PHEV charging. New capacity that is added over the model time horizon is generally lower in GHG emissions than the current generating capacity. Capacity retirements increase the rate at which newer, lower emitting capacity is created. In addition, NESSIE simulates how technologies change over time, including gradual performance improvements for commercially available technologies such as combustion turbines or the emergence of advanced technologies such as Integrated Gasification Combined Cycle (IGCC) coal plants. Technology improvement is an important factor for reducing the GHG intensity of the future electric grid.

In the model, decision-making algorithms simulated capacity choices from among the alternative generation technologies based on their costs, which represent additional model inputs. The costs cover all of the cash flows that occur over the operating life of the technology, including those for capital costs and all commodities. Commodities include fuel and allowances for SO_2, NOx, Hg, and CO_2 emissions. The prices for these emissions allowances are also sensitive to the quantities of emissions, through an elasticity of supply. All cash flows are present valued to startup and divided by the plant output to produce a $/MWh measure that may be compared across technologies. Thus, technologies with higher capital costs and lower operating costs can compete with options having lower capital costs and higher operating costs. The model also recognizes three duty cycles—baseload, intermediate, and peaking service—so that the chosen capacity mix reflects the different economics of the different cycles.

Dispatch Modeling

After simulating the capacity additions and retirements, the model operates this capacity to meet the electricity demand. Electric sector analysts call this a "production simulation" or "dispatch modeling." The load varies across the year. The capacity available to serve the load depends on both planned (maintenance) and unplanned (forced) outages. Since forced outages are random, the model solves for system operations with several different available capacities, and it combines these results using the likelihood of each capacity state. Each technology has a bid price for energy that it offers to the market based on its variable cost of production. The market selects the lowest possible bids. The price for all operating generators is set by the technology with the highest bid price that is operating at the time. This production simulation identifies the load served by every technology, cost of electricity, and emissions of SO_2, NOx, Hg, and GHG.

The electric sector model of the United States is divided into thirteen distinct study regions based on the North American Electric Reliability Corporation (NERC) Regional Reliability Councils and Federal Energy Regulatory Commission (FERC) regions. The members of these Regional Reliability Councils comprise all segments of the electric industry, including investor-owned utilities; public utilities; federal power agencies; rural electric cooperatives; and independent power producers and marketers. The existence of the regions allows a careful accounting of how different regional capacity mixes affect GHG emissions and presents the opportunity to make some preliminary comments on the regional GHG impacts of the PHEV.

Power Plant Technologies

The power plant technologies used in NESSIE are an important determinant in electric sector carbon intensity. In this study NESSIE incorporates eighteen different generation technologies. Fourteen technologies are thermal plants based on coal, natural gas, oil, nuclear power, and biomass. There are additional renewable technologies based on geothermal, wind, solar, and hydroelectric. The thermal technologies are defined below, and the heat rate and greenhouse gas emissions performance of each are listed in **Table 2-1**.

The cost, performance, and other characteristics of these generation technologies are derived from EPRI data and extensive experience with fossil, nuclear, and renewable generation technologies.[7] With respect to the performance of future technologies, the assumptions used in this report represent consensus industry and supplier views on the rate of improvement in plant technology.

Coal

- *Old 2010 Coal* – Older subcritical pulverized coal (PC) plants in operation in 2010. This technology has the highest emissions and operating and maintenance costs (O&M) of the PC plants.
- *New 2010 Coal* – Newer, slightly more efficient pulverized coal plants in operation in 2010.
- *Advanced SCPC* – More efficient, lower emitting, supercritical PC plants built in 2010 or later.
- *IGCC* – Integrated Gasification Combined Cycle coal plants built in 2010 or later, without carbon capture and storage (CCS).
- *IGCC with CCS* – Integrated Gasification Combined Cycle coal plants built in 2010 or later, with carbon capture and storage (CCS).

Natural Gas

- *Old 2010 CC* – Combined cycle natural gas plants in operation in 2010.
- *New 2010 CC* – New combined cycle natural gas plants in operation in 2010. Plant efficiency and O&M costs are significantly improved over Old 2010 CC.
- *Advanced CC* – Improved efficiency combined cycle plants built in 2010 or later.
- *Old 2010 GT* – Older gas turbine "peaking" plants in operation in 2010
- *New 2010 GT* – Newer, more efficient gas turbine peaking plants either in operation or built after 2010.

Oil/Gas

- *Oil/Gas Boiler* – Older gas-fired or oil-fired plants in operation in 2010. No further plants of this type are built in the future.

[7] *Role of Renewable Energy in Sustainable Electricity Generation Portfolios: Preliminary Results and Next Steps.* EPRI, Palo Alto, CA: 2007. 1012730.

Nuclear

- *Nuclear* – Existing light-water reactors of current generation of technology either in operation in 2010 or built during the study horizon.
- *Advanced Nuclear* – Next-generation nuclear plants built after 2010 with lower heat rate and improved O&M costs.

Biomass

- *Central Biomass* – Central station biomass plants either in operation in 2010 or built after 2010.

Other Renewable Generation

In addition to central biomass, other renewable technologies include geothermal, central station solar, wind, and hydroelectric generation. In this study all are considered non-emitting with respect to greenhouse gas emissions. The study also assumes zero marginal availability of new hydroelectric capacity.

Table 2-1
EPRI cost and performance data of thermal power plant technologies used by NESSIE. Plant heat rate and greenhouse gas emissions performance is shown in 2010 and 2050

Technology	Fuel Type	2010 Heat Rate (Btu/kWh)	2010 GHG Emissions (gCO_2e/kWh)	2050 Heat Rate (Btu/kWh)	2050 GHG Emissions (gCO_2e/kWh)
Old 2010 Coal	Coal	10,500	1,041	10,500	1,041
New 2010 Coal	Coal	9,300	922	9,300	922
Advanced Coal (SCPC)	Coal	8,800	872	6,539	649
IGCC	Coal	8,800	872	5,144	510
IGCC with CCS	Coal	11,300	100	8,292	73
Old 2010 CCNG	Natural Gas	9,000	538	9,000	538
New 2010 CCNG	Natural Gas	7,440	445	7,002	419
Advanced CCNG	Natural Gas	7,000	419	5,725	342
Old 2010 GT	Natural Gas	13,000	778	13,000	778
New 2010 GT	Natural Gas	10,500	628	8,109	485
Oil/Gas Boiler	Oil/Gas	9,800	586	9,800	586
Nuclear	Nuclear Fuel	10,000	15	9,004	14
Advanced Nuclear	Nuclear Fuel	8,000	12	7,004	11
Central Biomass	Biomass	12,200	3	9,013	2

SCPC Supercritical Pulverized Coal
CCNG Combined Cycle Natural Gas
GT Gas Turbine (Natural Gas)
CCS Carbon Capture and Storage

Technology Improvement in the Future

Power plant technology cost and performance improves over time. In certain technology categories plants built in out years are more efficient, less costly to build and operate, and produce fewer emissions. Capacity that either already exists in 2010 or is added in NESSIE has the characteristic performance of the year it was built for its entire operating life. Advanced coal, natural gas, nuclear, and biomass plants built after 2010 will demonstrate improved efficiency, shown in Table 2-1. The impact of technology improvement on greenhouse gas emissions is most evident with coal and natural gas plants as illustrated in **Figure 2-3**.

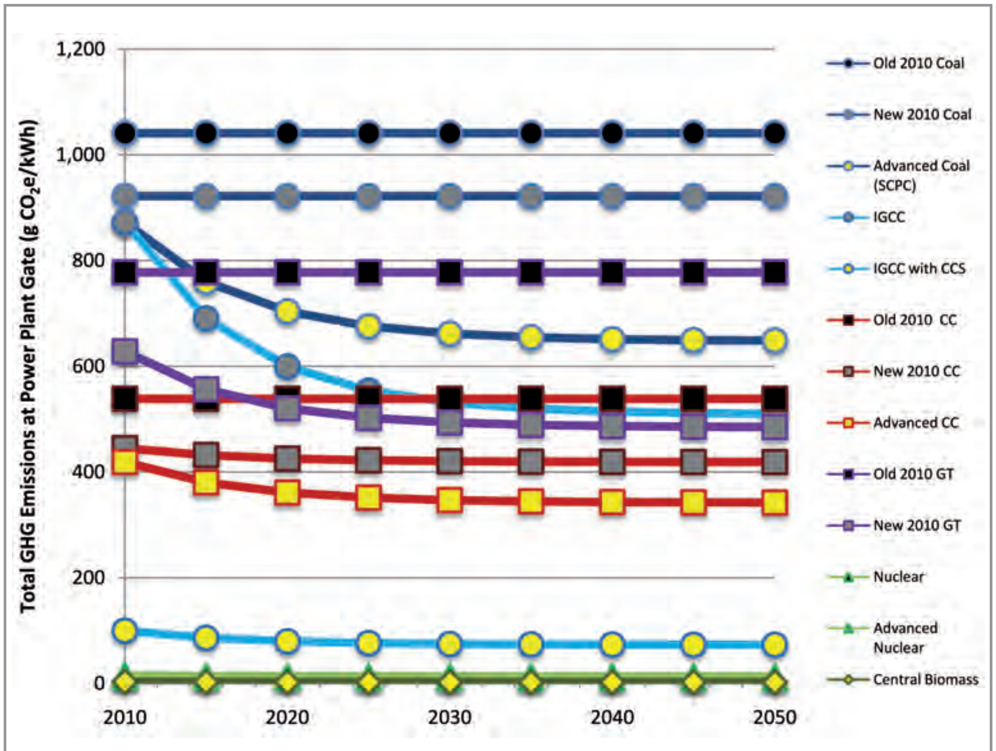

Figure 2-3
Evolution of greenhouse gas emissions intensity of different plant technologies between 2010 and 2050

3 Electric Sector Scenarios

The future of the U.S. electric sector may follow different paths. These paths would differ in such aspects as the environmental policies applied to its operations, the electricity demand that the sector serves, and the generating technologies that are available. Rather than trying to generate a single consensus view of the future, the team decided to produce scenarios that span the impact of the PHEV technology over many different futures.

EPRI and NRDC developed scenarios to represent three possible futures of the U.S. electric sector. The scenarios are distinguished by the following attributes:

1. Price of CO_2 emissions allowances.
2. Rate at which older power plants are retired.
3. Availability and performance on new generation technologies.
4. Annual growth in electricity demand.

These attributes are modified in each scenario to create different levels of carbon intensity in the different scenarios. The three scenarios are defined as:

1. High CO_2 intensity scenario: There is limited availability of higher efficiency and non-emitting generation technologies and a low cost associated with allowances to emit CO_2 in this scenario. Total annual electric sector CO_2 emissions increase by 25% from 2010 to 2050.
2. Medium CO_2 intensity scenario: Advanced renewable and non-emitting generation technologies, such as biomass and IGCC with carbon capture and storage, are available in this scenario. There is a moderate cost associated with allowances to emit CO_2. Total annual electric sector emissions decline by 41% between 2010 and 2050.
3. Low CO_2 intensity scenario: Similar to the medium CO_2 intensity scenario, with the addition of carbon capture and storage retrofit technology for existing coal plants. In addition, there is significantly slower load growth indicative of nationwide adoption of energy efficiency, or other demand reduction, and a higher cost to emit CO_2. Total electric sector emissions decline by 85% from 2010 to 2050 in this scenario.

The NESSIE model described in Chapter 2 was used to model each of the above scenarios and to output the detailed results. Each scenario used a different set of input data and was run through the entire model to produce the measures of interest.

Table 3-1 shows the key differences between each electric sector scenario that govern input data for each.

Table 3-1
Key parameters of the High, Medium, and Low CO_2 Intensity electric scenarios

Scenario Definition	High CO_2 Intensity	Medium CO_2 Intensity	Low CO_2 Intensity
Price of Greenhouse Gas Emission Allowances	Low	Moderate	High
Power Plant Retirements	Slower	Normal	Faster
New Generation Technologies	Unavailable: Coal with CCS New Nuclear New Biomass	Available: IGCC Coal with CCS New Nuclear New Biomass Advanced Renewables	Available: Retrofit of CCS to Existing IGCC and PC Plants
	Lower Performance: SCPC, CCNG, GT, Wind, and Solar	Nominal EPRI Performance Assumptions	Higher Performance: Wind and Solar
Annual Electricity Demand Growth	1.56% per year on average	1.56% per year on average	2010-2025: 0.45% 2025-2050: None

PC – Pulverized Coal
SCPC – Supercritical Pulverized Coal
CCNG – Combined Cycle Natural Gas
GT – Gas Turbine (Natural Gas)
CCS – Carbon Capture and Storage

Treatment of Greenhouse Gas Emissions

The NESSIE model accounts for all emissions related to the production of electricity, including greenhouse gases, by monetizing emissions allowances. These are model inputs generated either by assumption or by prior modeling work. In the case of greenhouse gases, a temporally varying value is given to CO_2e emissions allowances from CO_2, N_2O, and CH_4 emissions associated with fuel production, transport, and combustion.

For each electric sector scenario, a relationship of the value of GHG emissions versus time was determined by using NESSIE model runs to determine appropriate emission allowance values. The monetization of greenhouse gas emissions impacts both power plant capacity and dispatch decisions as it raises the cost of electricity produced from higher-emitting technologies.

It should be noted that the effect of the value of GHG emissions allowances is directly related to the specific characteristics of the electric system in each of the scenarios constructed for this study. The GHG emissions allowance values used are meaningful only to the narrow framework of this study and are not meant to represent the opinion, expectation, or recommendations of either EPRI or NRDC regarding the future value of CO_2 and other greenhouse gas emissions.

Capacity Retirement

Power plant capacity retirement is an important component of electric sector modeling. Older plants tend to have higher emissions and lower efficiency. Older power plant capacity is generally replaced by newer units with significantly better performance.

Coal and natural gas-fired capacity that exists in 2010 is gradually retired over time. Several factors determine the quantity and timing of the retirements. The age of the equipment influences the rate of retirement, with older equipment more likely to be shut down. Retirement is also based on economic decisions about the economic performance of capacity. A higher assumed cost for emitting GHGs erodes profitability of higher emitting plants. In addition the introduction of newer and lower variable cost generators further reduces the dispatch of existing higher-cost units.

The new technologies that replace retired units and serve new growth in demand also differ between the scenarios. The High CO_2 intensity emissions scenario assumes limited improvement from today's suite of options. In the Medium CO_2 intensity scenario, improved technologies are assumed to be deployed, such as Integrated Gasification Combined Cycle (IGCC), IGCC with CO_2 capture and storage (CCS), nuclear, and biomass. This scenario also assumes differences in the long-run efficiency (for thermal plants) and better wind and solar options. Finally, the Low CO_2 intensity scenario assumes some additional improvements in wind and solar. In addition, the scenario incorporates the retrofit of CCS to existing coal-fired power plants if the GHG allowance cost is high enough to make this a least-cost option for marginal emission reductions. There is one final change in the Low CO_2 intensity scenario: the demand growth is lower due to an assumed widespread deployment of energy-efficiency technologies that reduce electricity demand from the other scenarios.

Base Electric Sector Scenario Results

Table 3-2 shows some of the summary results for each of the electric sector CO_2 emission scenarios. As expected, both aggregate and annual GHG emissions vary significantly across the scenarios. In general, GHG intensity is significantly affected by capacity retirements, value of GHG allowances, electricity demand, and technology availability, cost, and performance. No single factor has a dominant impact on the GHG intensity of a given scenario. These results indicate that varying these key parameters is an effective strategy to create three distinctive future scenarios of the electric sector.

Table 3-2
Selected results from electric sector carbon emissions scenarios

Selected Results		Electric Sector CO_2 Emissions		
		High	Medium	Low
Cumulative CO_2e Emissions from 2010 to 2050 (billion metric tons)		116.3	89.4	60.4
Annual CO_2e Emissions in 2050 (billion metric tons)		3.25	1.57	0.45
Electric Sector Average CO_2e Intensity (g/kWh)	2010	573		
	2050	412	199	97

For comparison, the average CO_2 intensity of the electric sector in 2005 is 612 g/kWh.[8]

[8] Energy Information Administration, *Annual Energy Outlook 2006*.

4 Vehicle Emissions Model

There are two primary components to the vehicle emissions model:

1. Vehicle Characterization— Assumptions about the energy consumption and other performance attributes of a single plug-in hybrid electric vehicle.
2. Fleet Expansion — Assumptions about the penetration rate of the characterized vehicles (plug-in hybrid, hybrid, and conventional) across multiple vehicle categories, throughout the lower 48 states, over a time horizon of 2010 to 2050.

Vehicle Characterization

The first step in the process of developing nationwide fleet emissions is to determine the properties of the individual vehicles in the model. This study accounts for three different vehicle configurations:

1. Conventional vehicles (CV), powered by an internal combustion engine and using either gasoline or diesel fuel.
2. Hybrid electric vehicle (HEV), powered by a combination of internal combustion engine and electric drive system and using either gasoline or diesel fuel.
3. Plug-in hybrid electric vehicles (PHEV), powered by a combination of internal combustion engine and electric drive system and using electricity plus either gasoline or diesel vehicles. This report examines three different PHEV battery capacity assumptions: sufficient energy in the onboard battery system to power the vehicle from the battery alone for the equivalent of 10, 20, or 40 miles.

Data Sources

The development of the nationwide fleet emissions model relied on three primary data sources:

1. Prior EPRI analysis – *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* and *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedans and Sport Utility Vehicles.* These reports contain detailed modeling comparisons of conventional, hybrid, and plug-in hybrid vehicles of equivalent performance and capabilities.[9,10]
2. Mobile Source Emission Factor Model (MOBILE6) – MOBILE6 contains vehicle miles traveled (VMT) data for the entire lower 48 states and 28 different vehicle classifications. MOBILE6 also contains "real-world" fuel economy data per vehicle classification. This allowed adjustment of the energy consumption of each vehicle to be tailored to its vehicle category[11].
3. Emissions Factor Model (EMFAC) – EMFAC is a similar emissions model to MOBILE6 preferred by the state of California.[12]

In this study, MOBILE6 parameters are used to calculate vehicle energy consumption. EMFAC is used to determine fleetwide emissions and petroleum consumption in California, while MOBILE6 is used outside California.

[9]EPRI, 2001. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* EPRI, Palo Alto, CA: 2001. 1000349.
[10]EPRI, 2002. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedans and Sport Utility Vehicles*, EPRI, Palo Alto, CA: 2002. 1006892.
[11]*User's Guide to MOBILE6.1 and MOBILE6.2 Mobile Source Emission Factor Model,* U.S. EPA, EPA420-R-03-010. 2004.
[12]*Public Meeting to Consider Approval of Revisions to the State's On-Road Motor Vehicle Emissions Inventory*: *Technical Support Document*, California Air Resources Board, Sacramento, CA. May 2000.

Vehicle Model Inputs

MOBILE6 and EMFAC vehicle emission models use similar, but not identical categorizations of the vehicle fleet. EMFAC vehicle emissions have been correlated and added to the MOBILE6 data to provide a complete 48-state dataset.

Table 4-1 shows the 29 different vehicle categories in the MOBILE6 vehicle inventory. Vehicles are categorized by fuel (gasoline and diesel) and by Gross Vehicle Weight Rating (GVWR). In general, vehicle classifications that were eligible for PHEV market share were limited to those with GVWR of less than 19,500 lbs. Motorcycles, specific bus categories, and vehicles of greater than 19,500 lb GVWR were excluded. These classifications were excluded not because of their unsuitability for

Table 4-1
MOBILE6 Vehicle Classifications

Individual Vehicle Type	GVWR (lb)	Individual Vehicle Type – Description
LDGV	-	Light-Duty Gasoline Vehicles (Passenger Cars)
LDGT1	0-6000	Light-Duty Gasoline Trucks 1 (0-6,000 lb GVWR, 0-3750 lb LVW)
LDGT2	0-6001	Light Duty Gasoline Trucks 2 (0-6,001 lb GVWR, 3751-5750 lb LVW)
LDGT3	6001-8500	Light Duty Gasoline Trucks 3 (6,001-8500 lb GVWR, 0-3750 lb LVW)
LDGT4	6001-8500	Light Duty Gasoline Trucks 4 (6,001-8500 lb GVWR, 3751-5750 lb LVW)
HDGV2B	8501-10000	Class 2b Heavy Duty Gasoline Vehicles (8501-10,000 lb GVWR)
HDGV3	10001-14000	Class 3 Heavy Duty Gasoline Vehicles (10,001-14,000 lb GVWR)
HDGV4	14001-16000	Class 4 Heavy Duty Gasoline Vehicles (14,001-16,000 lb GVWR)
HDGV5	16001-19500	Class 5 Heavy Duty Gasoline Vehicles (16,001-19,500 lb GVWR)
HDGV6	19501-26000	Class 6 Heavy Duty Gasoline Vehicles (19,501-26,000 lb GVWR)
HDGV7	26001-33000	Class 7 Heavy Duty Gasoline Vehicles (26,001-33,000 lb GVWR)
HDGV8A	33001-60000	Class 8a Heavy Duty Gasoline Vehicles (33,001-60,000 lb GVWR)
HDGV8B	>60000	Class 8b Heavy Duty Gasoline Vehicles (>60,000 lb GVWR)
LDDV	-	Light Duty Diesel Vehicles (Passenger Cars)
LDDT12	0-6000	Light Duty Diesel Trucks 1 (0-6,000 lb GVWR)
HDDV2B	8501-10000	Class 2b Heavy Duty Diesel Vehicles (8501-10,000 lb GVWR)
HDDV3	10001-14000	Class 3 Heavy Duty Diesel Vehicles (10,001-14,000 lb GVWR)
HDDV4	14001-16000	Class 4 Heavy Duty Diesel Vehicles (14,001-16,000 lb GVWR)
HDDV5	16001-19500	Class 5 Heavy Duty Diesel Vehicles (16,001-19,500 lb GVWR)
HDDV6	19501-26000	Class 6 Heavy Duty Diesel Vehicles (19,501-26,000 lb GVWR)
HDDV7	26001-33000	Class 7 Heavy Duty Diesel Vehicles (26,001-33,000 lb GVWR)
HDDV8A	33001-60000	Class 8a Heavy Duty Diesel Vehicles (33,001-60,000 lb GVWR)
HDDV8B	>60000	Class 8b Heavy Duty Diesel Vehicles (>60,000 lb GVWR)
MC	-	Motorcycles (Gasoline)
HDGB	-	Gasoline Busses (School, Transit and Urban)
HDDBT	-	Diesel Transit and Urban Busses
HDDBS	-	Diesel School Busses
LDDT34	6001-8500	Light Duty Diesel Trucks 1 (6,001-8500 lb GVWR)

adaptation to a PHEV architecture, but due to a desire to account for the categories with a combination of the highest fraction of fleet vehicle miles traveled (VMT) and relatively high confidence that PHEV technology could be applied to the category in the near-term.

Table 4-2 shows the seventeen categories selected for PHEV and HEV market share in the PHEV scenarios. Energy consumption for both hybrid and plug-in hybrid vehicles is based on existing EPRI simulation data and adjusted for relative compatibility with MOBILE6 fuel economy data. For this study, a hybrid vehicle is assumed to have 35% lower fuel consumption than a conventional vehicle. This number is comparable to both simulated and EPA-certified differentials between conventional and hybrid vehicles.[11,12]

Table 4-2
Initial attributes of conventional, hybrid and plug-in hybrid per category in 2006

Individual Vehicle Type	GVWR (lb)	Test Mass (kg)	DC Electricity Consumption Wh/mile	Mobile6 Fuel Economy (mpg)	Adjusted Mobile6 HEV Fuel Economy (mpg)	Mobile6 Adjusted DC Wh/mile	Mobile6 Adjusted AC Wh/mile
Gasoline Vehicles							
LDGV	-	1651	237	24.1	37.1	280.0	318.2
LDGT1	0-6000	2268	296	18.5	28.5	346.9	394.2
LDGT2	0-6001	2268	296	18.5	28.5	346.9	394.2
LDGT3	6001-8500	3289	393	14.2	21.8	434.0	493.2
LDGT4	6001-8500	3289	393	14.2	21.8	434.0	493.2
HDGV2B	8501-10000	3776	439	10.1	15.6	584.7	664.4
HDGV3	10001-14000	4899	547	9.4	14.4	626.1	711.5
HDGV4	14001-16000	6124	663	9.4	14.4	628.5	714.3
HDGV5	16001-19500	7246	771	8.0	12.3	723.8	822.5
Diesel Vehicles							
LDDV	-	1726	244	32.4	49.8	288.5	327.9
LDDT12	0-6000	2375	306	22.1	34.0	358.8	407.8
HDDV2B	8501-10000	3886	450	13.0	19.9	598.6	680.2
HDDV3	10001-14000	5042	560	11.7	17.9	641.7	729.2
HDDV4	14001-16000	6303	681	10.2	15.7	644.8	732.7
HDDV5	16001-19500	7460	791	9.9	15.2	742.9	844.2
HDDV6	19501-26000						
LDDT34	6001-8500	3446	408	17.0		450.6	512.1

For this study, we assume a PHEV has equivalent fuel consumption attributes to a hybrid for the portion of VMT not powered by electricity.[13] Electric energy consumption attributes of each vehicle category are calculated from EPRI simulation data for plug-in hybrid vehicles[11,12] and adjusted for baseline MOBILE6 fuel consumption. DC Electricity Consumption represents the average performance of that

[13] For a given battery chemistry, a PHEV will carry more total battery mass, resulting in a slight decrease in fuel economy relative to a hybrid vehicle. Detailed studies of this effect have shown that the higher electric drive system performance of a PHEV will typically compensate for the slight increase in additional weight.[11,12]

vehicle category on the Federal Urban Driving Schedule (FUDS). MOBILE6 Adjusted DC Electricity Consumption (column 6) represents "real-world" electrical energy consumption at the vehicle and is calculated by applying a correction factor based on MOBILE6 Fuel Economy.

MOBILE6 Adjusted AC Electricity Consumption represents AC electricity consumption per mile, used to calculate vehicle energy demand to the electric sector. DC electrical energy is converted to AC electrical energy from the wall outlet (supplied by the electrical grid) using an 88% conversion efficiency from AC energy at the outlet to stored DC energy in the battery pack of the vehicle. This conversion efficiency includes charger and battery losses and is based on prior simulation data[7] and adjusted for recent Lithium Ion battery charging test data.[14]

The nationwide fleet of PHEVs is distributed to seventeen different vehicle categories specified from the MOBILE6 database. The first four categories, LDGV, LDGT1, LDGT2, and LGDT3, account for 82.2% of the total vehicle miles traveled in the study.

Vehicle Fuel Economy

The three vehicle types in this study all use liquid fuels and fuel consumption is an important parameter for determining total GHG emissions. The MOBILE6 and EMFAC databases assume that vehicle fuel efficiency does not improve over time.

For logical consistency, this study assumes that market conditions sufficient to produce significant market shares for PHEVs will also create similar motivation for automotive manufacturers to offer, and for consumers to purchase, more fuel efficient conventional and hybrid vehicles. This reasoning creates the following study assumptions, expressed for the gasoline Light-Duty Gasoline Vehicle (LDGV) category, but applied consistently—in terms of percentage energy consumption reduction—throughout the other vehicle categories:

1. Initial fuel economy for a model year 2006 conventional gasoline LDGV is 24.1 mpg.
2. Initial fuel economy for a model year 2006 gasoline HEV LDGV is 37.1 mpg.
3. PHEVs, when not using electrical energy, have identical fuel economy to the HEV
4. Fuel consumption for both CVs and HEVs improves by 0.5% per year, therefore
    - 2010 new vehicle fuel economy is 24.6 for the CV and 37.9 for the HEV (LDGV)
    - 2050 new vehicle fuel economy is 30.0 mpg for the CV and 46.3 mpg for the HEV (LDGV)

[14] *Sprinter PHEV Battery Testing,* Project Report No. TC-04-176-TR06, Southern California Edison, Pomona, CA. January 2007.

Figure 4-1 shows the improvement in fuel economy over the study timeframe of 2010 to 2050 for the gasoline LDGV category.[15]

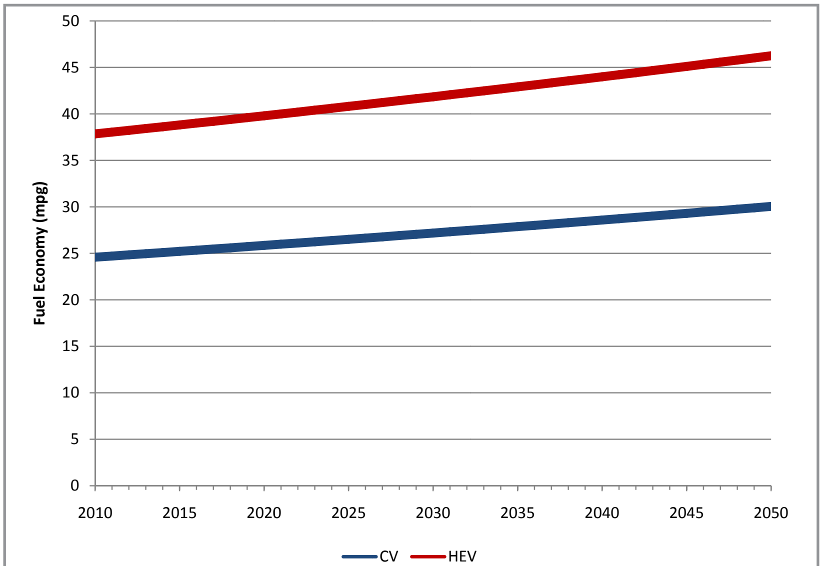

Figure 4-1
Evolution of conventional and hybrid vehicle fuel economy for the LDGV category

PHEV Utility Factor

Utility factor is a term used to describe the fraction of driving in a PHEV that is performed by electricity. Utility factor varies with each individual vehicle and is limited by opportunities to charge the vehicle. In general, vehicles that are driven extremely long distances between recharging events will have a low utility factor. Vehicles that are driven on many short trips will have a very high utility factor. On average, utility factor is heavily (but not entirely) dependent on two primary factors—annual VMT and vehicle All-Electric Range (AER). AER is a design parameter of the vehicle and indicates the number of miles the vehicle is capable of being driven using only battery energy (between recharges). EPRI identifies AER by attaching the AER, in miles, immediately after the term PHEV. For example, a PHEV 10 is a plug-in hybrid with 10 miles of electric range. For simplicity, this study considers PHEV 10, PHEV 20, and PHEV 40 configurations. Over time, the new vehicle market shares of PHEV 20 and PHEV 40 increases.

[15]The assumptions regarding vehicle energy efficiency represent a simplified assumption of improvement in fuel consumption over time.

Figure 4-2 shows the Utility Factor relationships that have been established for each of the PHEV configurations. This data is derived from prior EPRI data,[9] taking into account charging frequency, annual mileage in different driving scenarios, and proportion of urban and highway driving.

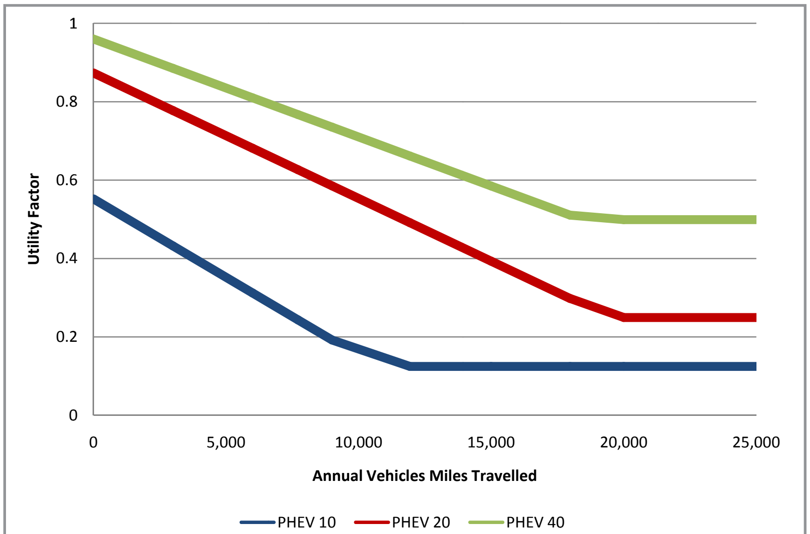

Figure 4-2
PHEV Utility Factor as a function of AER and annual VMT, assuming nightly charging

PHEV Market Penetration

Three distinct PHEV market adoption scenarios were developed, each based on PHEVs entering the market gradually in 2010, experiencing rapid adoption and achieving maximum new vehicle market share in 2050. As shown in **Figure 4-3**, PHEVs reach a maximum of 20% new vehicle market share in the Low PHEV fleet penetration scenario, 62% in the Medium PHEV fleet pentration scenario, and 80% in the High PHEV fleet penetration scenario. Market share is based on each of the seventeen vehicle types considered in this study.

For the purpose of calculating GHG reductions, each PHEV scenario is compared to a base case without PHEVs. In the absence of PHEVs, HEVs and conventional vehicles expand their market share under the assumption that the proportion of conventional vehicles to HEVs remains the same as for the respective PHEV case in question (**Table 4-3**). For example, under the High PHEV scenario in 2050, the new vehicle market shares of HEVs and CVs are 15% and 5%, respectively. This proportion of HEVs to CVs (3:1) is constant when PHEVs are removed, resulting in respective market shares of 75% and 25%. This has the practical effect of comparing fleet GHG reductions with PHEVs to a base fleet of similar level of hybridization.

The MOBILE6 and EMFAC databases contain the entire nationwide fleet inventory of all vehicles of all ages. For each year, new vehicles are added to the model databases and a certain percentage of older vehicles are retired. Average VMT assigned to a single vehicle declines over time—newer cars tend to be driven more than older cars.

Table 4-3
Peak new vehicle market share in 2050 for the three PHEV adoption scenarios

2050 New Vehicle Market Share by Scenario		Vehicle Type		
		Conventional	Hybrid	Plug-In Hybrid
PHEV Scenario	Low PHEV	56%	24%	20%
	Medium PHEV	14%	24%	62%
	High PHEV	5%	15%	80%

Table 4-4
Baseline market share of Conventional and Hybrid vehicles for each PHEV scenario but without PHEVs

2050 New Vehicle Market Share by Scenario		Vehicle Type		
		Conventional	Hybrid	Plug-In Hybrid
PHEV Scenario	Low PHEV	70%	30%	0%
	Medium PHEV	37%	63%	0%
	High PHEV	25%	75%	0%

Figure 4-3 shows the annual new vehicle market share of conventional, hybrid, and plug-in hybrid vehicles for the Medium PHEV fleet penetration case from 2006 to 2050. The market shares of each vehicle are assumptions developed from choice based market modeling of customer preference between PHEV, HEV, and conventional vehicle options. Market adoption is initially limited by vehicle cost and assumed maximum new vehicle availability. In each year, the new vehicles added to the model will be added in the proportion for that year. In the absence of PHEVs, HEVs and CVs occupy the market in the same relative proportions.[16]

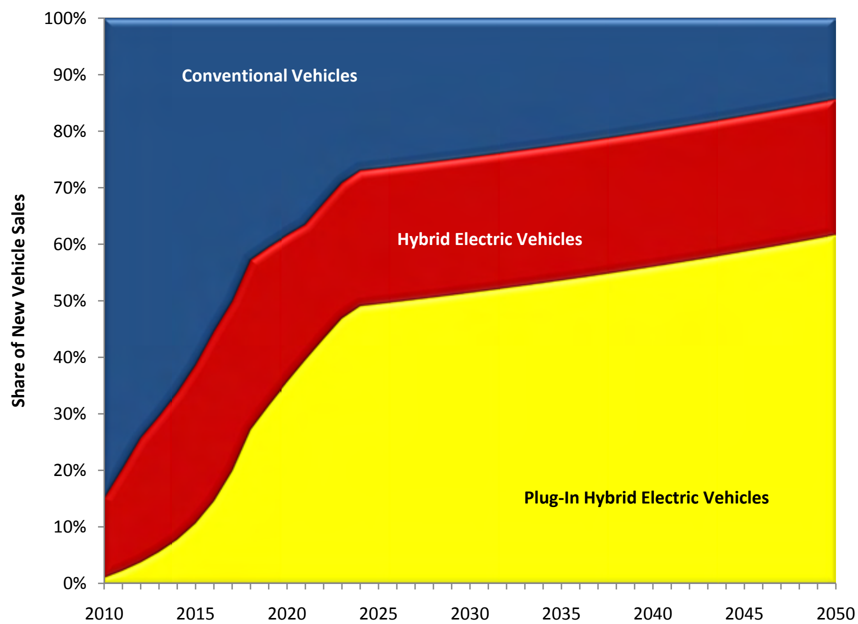

Figure 4-3
Assumed new car market share for the Medium PHEV scenario conventional vehicles (CV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehciles (PHEV) for each vehicle category

[16]For example, in the High PHEV scenario in the absence of PHEV, HEVs would comprise 75% of the new vehicle market and CVs 25% in 2050.

Upon market entry, PHEVs are a relatively small percentage of new vehicle sales. It will also take many years for the fleet to "turn over" as older vehicles are retired. MOBILE6 assigns different vehicle lifetime projections to the different vehicle classes. **Figure 4-4** shows this evolution of the PHEV component of the fleet over the 2010 to 2050 time horizon.

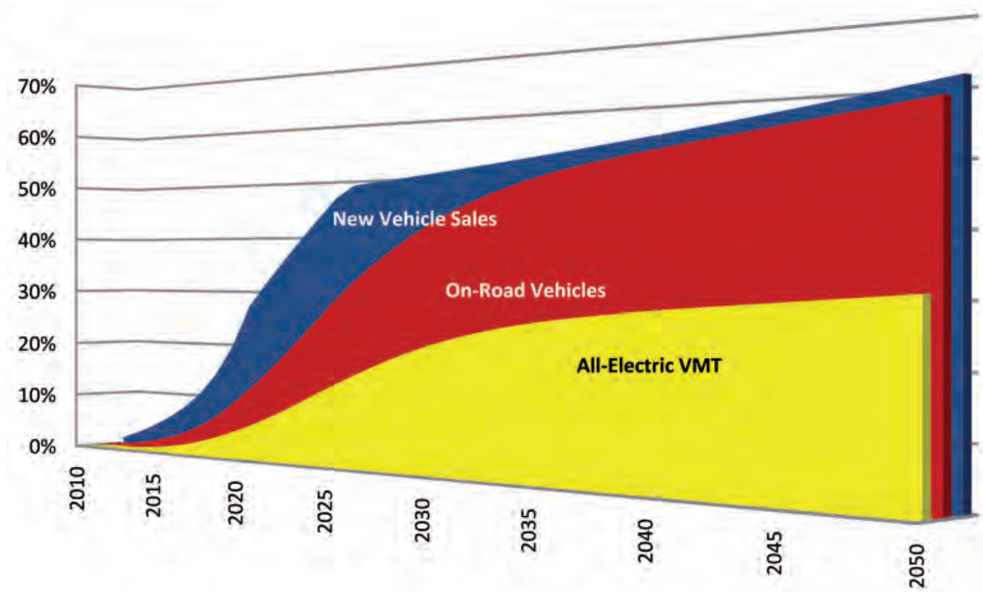

Figure 4-4
Fleet share growth over time of PHEVs in the Light Duty Gasoline Vehicle (LDGV) category for the Medium PHEV case

In Figure 4-4, the ***New Vehicle Sales*** curve shows the percentage of new vehicles sales in each year attributed to PHEVs. ***PHEV VMT*** is the fraction of LDGV miles driven in each year by PHEVs. ***All Electric VMT*** represents the fraction of total LDGV miles attributed to electric energy. The fraction of LDGV VMT attributed to PHEVs lags PHEV new vehicle market share, indicative of the time necessary for them to significantly penetrate the existing vehicle fleet. The two converge over time as PHEVs market penetration increases. New vehicles have higher VMT than older vehicles, accounting for the close correlation between PHEV market share and fleet VMT fraction after about 2035.

PHEV Charge Profile

An aggregated charge profile was created for the fleet of PHEVs in the model (**Figure 4-5**, below). 100% of the charge energy requirements are apportioned to each hour of the day. The analysis assumes that the highest charging loads occur during late night and early morning hours, with modest loads—presumably from daytime public or workplace charging -- occurring in the middle of the day. Hours of minimal charging correspond roughly with commute times.

This specific charge profile creates a scenario where 74% of the charging energy is delivered from 10:00 p.m. to 6:00 a.m. (nominally off-peak). The remaining 26% is provided between 6:00 a.m. to 10:00 p.m. This is simply one of many possible scenarios and represents an initial approximation of aggregate charging behavior in a fleet of PHEVs. The scenario is supported by the following assumptions:

1. *PHEVs are charged primarily, but not exclusively, at each vehicle's "home base".*
2. *Owners are incentivized or otherwise encouraged to use less expensive off-peak electricity.*
3. *Near-term vehicles are likely to have charge onset delays built into their systems to allow battery system rest and cooling before recharge.*
4. *Long-term, large PHEV fleets will likely encourage utilities to use demand response or other programs to actively manage the charging load.*

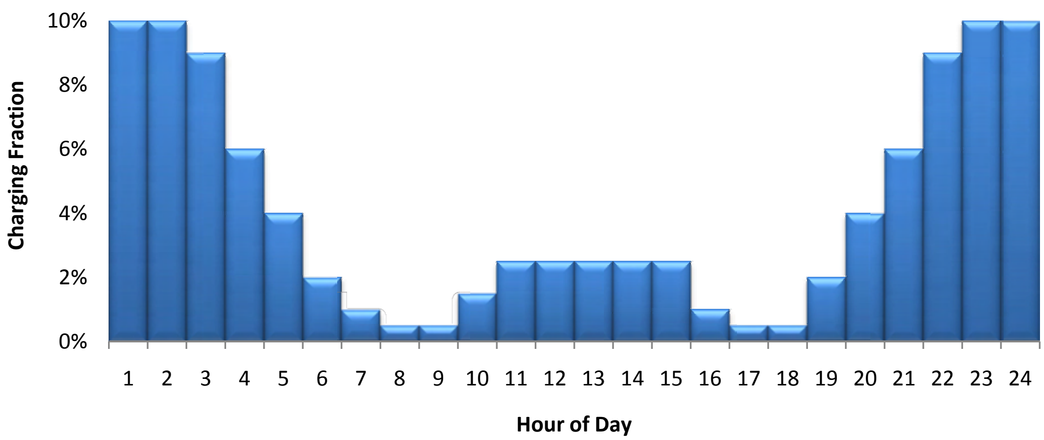

Figure 4-5
PHEV Charge Profile (Hour 1 represents 12:01 a.m. to 1:00 a.m. Hour 24 represents 11:01 p.m. to 12:00 a.m.)

5 Results

The methodology followed in this assessment starts with specific performance characteristics of both vehicles and electric power plants of different configurations, technologies and levels of performance. The attributes of these single entities are then expanded in scope and numbers to allow for analysis of a nationwide approach. For the transportation sector, vehicle performance characteristics are propagated throughout the MOBILE6 database of light-duty and medium-duty vehicles for the United States. For the electric sector, power plant characteristics are incorporated into a nationwide capacity retirement/ expansion model and electricity production simulation.

The results of this analysis are presented in two ways:

1. Individual vehicle type examples comparing GHG emissions of conventional, hybrid, and plug-in hybrid vehicles; and
2. Nationwide scenario results comparing total GHG emissions of the different scenarios constructed from High CO_2, Medium CO_2, and Low CO_2 Intensity electric sector emissions cases and Low, Medium, and High PHEV market adoption cases.

Individual Vehicle Results

The combination of a forty-year time horizon, seventeen vehicle categories, and nine scenarios results in thousands of distinct individual vehicle results within the model. The following is a single example, or snapshot, of the comparative performance of conventional, hybrid and plug-in hybrids in the Light Duty Gasoline Vehicle (LDGV) category. There are five possible configurations for each vehicle category—conventional, hybrid, and plug-in hybrid (10, 20, and 40 miles of electric range).

Table 5-1 shows the energy efficiency, gasoline consumption, and AC electrical usage of each of the five vehicle types—all model year 2010 (MY2010) vehicles in the year 2010, with an assumed annual VMT of 15,000 miles. The CV, with a fuel economy of 24.6 mpg, consumes 488 gallons of gasoline in 2010. The hybrid, with higher fuel economy of 37.9 mpg, consumes 317 gallons. Each PHEV has a utility factor (Figure 4-2) dependent on range and annual VMT that dictates the quantity of VMT that are powered by electricity (eVMT fraction). For the PHEV 20, the utility factor, or eVMT fraction is 0.49, resulting in the consumption of 161 gallons of fuel and 1,840 kWh of electricity. In this example, the PHEV 10 has a lower eVMT fraction of 0.125 and correspondingly higher gasoline consumption. The PHEV 40 has an eVMT fraction of 0.66 and consumes only 107 gallons of gasoline (and 2,477 kWh of electricity).

Table 5-1
Example of Vehicle Energy Consumption in 2010 (LDGV)

		CV	HEV	PHEV 10	PHEV 20	PHEV 40
Annual mileage	mi	12,000	12,000	12,000	12,000	12,000
Utility Factor		n/a	n/a	0.12	0.49	0.66
Gasoline consumption	gal	487.8	316.6	277.1	161.0	107.2
Electricity consumption	kWh	-	-	467	1,840	2,477
Fuel economy	mpg	24.6	37.9	37.9	37.9	37.9
Electric efficiency	AC kWh/mi	n/a	n/a	0.312	0.312	0.312

Figure 5-1 compares total GHG emissions of the CV, HEV, and the PHEV 20, with the PHEV 20 receiving its energy entirely from each of the fourteen distinct power plant technologies defined in Chapter 2. The bottom bar (blue) represents all of the GHGs emitted in the process of producing and delivering gasoline to the vehicle (well-to-tank). The next bar (red) represents GHGs emitted at the vehicle level (tank-to-wheels). The top bar (yellow) represents GHGs emitted during the generation of electricity for the PHEV 20.

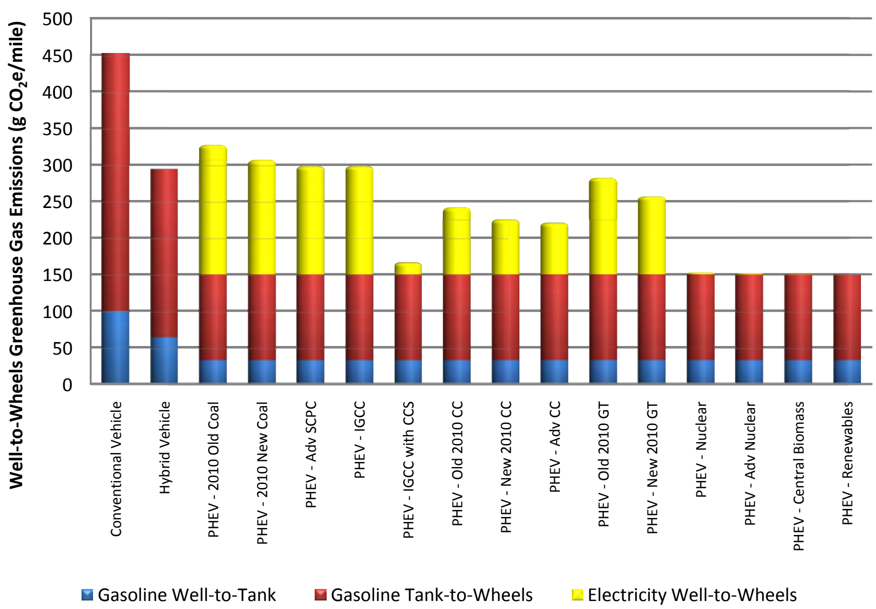

Figure 5-1
Year 2010 comparison of LDGV PHEV 20 GHG emissions when charged entirely with electricity from specific power plant technologies (12,000 miles driven per year)

There are a number of conclusions from this comparison of PHEV 20 GHG emissions to the CV and HEV in Figure 5-1. **For the PHEV 20**:

- Both HEV and PHEV 20 regardless of electricity supply, result in significantly lower GHG emissions than a comparable conventional vehicle (28% to 67% lower)
- With power provided by current coal generation technologies, the PHEV 20 has somewhat higher GHG emissions than HEV (11.1% and 4.3% higher, respectively)
- With power provided by the assumed advanced coal technologies (Advanced SCPC and IGCC) PHEV 20 GHG emissions are comparable to the HEV (1.4% higher)
- With power provided by combined cycle natural gas technologies (current and advanced) show significant GHG reductions compared to HEV (18% to 25% lower).
- The two "peaking" technologies (Old 2010 Gas Turbine and New 2010 Gas Turbine) show modest reductions compared to HEV (4% and 13% lower, respectively)
- The PHEV 20 recharged by low- and non-emitting generation technologies emits the lowest level of GHGs per mile (Note the analysis conducted for this report assumes Adv Nuclear and IGCC with carbon capture and storage are not available in 2010).

From this examination of generation options for PHEVs in 2010, it is clear that the carbon intensity of the generation technology plays a significant role in the total GHG emissions due to PHEV use. In 2010, current coal technologies result in somewhat higher GHG emissions compared to the hybrid and 28% to 34% reductions compared to the conventional vehicle.

Table 5-2
Example of Vehicle Energy Consumption in 2050 (LDGV)

		CV	HEV	PHEV 10	PHEV 20	PHEV 40
Annual mileage	mi	12,000	12,000	12,000	12,000	12,000
Utility Factor		n/a	n/a	0.12	0.49	0.66
Gasoline consumption	gal	400.0	259.2	226.8	131.8	87.7
Electricity consumption	kWh	-	-	382	1,504	2,024
Fuel economy	mpg	30.0	46.3	46.3	46.3	46.3
Electric efficiency	AC kWh/mi	n/a	n/a	0.255	0.255	0.255

Table 5-2 shows five different LDGV types for MY2050 vehicles. Cumulative annual decreases in fuel consumption of 0.5% have resulted in MY2050 fuel economy of 30 mpg for the conventional vehicle and 46.3 mpg for the hybrids. PHEV electric energy consumption has decreased from 0.312 kWh/mi to 0.255 kWh/mi.

Figure 5-2 is similar to Figure 5-1 with higher emitting conventional generation technologies (2010 Old Coal, New Coal, Old CC, New CC, Old GT) removed as they no longer form part of the generating fleet. In 2050, vehicle efficiency has improved, so all three components of well-to-wheels GHG emissions are lower. The PHEV 20 produces approximately the same GHG emissions as an HEV if powered by electricity from coal plants that do not capture CO_2 and has 37% lower GHG emissions than the HEV if coal with CO_2 capture and storage is the power source.

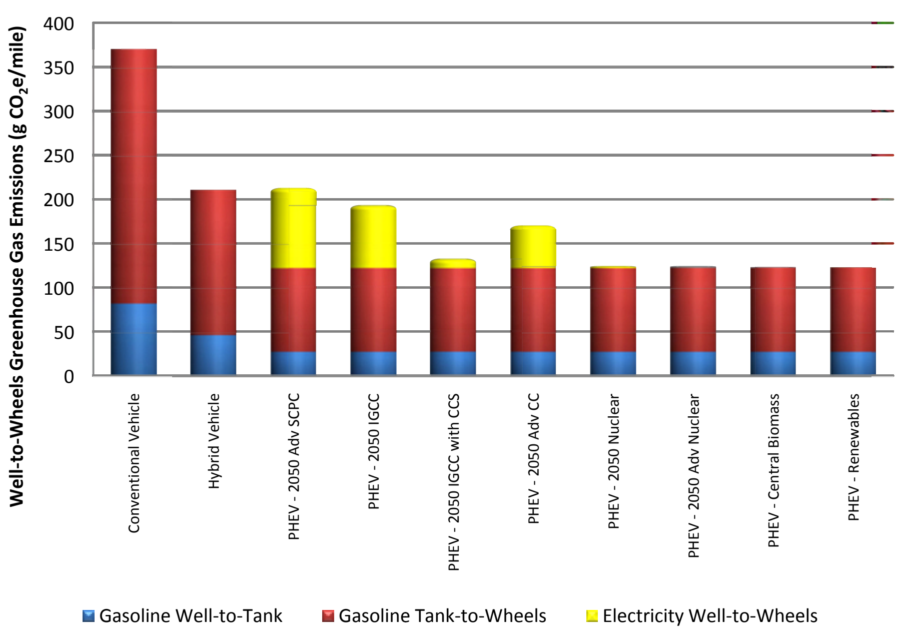

Figure 5-2
Year 2050 comparison of LDGV PHEV 20 GHG emissions charged entirely with electricity from specific power plant technologies (12,000 miles driven per year)

Electric Sector Scenario Impact on GHG Emissions

The previous analyses illustrate the strong dependence of PHEV GHG emission intensity on the source of electricity. Total system emissions from a given level of PHEV use will be determined by a combination of the vehicle type (PHEV 10, 20, 40), annual VMT patterns by vehicle type, and the type of generating resources that are built and dispatched to serve the electrical load from grid-connected PHEVs. These aggregate impacts are discussed in this section.

In **Figure 5-3** GHG emissions of MY2050 conventional and hybrid vehicles are compared to the three PHEV types (10, 20 and 40 miles of electric range) in each of the three electric sector scenarios (High CO_2, Medium CO_2, and Low CO_2, intensity). PHEVs have lower GHG emissions in all nine cases than either the conventional or the hybrid vehicles, ranging from a 40% to 65% improvement over the conventional to a 7% to 46% improvement over the hybrid. It should be noted that substantial improvements in electric sector intensities are assumed even for the High CO_2 case in 2050. The high CO_2 intensity case electric sector emission rate in 2050 is 33% lower than 2006 electric sector rate (Table 3-2).

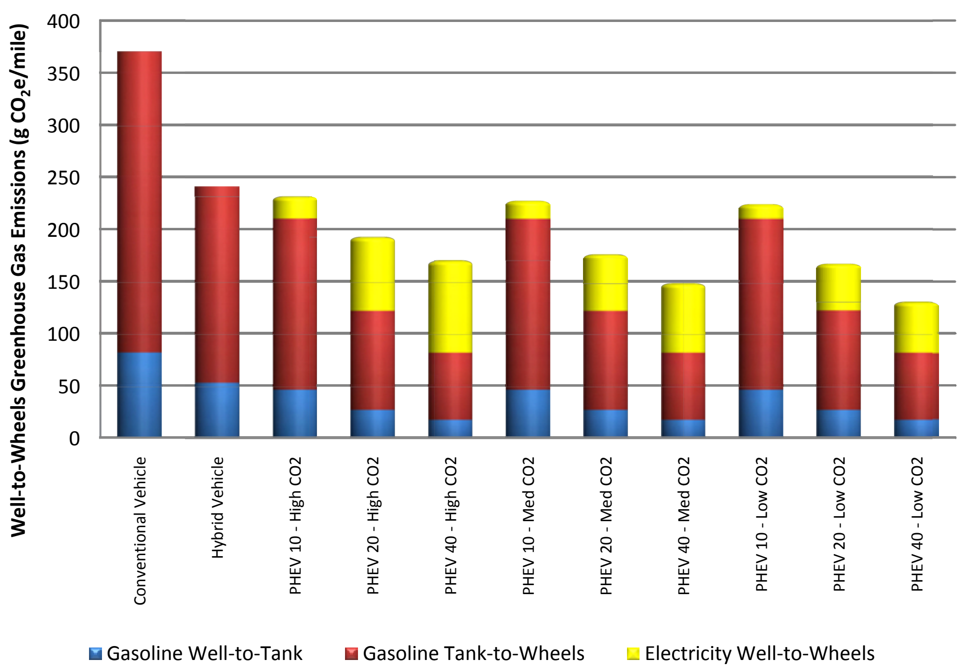

Figure 5-3
Year 2050 comparison of LDGV PHEV GHG emissions from within the High CO_2, Medium CO_2, and Low CO_2 electric sector scenarios (12,000 miles driven per year)

Table 5-3 lists the reduction in GHG emissions of each PHEV versus the HEV for each level of electric range and each electric sector scenario. The PHEV 10, by nature of its smaller battery system and the

Table 5-3
GHG Emissions Reductions of PHEVs Compared to the HEV for MY2050

Relative GHG Emissions Reductions vs. Hybrid MY2050		Electric Sector CO_2 Scenario		
		High	Medium	Low
Vehicle Type	PHEV 10	-6.9%	-7.7%	-8.6%
	PHEV 20	-27.1%	-30.5%	-34.0%
	PHEV 40	-36.5%	-41.4%	-45.8%

12,000-mile annual VMT assumption, shows the smallest percentage gains.

Annual Nationwide Fleet GHG Reductions

The previous section showed effect of each of the electric sector scenarios on the individual GHG emissions of different PHEV configurations. In aggregate, PHEVs enter the nationwide fleet at varying rates of market penetration for each vehicle configuration, represent numerous vehicle classifications, and age over time, affecting annual VMT and utility factor. The Vehicle Emissions Model described in Chapter 4 tracks the aggregate energy consumption and GHG emissions on a fleetwide basis from 2010 to 2050.

Figure 5-4 tracks annual GHG reductions due to PHEVs in the nationwide fleet for the Medium PHEV fleet penetration/Medium CO_2 intensity case. Three comparisons are made:

1. A nationwide fleet consisting of only conventional gasoline and diesel vehicles
2. A nationwide fleet consisting of only hybrid electric vehicles
3. A baseline fleet composed of both hybrid and conventional vehicles (Table 4-3)

Each of the three comparisons provide perspective on the relative contributions on PHEVs to mobile source GHG reductions. When compared to the hybrid-only fleet, the aggregate GHG reductions (433 million tons in 2050) are attributed entirely to the effect of electricity as a transportation fuel.[17]

The three electric-sector CO_2 scenarios (High CO_2, Medium CO_2, and Low CO_2 intensity) are combined with the three PHEV scenarios (Low PHEV, Medium PHEV, and High PHEV fleet penetration) to create a 3×3 matrix of nine different outcomes or modeling results. **Table 5-4** lists the annual GHG reductions in the nationwide fleet from PHEV adoption in each of the nine combined scenarios. Annual reductions are significant in each case, ranging from 163 million metric tons in the high CO_2 intensity/Low PHEV fleet scenario to 612 million metric tons in the Low CO_2 intensity/High PHEV fleet penetration scenario.

The impacts of each parameter are straightforward—as PHEV fleet penetration increases, the fraction of electric VMT rises, displacing higher quantities of liquid fuels with electricity and increasing demand on the electric sector. As the CO_2 intensity of the electric sector decreases, the GHG emissions from a

[17] It is important to note that market shares of different vehicle technologies are input assumptions to this study. The fraction of diesel vs. gasoline vehicles is taken directly from MOBILE6 and EMFAC data. One important market share assumption of this study is that the total combined market penetration of PHEVs and HEVs is greater than the market penetration of either vechicle type alone.

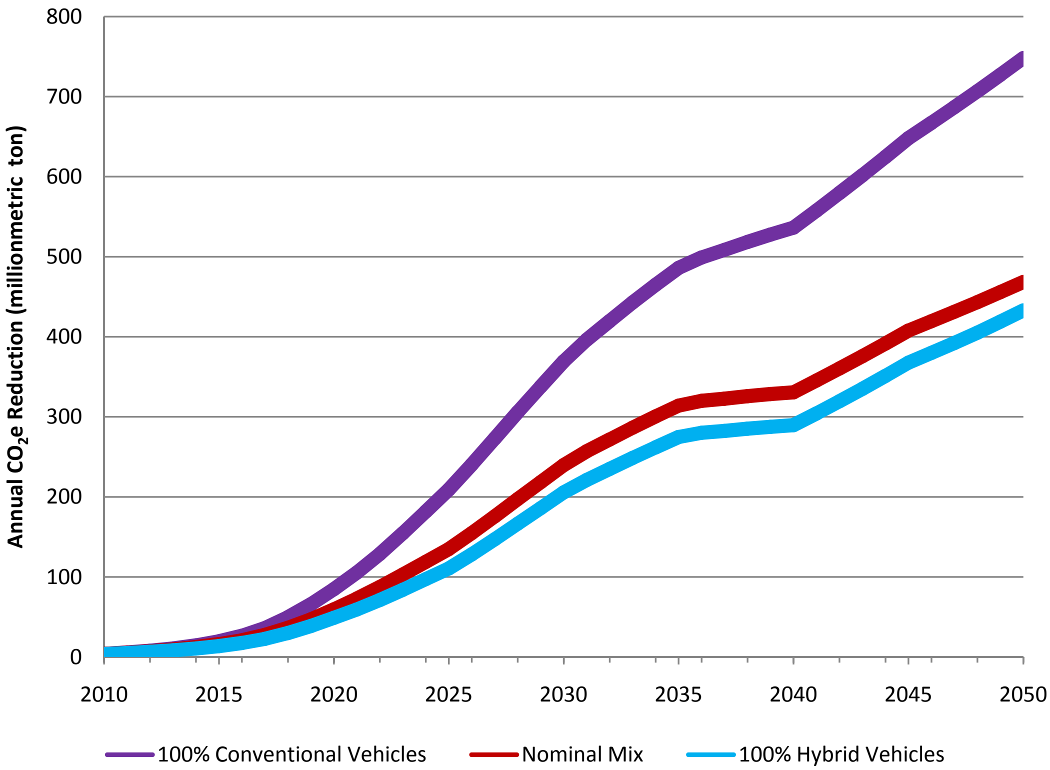

Figure 5-4
Annual GHG reductions of the Medium PHEV penetration scenario compared to a fleet of (1) 100% conventional vehicles, (2) base vehicle fleet of conventional and hybrid vehicles, and (3) 100% hybrid vehicles (no PHEVs)

Table 5-4
Annual CO_2 reduction from PHEVs in the year 2050

2050 Annual CO_2 Reduction (million tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

Aggregate Greenhouse Gas Reductions from 2010 to 2050

Cumulative GHG emissions over the study horizon of 2010 to 2050 are a measure of the overall impact of a technology's potential contribution to GHG reduction. **Table 5-5** presents the results of the nine modeling scenarios. In each case, GHG reductions represent the total GHG reductions of the nationwide vehicle fleet, with its specified penetration of PHEVs versus the GHG of the base vehicle fleet, a proportional mix of hybrid and conventional vehicles.

Table 5-5
Cumulative 2010 – 2050 GHG reduction from PHEVs (billion tons of GHG)

2010 -2050 Total GHG Reduction (billion metric tons)		Electric Sector CO_2 Intensity		
		High	Medium	Low
PHEV Fleet Penetration	Low	3.4	3.4	3.4
	Medium	7.9	8.9	8.0
	High	9.8	10.1	10.3

The key conclusion from this table is that in each of the nine scenarios, GHG emissions are reduced significantly. Each modeling scenario represents a distinct simulation of the electric system with numerous complex interactions. PHEVs reduce GHG emissions in two general ways. First, a PHEV uses gasoline more efficiently—in this study a PHEV has equivalent fuel consumption to a hybrid vehicle. Second, if the carbon intensity of the electricity used to recharge PHEV batteries is below a certain level, this electricity will function as an inherently lower carbon fuel compared with gasoline. The three electric sector carbon emission scenarios assumed in this study each would result in an electric sector that will deliver marginal electricity to PHEVs at a low enough carbon intensity to achieve significant reductions from scenarios where gasoline or diesel fuel is used instead of electricity to provide energy for VMT.

A secondary conclusion from Table 5-5 is that the aggregate 2010 – 2050 GHG reductions are less dependent on electric sector GHG intensity than Table 5-4 would indicate, particularly for the Medium CO_2 Intensity/Medium PHEV case, which shows greater aggregate reductions than the Low CO_2 Intensity/High PHEV case. This analysis uses marginal analysis of the electric sector to determine the origin and environmental characteristics of the electricity that is specifically sourced to charge PHEVs. In the intermediate years of the study time horizon, significant changes are occurring in the electric sector in terms of new plant construction and its effect on plant dispatch order. This has the effect of pushing some higher-emitting plants upward in the dispatch order—the net effect is that these plants contribute less electricity to existing loads, but are somewhat more likely to be dispatched to charge PHEVs.

Another result of the marginal analysis is that combined cycle natural gas is an important contributor to PHEV charging. In general, CCNG is an important marginal resource in the electric sector. The lower capital cost of CCNG relative to coal and nuclear baseload plants tends to favor the construction of CCNG for plants that run at lower capacity factors. The use of CCNG for PHEV charging has a number of interesting effects on GHG emissions, including:

1. In the early years of the study, CCNG reduces GHG intensity in all electric sector scenarios
2. For the High CO_2 intensity scenario, the GHG intensity of CCNG is lower than the average.
3. For the Medium CO_2 and Low CO_2 intensity scenarios, the GHG intensity of CCNG is higher than the average of the entire electric sector.

It is necessary to place these results in context—each of the nine scenarios results in significantly lower GHG emissions from PHEV adoption. In addition, average GHG intensity in the Medium CO_2 and Low CO_2 intensity scenarios is quite low, below that of electricity from efficient combined cycle natural gas plants. The periodic appearance of older, higher emitting plants on the margin for charging PHEVs will serve to increase the specific emissions signature of the PHEV, but is a very minor contribution to total electric sector emissions.

Figure 5-5 places the relative impact of the added load of PHEVs (High PHEV penetration case with 80% new vehicle market share by 2050) on the three electric sector scenarios. In each case, average GHG intensity decreases over time without PHEVs. Adding PHEVs to the High CO_2 intensity case has the effect of slightly reducing total electric sector GHG intensity: CCNG is less GHG intense than the sector average and is a large marginal contributor to PHEV charging. In the Medium CO_2 and Low CO_2 intensity cases, renewable and other low-emitting and non-emitting technologies tend to dominate—adding PHEVs in these cases slightly increases average GHG intensity.

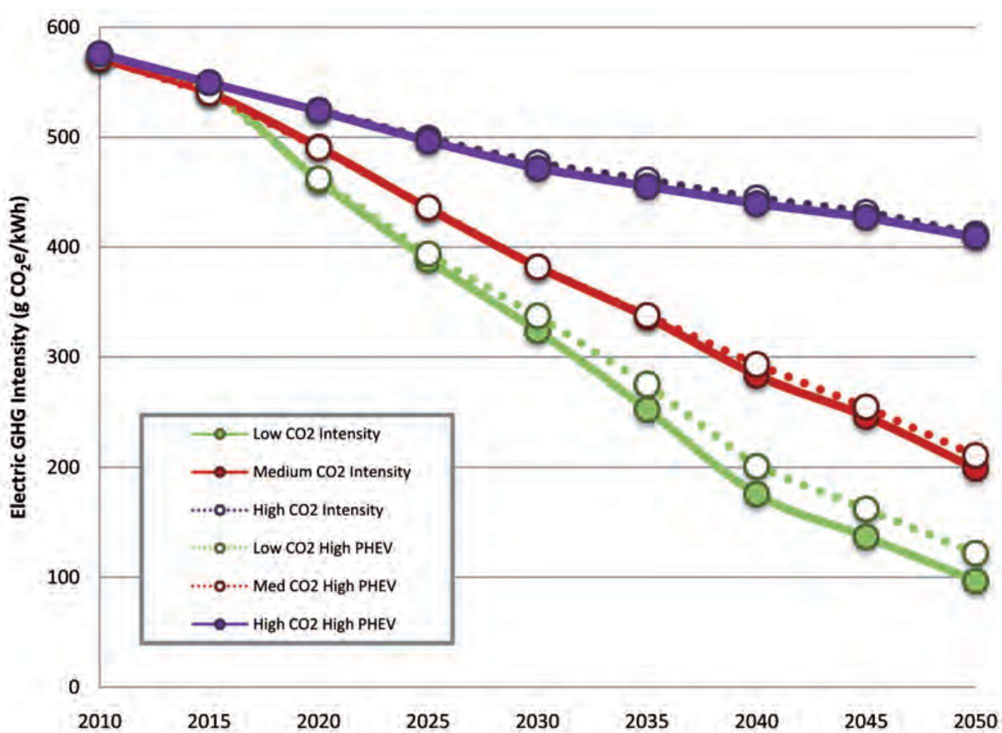

Figure 5-5
Effect of High PHEV market share on average electric sector GHG intensity

The Low CO_2 intensity case also has one specific difference from the high and medium cases. The assumption of greater progress in improving the efficiency of electricity use results in an electric sector of lower capacity than either the high or medium cases (**Figure 5-6**). As the electric sector in the Low CO_2 intensity case features less total capacity, the impact of PHEV charging is somewhat higher than for the other sectors.

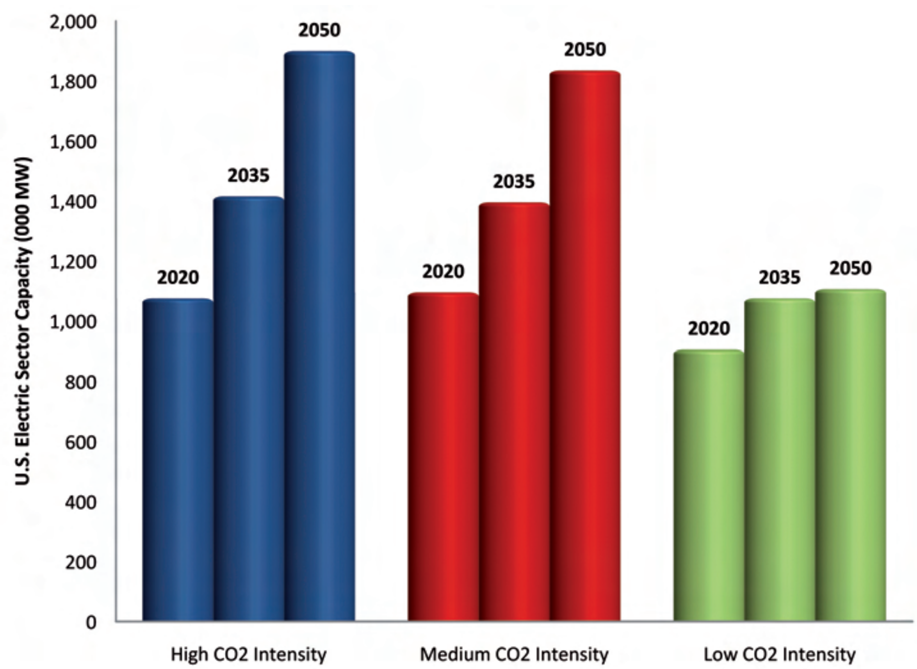

Figure 5-6
U.S. electric sector generating capacity for low, medium, and high CO_2 intensity cases

PHEV Energy Usage

The nationwide fleet model also outputs the energy consumption of PHEVs. For the Medium PHEV case, petroleum consumption of the light-duty and medium-duty vehicle fleet was reduced by the equivalent of 2.0 million barrels per day in 2030 and 3.7 million barrels per day in 2050. Electricity consumption due to PHEVs increases by 282 MMWh (million megawatt hours) in 2030 and 598 MMWh in 2050. These increases in electricity production and delivery over the base case (no PHEVs) are 4.8% and 7.6%, respectively.

Summary

This report represents the first nationwide detailed analysis of likely GHG impacts of plug-in hybrid electric vehicles. For this study, both transportation sector and electric sector modeling tools are used to examine assumed changes in these sectors over the 2010 to 2050 timeframe of the study.

To account for a range of future transportation and electric sector scenarios, nine total modeling scenarios were created at the intersection of High CO_2, Medium CO_2, and Low CO_2 Intensity electric sectors and low, medium, and high fleet penetrations of PHEVs. The following conclusions were drawn from these modeling exercises:

- Each of the nine scenarios showed significant GHG reductions due to PHEV fleet penetration;
- Cumulative GHG savings from 2010 to 2050 can be large, ranging from 3.4 to 10.3 billion metric tons CO_2e;
- Annual GHG savings were significant in every scenario for every year of the study timeframe —reaching a maximum of 612 million tons in 2050 (High PHEV fleet penetration, Low CO_2 intensity case);
- Marginal GHG intensity of the PHEV charging load can vary significantly from average GHG intensity, particularly for the Low CO_2 Intensity scenario.
- PHEVs adoption results in significant reduction in the consumption of petroleum fuels. In the Medium PHEV case, fuel savings were equivalent to 3.7 million barrels per day by 2050.

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