Argonne NATIONAL LABORATORY

ANL/ESD/09-2

Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/ESD/09-2

Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles

By
A. Elgowainy, A. Burnham, M. Wang, J. Molburg, and A. Rousseau
Center for Transportation Research
Energy Systems Division, Argonne National Laboratory

February 2009

CONTENTS

TABLES

FIGURES

FIGURES (CONT.)

FIGURES (CONT.)

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, the Hydrogen, Fuel Cells, and Infrastructure Technologies Program, under contract DE-AC02-06CH11357. We thank Fred Joseck of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program for his input to this study, Phillip Sharer and Sylvain Pagerit of Argonne National Laboratory for their support of PSAT simulations for this analysis, and Anant Vyas and Danilo Santini for their input regarding vehicle miles driven with grid power. We also thank Stanton Hadley for providing us with the raw data of the marginal generation mix charts for each NERC region.

WELL-TO-WHEELS ENERGY USE AND GREENHOUSE GAS EMISSIONS ANALYSIS OF PLUG-IN HYBRID ELECTRIC VEHICLES

Amgad Elgowainy, Andrew Burnham, Michael Wang,
John Molburg, and Aymeric Rousseau

ABSTRACT

Researchers at Argonne National Laboratory expanded the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model and incorporated the fuel economy and electricity use of alternative fuel/vehicle systems simulated by the Powertrain System Analysis Toolkit (PSAT) to conduct a well-to-wheels (WTW) analysis of energy use and greenhouse gas (GHG) emissions of plug-in hybrid electric vehicles (PHEVs). The WTW results were separately calculated for the blended charge-depleting (CD) and charge-sustaining (CS) modes of PHEV operation and then combined by using a weighting factor that represented the CD vehicle-miles-traveled (VMT) share. As indicated by PSAT simulations of the CD operation, grid electricity accounted for a share of the vehicle's total energy use, ranging from 6% for a PHEV 10 to 24% for a PHEV 40, based on CD VMT shares of 23% and 63%, respectively.

In addition to the PHEV's fuel economy and type of on-board fuel, the marginal electricity generation mix used to charge the vehicle impacted the WTW results, especially GHG emissions. Three North American Electric Reliability Corporation regions (4, 6, and 13) were selected for this analysis, because they encompassed large metropolitan areas (Illinois, New York, and California, respectively) and provided a significant variation of marginal generation mixes. The WTW results were also reported for the U.S. generation mix and renewable electricity to examine cases of average and clean mixes, respectively. For an all-electric range (AER) between 10 mi and 40 mi, PHEVs that employed petroleum fuels (gasoline and diesel), a blend of 85% ethanol and 15% gasoline (E85), and hydrogen were shown to offer a 40–60%, 70–90%, and more than 90% reduction in petroleum energy use and a 30–60%, 40–80%, and 10–100% reduction in GHG emissions, respectively, relative to an internal combustion engine vehicle that used gasoline. The spread of WTW GHG emissions among the different fuel production technologies and grid generation mixes was wider than the spread of petroleum energy use, mainly due to the diverse fuel production technologies and feedstock sources for the fuels considered in this analysis.

The PHEVs offered reductions in petroleum energy use as compared with regular hybrid electric vehicles (HEVs). More petroleum energy savings were realized as the AER increased, except when the marginal grid mix was dominated by oil-fired power generation. Similarly, more GHG emissions reductions were realized at higher AERs, except when the marginal grid generation mix was dominated by oil or coal. Electricity from renewable sources realized the largest reductions in petroleum energy use and GHG emissions for all PHEVs as the AER increased. The PHEVs that employ biomass-based fuels (e.g., biomass-E85 and -hydrogen) may not realize GHG emissions benefits over regular HEVs if the marginal generation mix is dominated by fossil sources.

Uncertainties are associated with the adopted PHEV fuel consumption and marginal generation mix simulation results, which impact the WTW results and require further research. More disaggregate marginal generation data within control areas (where the actual dispatching occurs) and an improved dispatch modeling are needed to accurately assess the impact of PHEV electrification. The market penetration of the PHEVs, their total electric load, and their role as complements rather than replacements of regular HEVs are also uncertain. The effects of the number of daily charges, the time of charging, and the charging capacity have not been evaluated in this study. A more robust analysis of the VMT share of the CD operation is also needed.

1 INTRODUCTION

The U.S. Department of Energy's (DOE's) Vehicle Technology Program examines the precompetitive, high-risk research needed to develop the component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks that will reduce the U.S. dependence on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice.[1] Currently, plug-in hybrid electric vehicles (PHEVs) are being developed for mass production by the automotive industry and have been touted for their potential to reduce the transportation system's petroleum dependence and greenhouse gas (GHG) emissions by using off-peak excess electric generation capacity and increasing the vehicle's energy efficiency. These vehicles are similar to regular hybrid electric vehicles (HEVs), except that the battery uses electricity from the grid by being recharged through a wall outlet. They share similar characteristics of regular HEVs, having an electric motor and an on-board power unit, such as an internal combustion engine (ICE) or fuel cell (FC), hereinafter referred to as "engine" for simplicity. The PHEV category can cover a wide variety of options with respect to technical attributes, such as the battery chemistry, the amount of grid electricity that can be stored in the battery, and the powertrain and fuel choices, which could significantly impact the environment. In addition, the behavior of consumers, revealed by where they live, when they charge, and how they drive, could also significantly affect the energy use and emissions of PHEVs.

In the 1990s, PHEV prototypes were built in student competitions cosponsored by U.S. automakers and DOE, while Japanese automakers introduced commercial HEVs that provided significantly lower fuel consumption than similar internal combustion engine vehicles (ICEVs) (Gaines et al. 2007). In 2001, as a response to these developments, both the Electric Power Research Institute (EPRI) and DOE's national laboratories began evaluating PHEVs (Graham et al. 2001; Plotkin et al. 2001). Although these reports examined vehicles with nickel metal hydride batteries, the recent interest in studying the effects of PHEVs has been spurred by improvements in the energy density and cost of lithium-ion batteries.

While PHEVs offer the potential for significant reduction in the vehicle's petroleum energy use and GHG emissions, the significance of these benefits may not be fully realized due to the upstream energy and emissions penalties associated with the electricity generation needed to power the electric vehicle-miles-traveled (VMT) share. The implications of the upstream marginal electricity generation mix as well as the PHEV's powertrain technology, fuel source, and all-electric range(AER) rating can be fully understood through a well-to-wheels (WTW) assessment of energy use and GHG emissions, as provided by this analysis.

With funding from DOE, the Center for Transportation Research at Argonne National Laboratory (Argonne) developed the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model to estimate the full fuel-cycle energy use and emissions for alternative transportation fuels and advanced vehicle systems (Wang 1999). In estimating the

[1] U.S. DOE Plug-in Hybrid Electric Vehicle R&D Plan, available at: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/phev_rd_plan_02-28-07.pdf. Last accessed October 2008.

fuel-cycle energy use in British thermal units per mile (Btu/mi) and GHG emissions in grams per mile (g/mi) for advanced vehicle technologies, including PHEVs, GREET tracks their occurrences from the primary energy source to the vehicle's operation, which is known as a "well-to-wheels" analysis. A WTW analysis is often divided into well-to-pump (WTP) and pump-to-wheels (PTW) stages. The WTP stage starts with the fuel feedstock recovery, followed by fuel production, and ends with the fuel available at the pump, while the PTW stage represents the vehicle's operation activities.

When analyzing the energy and emission implications of alternative fuels and advanced vehicle technologies, a WTW analysis can provide important insight. In many cases, a comparison is done for a particular vehicle technology by using different fuels and the same powertrain system (with minor modification), or by using the same fuel/vehicle system with different feedstock sources of fuel. However, to assess the impact of PHEVs, both the engine fuel and the grid electricity powering the electric drive system must be examined.

The engine/fuel combinations examined in this analysis are: a spark ignition (SI) engine using reformulated gasoline (RFG), an SI engine using a blend of 85% ethanol and 15% reformulated gasoline (E85), a compression ignition engine using low-sulfur diesel (LSD), and a fuel cell power system using gaseous hydrogen (H2). The feedstock sources considered are corn and switchgrass for E85 and distributed natural gas (NG) steam methane reformation (SMR), distributed electrolysis and switchgrass (gasification) for H2. Table 1 summarizes the vehicle technologies and fuels considered in this analysis as well as the feedstock sources for these fuels.

TABLE 1 Vehicle Technologies, Fuels, and Feedstock Sources

Technology	Fuel	Feedstock
Spark ignition	Reformulated gasoline	Conventional crude (82%) and oil sand (18%)
	Ethanol	Corn
		Herbaceous biomass (switchgrass)
Compression ignition	Low-sulfur diesel	Conventional crude (82%) and oil sand (18%)
Fuel cell	Hydrogen	Natural gas (SMR)
		Electricity (electrolysis)
		Herbaceous biomass (switchgrass)

A conventional gasoline ICEV and regular HEVs employing ICE and fuel cells are compared with PHEVs using the same fuels to examine their relative benefits with respect to energy use and GHG emissions. However, Santini and Vyas argued that regular HEVs and PHEVs should be compared with ICEVs, but not to each other, since they will compete against the ICEV in different niche markets (Santini and Vyas 2008). Regular HEVs are expected to be more advantageous than PHEVs when operating at low average speeds and for shorter daily driving distances (e.g., congested urban areas) in areas with a lower percentage of single-family homes with garages. In contrast, PHEVs are expected to have an advantage over regular HEVs at higher speeds in areas with less congestion (e.g., suburban areas) and a higher percentage of single-family homes with garages available to recharge these vehicles.

Simulations for year 2020 with model year (MY) 2015 vehicles are chosen for this analysis in order to address the implications of PHEVs within a reasonable timeframe after their likely introduction in the next few years. The flexibility of GREET allows the user to modify key assumptions when performing a WTW analysis. However, the challenge comes in finding reliable data for inclusion in the model, especially for PHEVs that have not been commercially produced. Therefore, external models and data are used to characterize these important determinants of the WTW performance, such as the marginal electricity generation mix for charging PHEVs, the fuel consumption and electricity use on a per-mile basis, and the VMT on grid electricity. A recent study by Oak Ridge National Laboratory (ORNL) of region-specific marginal generation mixes for PHEVs is adopted by this analysis to calculate the WTP energy use and GHG emissions associated with the electric load from PHEVs. The Powertrain System Analysis Toolkit (PSAT) is used to simulate the vehicle's fuel economy and electricity use, which are key inputs for the calculation of PTW energy use and GHG emissions. The following sections provide an overview of the methodology used to obtain these determinants for inclusion into the WTW analysis using GREET.

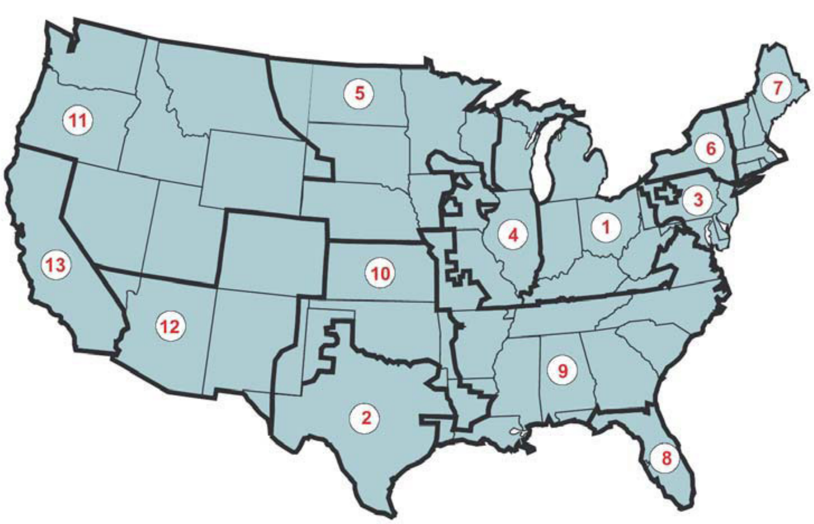
2 ELECTRICITY GENERATION MIX

A key factor in determining the environmental performance of PHEVs is the source of the electricity used to charge the battery. One goal of this analysis is to gather projections of regional generation mixes for a target year so that we can realistically examine how PHEVs will perform in different markets. The type of power plants varies by region, so it is important to examine these vehicles on a regional basis in order to better understand their effects.

A number of recent studies provided projections of the charging demand of PHEVs and matched the projected demand to the estimates of available generation capacities. These studies varied according to the regional scope and intent. Several nationwide studies produced results for all North American Electric Reliability Corporation (NERC) regions (Figure 1), while other studies were limited to specific regions. The generation mix at the time of charging became increasingly uncertain as the time for large-scale PHEV deployment increased, but the large current inventory of power plants, the availability of limited primary energy options for new plants, and the trends in costs and regulations provided guidance for projecting future plant inventories and their dispatch. By estimating the change in generating plant utilization due to PHEV load, these studies estimated the effect of PHEV deployment on reserve margins, fuel use, emissions, and costs.

2.1 FACTORS AFFECTING GENERATION MIX FOR PHEV CHARGING

The generation mix at the time of charging is a strong function of the time of day, time of year, geographic region, vehicle and charger design, load growth patterns, and the associated generation expansion in the years prior to the charging event of interest.



Region
1. ECAR
2. ERCOT
3. MAAC
4. MAIN
5. MAPP
6. NPCC-NY
7. NPCC-NE
8. FRCC
9. SERC
10. SPP
11. WECC-NW
12. WECC-RMP/ANM
13. WECC-CA

FIGURE 1 NERC Regions from the Annual Energy Outlook 2007 (Source: EIA 2007) (see Table 2 for definitions of abbreviations)

2.1.1 Time of Day

Figure 2, developed by Shelby and Mui, is an illustration of the diurnal peaks of demand for a hypothetical summer day (Shelby and Mui 2007). Sharp summer peaks are caused by air-conditioning demand, although such peaks typically occur in the late afternoon and early evening. However, demand is at a minimum overnight when businesses are closed, lights are off, and air-conditioning load is at its lowest (Hadley 2006).

As electricity demand increases, additional generating units are dispatched to meet the load. When a PHEV charger is activated, it causes additional load on the marginal generator (i.e., the last unit brought online). When that unit reaches full capacity, another unit is brought online as the marginal unit, and so forth. Therefore, when a large number of PHEVs are added to a system, several additional generation units may be required to meet the charging load. Consequently, the energy use and emissions of those units are allocated to the PHEV charging load. In an extensive interconnected region, transmission constraints can develop so that several geographically separated generating units must operate at part load to meet an increasing demand. Figure 3 displays an example of the marginal fuels during each hour of one day on the entire PJM Interconnection.[2] The PJM Interconnection includes parts of Region 1 (East Central

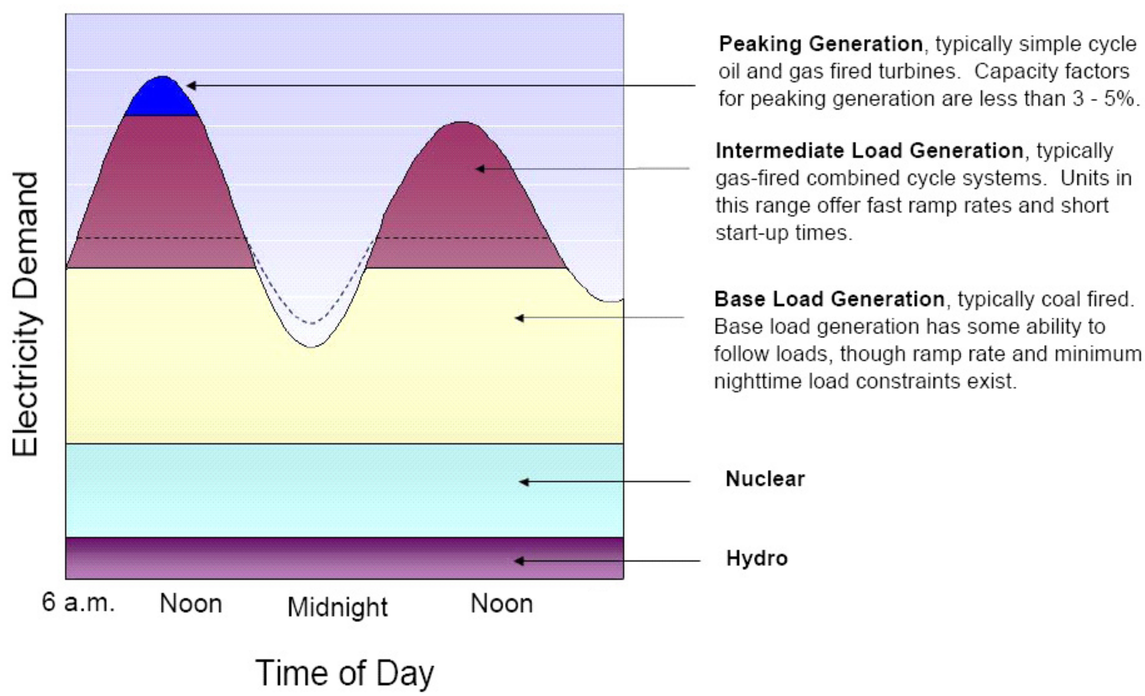


FIGURE 2 Typical Summer Load Profile and Dispatch Scheme for Many U.S. Utilities (Source: Shelby and Mui 2007)

[2] PJM Interconnection Marginal Fuel Type Data website, available at: ftp://ftp.pjm.com/pub/market/energy/marginal-fuel-type/200802_Marginal_Fuel_Postings.csv. Last accessed October 2008.

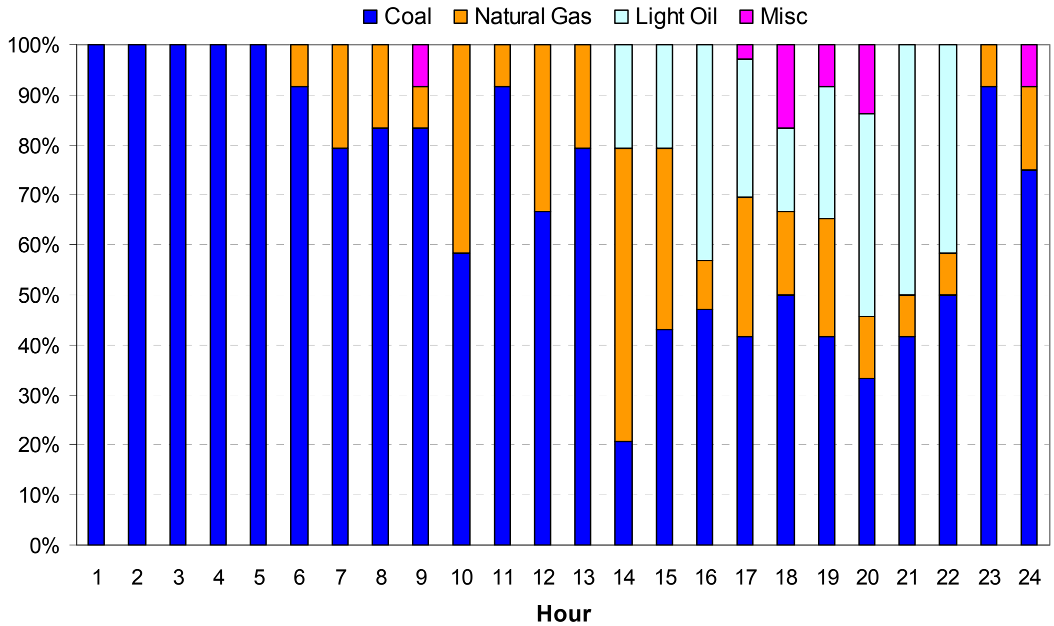


FIGURE 3 Example of Hourly Marginal Fuels Data by Time of Day (Source: PJM Interconnection Marginal Fuel Type Data website, available at: ftp://ftp.pjm.com/pub/market/energy/marginal-fuel-type/200802_Marginal_Fuel_Postings.csv

Area Reliability Coordination Agreement), Region 3 (Mid-Atlantic Area Council), and Region 9 (Southeastern Electric Reliability Corporation). The height of the bars represents the percentage of contribution from each fuel.

2.1.2 Time of Year

Seasonal load variations also affect the mix of units brought on-line to meet the PHEV charging demand. A typical trend is illustrated in Figure 4, which is based on operating data from the Southwest Power Pool (SPP) for 2006 and 2007, and it shows two data traces: the minimum and the maximum daily load (Roach et al. 2008). The annual pattern of relatively high summer loads is typical for most of the United States, reflecting power demand for air-conditioning. In some local areas, electric heating causes a winter peak or results in a more level annual load pattern.

2.1.3 Climate

The SPP is a summer peaking system because of air-conditioning loads, which add to the daytime peak. Electric heating loads tend to increase off-peak demands and may compete with the off-peak charging of PHEVs during the winter season. These are some of the ways in which regional climate affects the development of a generation mix and the nature of the generation

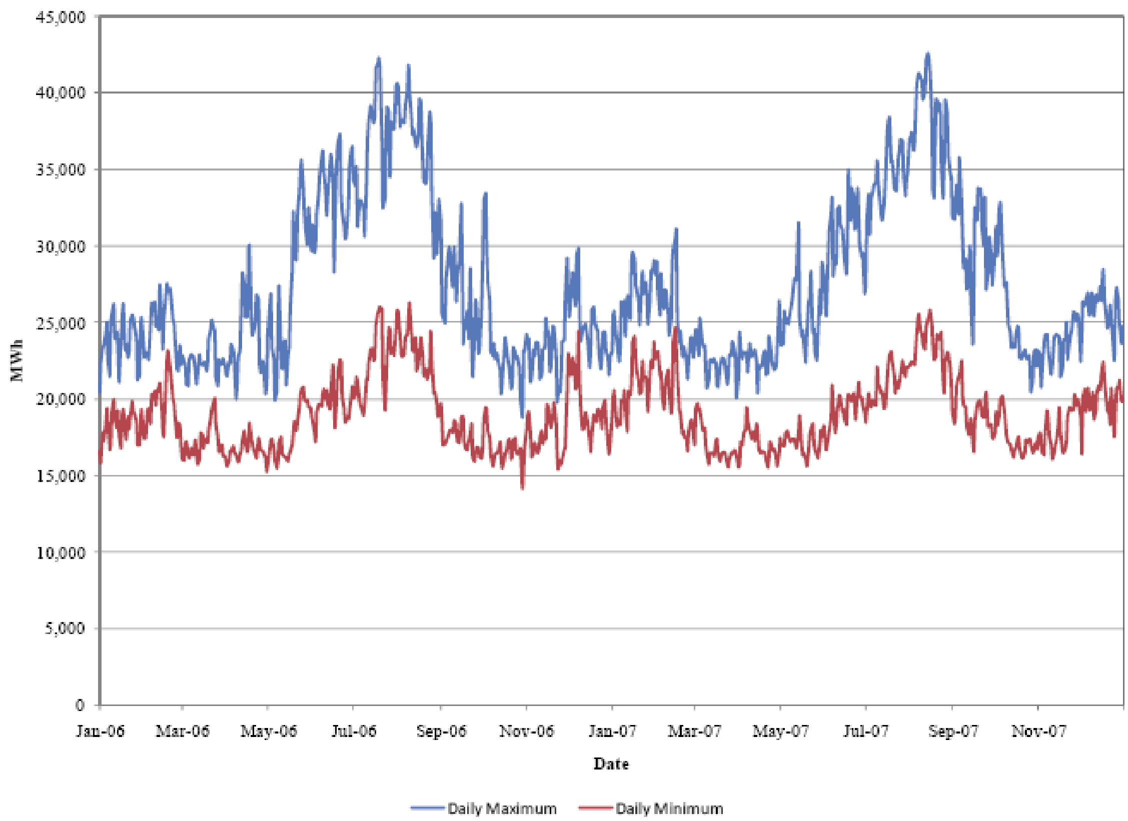


FIGURE 4 SPP Daily Maximum and Minimum Electricity Demand Source (Source: Roach et al. 2008)

mix at the time of PHEV charging. A more subtle time-of-year effect, which is incorporated in most generation expansion and load dispatching models, is the variation of power plant capacity with ambient temperature. This also affects the availability of capacity for dispatching to meet PHEV charging loads.

2.1.4 Generation Mix

Climate, fuel availability, population, industrial activity, local regulation, water availability, pollution levels, and other regional characteristics have influenced the development of each region's specific power system, including the generation mix. As a result, the generation mix varies substantially from region to region, as can be seen in Table 2, which shows the projection for the 2020 average mix from the Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2008 for different regions in the United States.

TABLE 2 Mix of Sources for Average Electric Generation among Regions in the United States (% in 2020) (Source: EIA 2008)

Region	Coal	Oil	Natural Gas	Nuclear	Other
1. East Central Area Reliability Coordination Agreement (ECAR)	83.9	0.5	5.7	9.0	0.9
2. Electric Reliability Council of Texas (ERCOT)	45.2	0.5	37.3	11.9	5.1
3. Mid-Atlantic Area Council (MAAC)	44.1	1.2	5.5	34.2	15.0
4. Mid-America Interconnected Network (MAIN)	52.9	0.3	4.2	31.8	10.8
5. Mid-Continent Area Power Pool (MAPP)	73.1	0.4	1.8	12.3	12.4
6. Northeast Power Coordinating Council / NY (NPCC-NY)	12.3	5.6	33.9	29.3	18.9
7. Northeast Power Coordinating Council / NE (NPCC-NE)	17.5	1.8	43.0	21.9	15.8
8. Florida Reliability Coordinating Council (FRCC)	53.9	5.5	26.3	11.9	2.4
9. Southeastern Electric Reliability Corporation (SERC)	49.9	0.6	11.9	33.0	4.6
10. Southwest Power Pool (SPP)	74.1	0.6	15.9	4.3	5.1
11. Western Electricity Coordinating Council / Northwest Power Pool Area (WECC-NW)	28.8	0.1	6.4	3.2	61.5
12. Western Electricity Coordinating Council / Rocky Mountain and AZ-NM-Southern NV Power Area (WECC-RMP/ANM)	60.8	0.4	21.2	8.0	9.6
13. Western Electricity Coordinating Council / California (WECC-CA)	13.0	0.0	40.4	17.3	29.3

2.1.5 Vehicle and Charger Design Factors

The vehicle design characteristic with the greatest influence on PHEV charging load is the battery capacity, which is related to the AER and weight of the vehicle. It is most commonly assumed that the charger will operate at normal household power levels, typically 110 V and no more than 20 amps. A sport utility vehicle (SUV) type of PHEV may require larger batteries than a compact or sedan type of PHEV. In order to charge these batteries in a reasonable length of time, more charging current is required. This could be accomplished with a charger operating on 220 V at 30 amps. Single-phase, 220-V service is available to all residential customers, but typically will require professional installation of additional circuit breakers, lines, and a dedicated outlet. The benefit of reduced charging time comes at an additional cost of the higher demand.

2.1.6 Load Growth and Generation Expansion

The inventory of units available for PHEV charging is slowly changing as old units retire or are refitted with new environmental controls and as new units are constructed in anticipation of increasing demand. Also, existing units may change place in the dispatch order as they age or as new plants come on-line. Information on the dynamic nature of the generator inventory is provided by recent inventory statistics from the EIA. In 2006, there were 986,000 megawatts (MW) of generating capacity in the United States, including both utility and non-utility capacity. Also, in 2006, there were 275 generators added, for a total of 13,152 MW of new capacity. At the same time, 186 units retired, for a loss of about 3,500 MW, and net capacity revisions on existing units represented a loss of about 700 MW of capacity (EIA 2007). Although commercial introduction of PHEVs may occur as soon as 2010, it is likely to be one or two decades before a substantial PHEV charging demand exists. Ideally, the generation mix applied at the time of charging will reflect accumulated changes in the plant inventory.

Generation expansion planning, which optimizes changes to the generator inventory, is a complex process that takes into account load growth projections, known and potential changes in regulations, and the technical performance characteristics of current and future generator options. The final inventory, one or two decades, or more in the future, would likely be substantially different under carbon emission constraints than it would be in a business-as-usual case. While the use of the current generation inventory might be useful as an indicator of the potential capacity for PHEV charging, an understanding of the environmental trade-offs requires projected generation expansion consistent with broad planning policies.

Generation expansion may also be influenced by the PHEV charging demand itself, and this charging demand is likely to increase along with a general increase in transportation energy demand. Thus, generation expansion projections become linked to projections of transportation demand. In the AEO 2008, the EIA reference case is based on the historical (1980 to 2006) growth rate for transportation energy use (EIA 2008). The revised growth rate leads to an increase in transportation energy use from 28.2 quadrillion Btu (quads) in 2006 to 33.0 quads by 2030. The reduction in the rate of growth is due to higher fuel economy standards, higher fuel prices, and slower economic growth, all of which lead to efficiency improvements and slower growth in VMT.

Generation expansion planning must take into account both the extent of likely demand growth and the daily and seasonal dynamic structure of the projected demand. Relatively constant loads are best served by large base-load units with low fuel and variable costs. Daily peak loads may best be served by units with low fixed (investment) costs, such as gas turbines. However, lower fuel-cost options, including hydro, will be applied to peak loads if capacity is available. The generation mix applied at a specific time is predicted by dispatch models rather than by generation expansion models. The dispatch models match available capacity to the dynamic load by using cost, emissions, or other criteria to optimize the system. Dispatch models also take reliability and scheduled plant outages into consideration.

2.2 PHEV GRID IMPACT STUDIES

2.2.1 Background

Table 3 is an overview of U.S. energy consumption by fuel for 2007. It should be noted that 91% of coal use is for electric power generation, and 51% of electric power is produced by coal combustion. Petroleum has a virtual monopoly on transportation fuel, as the source of 96% of the energy consumed by that sector. Automotive fuels account for 70% of the total petroleum consumption. In total, the transportation energy demand is essentially equivalent to the primary energy consumed for the combined residential and commercial electricity demand. Clearly, a substantial shift from petroleum to electricity implies a substantial increase in the output of the electricity sector, so the prospect of electrified transportation presents a great challenge to the electric power infrastructure. Recognition of this challenge is one motivation for PHEV grid impact studies.

TABLE 3 Distribution of U.S. Energy Consumption (quads) (Source: EIA 2007)

Energy Source	Transportation	Industrial	Residential and Commercial	Electricity
Petroleum	27.8	9.5	2.0	0.8
Natural gas	0.6	8.0	8.0	7.0
Coal	0.0	1.9	0.0	20.7
Renewable	0.6	2.0	0.6	3.7
Nuclear	0.0	0.0	0.0	8.4

A second motivation is the need to understand the environmental trade-offs implicit in a switch from petroleum to electricity. This very broad issue includes, for example, land-use issues from minerals extraction, hazardous and radioactive waste disposal, and visual impairments from stacks and facilities. The PHEV studies we have examined limited their environmental considerations to air emissions — most prominently, emissions of GHGs.

Several studies have focused on the challenge of supplying electricity to a growing PHEV load by estimating the capacity of the existing generator inventory to supply additional power, primarily off-peak. Other studies allow for growth of the power generator inventory, recognizing that it may take several decades before PHEVs constitute a substantial new load and that, in the intervening years, other power demands are likely to increase as well, older units will retire, and the generation inventory may be quite different from that of today. A third-generation expansion scenario also recognizes the possibility that the growing PHEV demand will add to the demand growth rate, so that PHEVs will themselves eventually influence the generating options available for charging.

2.2.2 Methods

The PHEV impacts on the grid, including fuel use and emissions, occur in the context of the equilibrium between power demand and power generation. Equilibrium exists without the PHEV load, and it is changed by the addition of that load. The difference between these two states is the grid impact that we seek. So, in general, the grid impact studies identify a base case and at least one PHEV case. The PHEV case is defined first by the extent of PHEV power demand, which is the product of the vehicle market share held by PHEVs and the charging requirements and timing for the PHEV fleet. None of the reviewed studies offer anything beyond speculation or assumption as the basis of assumed PHEV market share. This is understandable, given the uncertainties of battery and vehicle development, vehicle costs, fuel costs, and other determinants of market share. Consequently, the most that can be expected of such studies is an estimate of outcomes consistent with assumptions about the vehicle market (i.e., scenario analysis of the PHEV market). Basically, what will the power generation inventory and operations look like if the PHEV deployment assumptions are realized? However, some studies have reversed this question and ask the following: What level of PHEV deployment could be supported by an assumed power generator inventory?

The charging load depends on the PHEV market penetration and the charging characteristics of various PHEV products. These charging characteristics include the voltage (110 V or 220 V), the amperage, and the length of time required for charging. Like the market share, these features are assumed rather than forecasted, but they are very narrowly constrained by limitations of residential power systems and by practical battery capacities.

On the utility side, the charging load is met by available units on the margin at the time of charging. The available units are selected from the full generator inventory by dispatch algorithms of various complexities or by simple heuristics. The simple approaches examine the dispatch order without the PHEVs and apply any remaining capacity from the marginal units to PHEV charging. The net result of interest from our perspective is the distribution of charging load among available generator types. This distribution or share is required by GREET to estimate the associated upstream and downstream emissions. A review of several grid impact studies can be found in the Appendix. We employed the most suitable study for our analysis, which is explained in detail in the next section.

2.3 ADOPTION OF MARGINAL MIX IN GREET

The 2008 ORNL report by Hadley and Tsvetkova[3] was found to be the most inclusive, publicly available, source for providing region-specific default marginal generation mixes for PHEVs. The report reflected AEO 2007 projections for generation capacity expansion and load growth through 2020, and it also employed a region-specific dispatch model.The following is a discussion of some of the major assumptions of that study, which addressed the following

---

[3] Argonne National Laboratory Powertrain Systems Analysis Toolkit website, available at: http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html. Last accessed October 2008.

questions: How is the PHEV load determined, when is the charging taking place, and where is the charging taking place?

What is the PHEV load?

Hadley and Tsvetkova used a PHEV penetration consistent with an EPRI base-case assumption that the market penetration of PHEVs could be greater than 25% for the light-duty vehicle market by 2020. New PHEV sales were assumed to start at 0% of the total vehicle sales in 2010 and grow to 25% by 2020, then hold steady after that, with the vehicle retiring after 10 years. This assumption appears to be aggressive, but it fits with the goal of this analysis to examine the effect of significant demand from PHEVs on the electric grid. The analysis assumed four vehicle classes of PHEVs to be sold, all with a 20-mi AER, ranging from a compact sedan (5.1-kWh battery) to a full-size SUV (9.3-kWh battery).

When is the charging taking place?

Two charging scenarios were examined: an “evening” case, where vehicles started charging at 5 p.m., and a “night” case, where vehicles started charging at 10 p.m. Three charging rates were evaluated (1.4 kW, 2 kW, and 6 kW), which, along with battery size, determined the number of hours required for charging. For this analysis, the night case was chosen, even though the true off-peak is probably close to midnight, because of its potential for lower electricity cost. The 2-kW charging rate was chosen, which would likely avoid any additional cost required for rewiring the household’s electrical system, as would likely be the case for the 6-kW charging rate.

Where is the charging taking place?

The study by Hadley and Tsvetkova covered the 13 NERC regions identified in the AEO 2007 generation expansion plan. The regional power plant inventory for 2020 was taken from the AEO 2007. That inventory reflected the necessary expansion to meet growth, anticipated unit retirements, and fuel and technology choices based on capital costs, projected fuel costs, and regulatory restrictions. Hadley and Tsvetkova determined the marginal electricity supply for PHEVs from the AEO 2007 baseline projections. However, since the AEO 2007 does not anticipate PHEV market penetration, PHEV charging demand is not incorporated in the generation expansion planning. However, PHEV loads at the assumed vehicle penetration level are not expected to have a significant effect on capacity expansion by 2020. As evidence of that, a study by Kintner-Meyer et al. (Rousseau et al. 2004), which took a very broad look at the ability of the existing U.S. capacity mix to serve PHEV load, estimated that up to 73% of the current light-duty vehicle usage could be accommodated by the existing power infrastructure. Thus, ignoring the possible effects of PHEV loads on generation expansion is a compromise that is not likely to be a significant source of error under the current assumptions for PHEV penetration and for the analysis year of 2020. For higher levels of PHEV penetration and a more distant time horizon, the PHEV load should be included in the generation expansion plan. The loading of generators to meet the demand pattern was developed with the Oak Ridge Competitive Electricity Dispatch Model (ORCED). The ORCED determined which units will be brought online or ramped up to meet the PHEV charging demand.

In this analysis, we focus on three regions — Region 4 (Illinois), Region 6 (New York), and Region 13 (California) — that encompass large metropolitan areas and provide a significant variation of marginal generation mixes. In addition, we examine a U.S. average generation case as a baseline and a renewable case that represents the upper limit on benefits from PHEVs. These five generation mixes are provided in Table 4. It should be noted that the selected NERC regions for this analysis exhibit a significant variation of generation mix, which could also serve as scenarios to predict the impact of employing PHEVs in regions with similar generation. The goal of this analysis is to provide the results of these specific mixes as a guide to any region that has similar generation. For example, a study that evaluates PHEV charging from a marginal mix that relies mostly on the natural gas combined cycle (NGCC) technology may consider the WTW results of this analysis for California. Similarly, a marginal mix that relies heavily on conventional coal or residual oil for power generation may consider the WTW results of this analysis for Illinois and New York, respectively.

This study is not meant to provide an interregional comparison or to impart a criticism of the relative environmental performance of various regions. Thus, the regions and states mentioned in this analysis should be viewed as short-hand labels for the underlying generation mixes associated with them, since the results of this analysis directly reflect the impact of these mixes.

TABLE 4 Generation Mixes for Recharging PHEVs for Use in GREET

Mix	Coal	Oil	Natural Gas	Nuclear	Other
U.S. Average	52.5	1.3	13.5	20.1	12.6
Illinois – Region 4 (MAIN) Marginal	75.2	0.0	24.7	0.0	0.1
New York – Region 6 (NPCC-NY) Marginal	3.4	67.2	29.4	0.0	0.0
California – Region 13 (WECC-CA) Marginal	0.0	0.0	99.0	0.0	1.0
Renewable	0.0	0.0	0.0	0.0	100.0

3 PSAT SIMULATION OF VEHICLE FUEL ECONOMY

The PSAT is a forward-looking tool designed to serve the requirements of automotive engineering throughout the development process, from modeling to control (Rousseau et al. 2004).[4] It uses the driver outputs to send commands to the different powertrain components in order to follow a specified drive cycle, and it has been validated within 5% for several vehicle powertrain configurations on a number of driving cycles (Pagerit 2006).

When analyzing the performance of PHEVs, the amount of electricity used by the vehicle compared with the amount of fuel used by the engine is a key factor. The higher the amount of energy storage (or capacity) the battery has, the less the engine power will need to be used. Initially, the concept of a PHEV's operation was to charge the battery to a high state-of-charge (SOC) (e.g. 90%), then the vehicle would operate in a charge-depleting (CD) mode by using only the stored electricity until it reached a low SOC (e.g. 30%). Once the battery reached the low SOC threshold, it would operate in charge-sustaining (CS) mode, which is similar to the operation of regular HEVs (Shidore 2007).This operation strategy allows the vehicle to operate as a zero-emission vehicle in CD operation. However, the high cost of batteries required for extended AER has led vehicle designers to rethink this control strategy and explore ways to extend the VMT driven on the battery by using it more efficiently. A "blended" CD mode, which intermittently turns on the engine during CD operation, increases the CD VMT range by utilizing both electricity and engine fuel. For example, the blended mode operation increases the VMT driven on a given amount of battery capacity by turning on the engine during high power demands in the CD mode; otherwise a significant amount of the battery's energy would be drained if not supplemented by the engine. Thus, the blended mode operation could reduce the initial size and cost of the PHEV battery, while providing a bridge between the current regular HEVs and the future all-electric PHEVs as battery performance and cost are improved.

The PHEV electrical components (i.e., battery and electric machine, such as an electric motor) were sized to be able to drive the Urban Dynamometer Driving Schedule (UDDS) cycle electrically. The constraint to drive all-electrically imposes specific size limitations on the battery and the electric machine, which also imply certain vehicle cost constraints, as mentioned above. To minimize the cost of the electric powertrain in these hybrids, PSAT employed a blended CD control strategy. In addition to lowering the power requirements for the battery and electric machines, there has been interest in employing CD strategies to reduce fuel consumption when the AER is exceeded. The batteries for each of the vehicles simulated with PSAT have their energy capacity and power sized to reach their vehicle's desired AER. Although the batteries were sized to power the vehicle through the target AER, the vehicle can extend the CD driving range by utilizing the engine during periods of the cycle when the road's load power demand is high. The CD extended range was constrained to within 20% (with a 10% tolerance) of the rated AER by adjusting a vehicle's control strategy parameter. This parameter was a power threshold that determined when the engine should be turned on. When the power demand exceeded this threshold, the engine was turned on. A study by Delorme et al. provides a detailed

[4] Argonne National Laboratory Powertrain Systems Analysis Toolkit website, available at: http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html. Last accessed October 2008.

explanation of the assumptions and methodology of PSAT for evaluating the fuel economy of advanced vehicle configurations (including ICEVs, HEVs, PHEVs, and electric vehicles for model years 2010 to 2045) (Delorme 2008). The vehicle assumptions for the PSAT simulations, which are incorporated in this study, are shown in Table 5.

Table 6 shows the electricity consumption and fuel economy results produced by PSAT simulations of the UDDS and Highway Federal Emissions Test (HWFET) cycles for CD and CS operations of different PHEVs assuming a MY 2015 midsize passenger car platform. Care should be taken when interpreting the fuel economy of the engine in CD operation, as it discounts the grid electric energy use during the same CD VMT distance. It should be noted that the per-mile energy use from the engine and electric motor are additive in CD operation, since the CD VMT is powered by the blended operation of both systems. Thus, the fuel economy data for the on-board power unit (i.e., engine or fuel cell) in CD operation should always be interpreted in conjunction with the CD electric consumption data shown in Table 6.

The CD VMT on UDDS and HWFET are shown in Figures 5 and 6, respectively. The average VMT for UDDS and HWFET on CD operation are calculated and shown in Figure 7. The fuel economy data for the engine in CD operation should be correlated with the actual CD VMT range shown in Figures 5 and 6, since the engine could be intermittently employed by the vehicle's control strategy to charge the battery in CD operation. The charging of the battery extends the VMT distance in CD mode beyond the rated AER and results in higher engine fuel consumption (i.e., lower fuel economy) in CD operation.

TABLE 5 Vehicle Assumptions for PSAT Simulations

		Vehicle mass (kg)	Engine Power (W)	Fuel Cell Power (W)	Motor 1 Power (W)	Motor 2 Power (W)	Battery Power (W)	Frontal Area (m^2)	Drag Coefficient	Wheel Radius (m)
Gasoline ICE	ICEV	1,515	102,109	n/a	n/a	n/a	n/a	2.23	0.26	0.317
	AER 0	1,563	82,530	n/a	60,134	49,474	26,748	2.23	0.26	0.317
	AER 10	1,592	70,373	n/a	64,461	42,186	46,610	2.23	0.26	0.317
	AER 20	1,617	71,263	n/a	65,477	42,720	47,335	2.23	0.26	0.317
	AER 30	1,646	72,257	n/a	66,594	43,316	48,093	2.23	0.26	0.317
	AER 40	1,674	73,285	n/a	67,739	43,932	48,968	2.23	0.26	0.317
Diesel ICE	AER 0	1,615	71,247	n/a	63,656	59,626	27,886	2.23	0.26	0.317
	AER 10	1,648	60,878	n/a	70,415	50,948	48,465	2.23	0.26	0.317
	AER 20	1,676	61,671	n/a	71,526	51,612	49,279	2.23	0.26	0.317
	AER 30	1,707	62,521	n/a	72,547	52,323	50,076	2.23	0.26	0.317
	AER 40	1,734	63,314	n/a	73,954	52,987	50,978	2.23	0.26	0.317
E85 ICE	AER 0	1,546	88,115	n/a	61,139	58,712	26,748	2.23	0.26	0.317
	AER 10	1,569	75,099	n/a	62,991	50,040	46,103	2.23	0.26	0.317
	AER 20	1,597	76,101	n/a	64,064	50,707	46,884	2.23	0.26	0.317
	AER 30	1,627	77,944	n/a	65,338	51,935	47,718	2.23	0.26	0.317
	AER 40	1,653	79,107	n/a	66,612	52,710	48,503	2.23	0.26	0.317
H_2 FC	AER 0	1,530	n/a	72,857	90,726	n/a	29,024	2.23	0.26	0.317
	AER 10	1,552	n/a	59,568	94,424	n/a	49,509	2.23	0.26	0.317
	AER 20	1,583	n/a	60,396	95,992	n/a	50,554	2.23	0.26	0.317
	AER 30	1,615	n/a	61,017	97,654	n/a	51,804	2.23	0.26	0.317
	AER 40	1,650	n/a	62,735	99,333	n/a	53,423	2.23	0.26	0.317

TABLE 6 PSAT Electricity Use and Fuel Economy Results (Wh/mi for CD electric operation, and miles per gasoline-equivalent gallons (mpgge) for CD and CS engine operations)

		ICEV	AER 0	AER 10			AER 20			AER 30			AER 40		
Engine Type	Cycle		Regular Hybrid	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine
Gasoline ICE	UDDS	27.6	45.6	148.1	132.4	47.1	141.3	122.3	46.9	174.1	184.3	46.6	165.1	153.4	46.2
	HWFET	34.0	39.7	107.8	78.3	41.1	136.9	103.9	41.0	158.2	134.5	40.6	168.0	152.6	40.2
E85 ICE	UDDS		42.9	146.1	125.5	44.4	141.2	118.4	44.2	172.6	179.7	43.8	164.3	148.6	43.4
	HWFET		37.5	106.3	73.8	38.9	136.9	99.3	38.8	156.8	126.2	38.3	167.0	144.4	37.9
Diesel ICE	UDDS		49.4	151.4	138.1	50.0	144.7	127.5	49.7	179.7	191.3	49.3	169.7	158.7	48.9
	HWFET		43.0	110.2	84.1	43.8	140.3	112.2	43.6	163.3	145.7	43.2	172.6	164.5	42.9
H_2 FC	UDDS		59.4	157.7	132.6	59.5	154.2	123.4	58.8	156.2	120.7	58.1	181.8	142.7	57.3
	HWFET		62.3	229.4	1514.4	61.5	224.0	601.5	60.9	170.1	189.6	60.3	184.7	225.4	59.7

Since the control parameters in PSAT have been designed to achieve a CD range within 20% of the rated AER, some VMT distances are greater than others, as shown in Figures 5–7. For example, the gasoline PHEV produced a longer CD range in the HWFET cycle than the CD range of the corresponding fuel cell PHEV at AER 10. This is because the gasoline engine is employed significantly during the HWFET cycle, resulting in a relatively low electric energy consumption of 107.8 Wh/mi for the AER 10 case, while the electricity consumption for the corresponding H2 FC PHEV is higher, at 229.4 Wh/mi. This indicates that the fuel cell is not significantly employed on that cycle, and hence the observed high fuel economy of 1,514.4 mpgge for the H2 FC in CD operation.

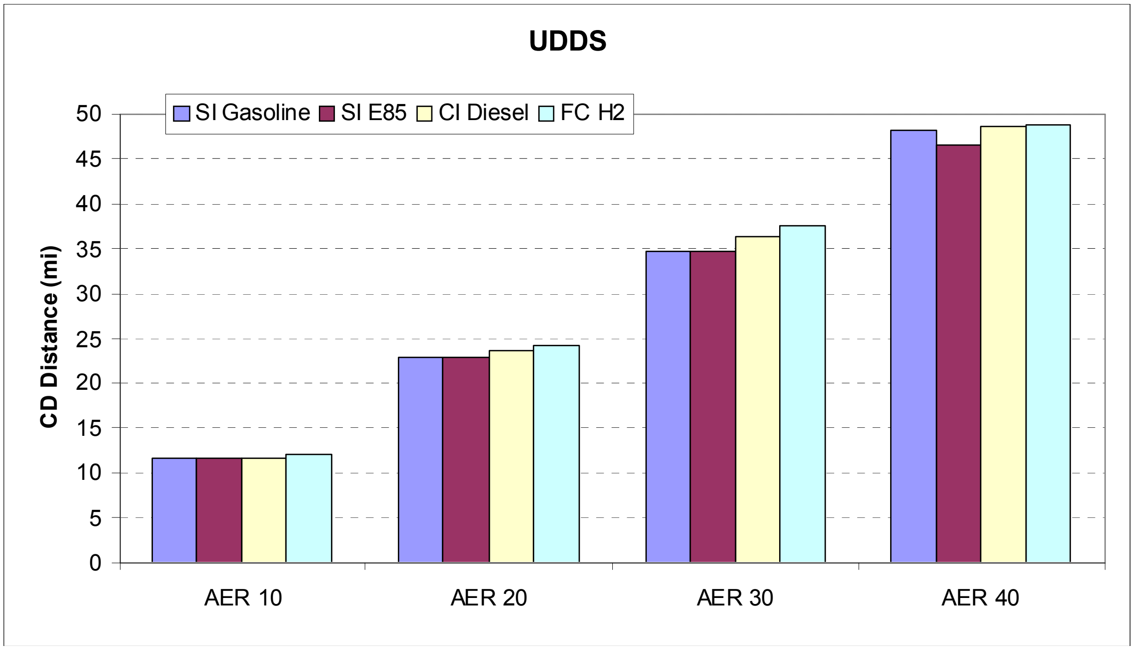


FIGURE 5 CD VMT on UDDS from PSAT Simulations

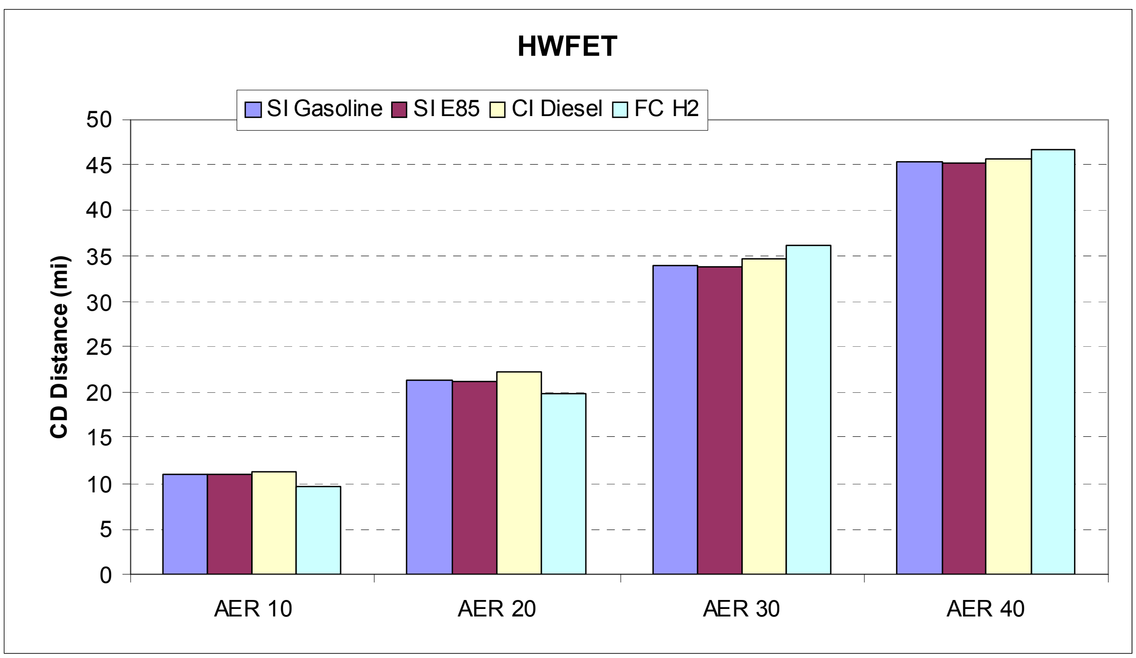


FIGURE 6 CD VMT on HWFET from PSAT Simulations

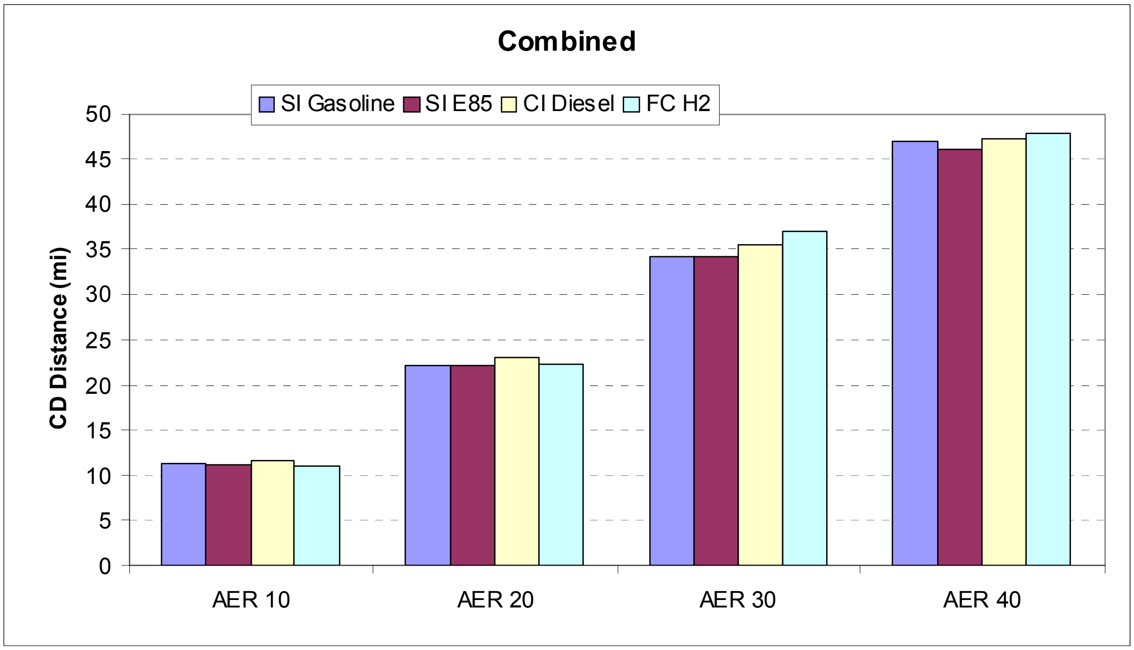


FIGURE 7 Average VMT for UDDS and HWFET on CD Operation

4 VEHICLE MILES TRAVELED SPLIT BY CHARGE-DEPLETING VERSUS CHARGE-SUSTAINING OPERATION

Graham et al. (2001) discussed two methods for evaluating the potential of PHEVs to replace miles driven by gasoline with miles driven by electricity. The mileage weighted probability (MWP) method by EPRI and the utility factor (UF) method by the SAE J1711 subcommittee were both developed by using the 1995 National Personal Transportation Survey (NPTS) to calculate the "average" VMT displaced by an all-electrical PHEV that is fully charged and discharged once per day. The MWP method resulted in a lower potential for electric mile substitution than the UF method. Vyas et al. investigated these results but were unable to find how the MWPs were developed (Vyas et al. 2007). When the 2001 NHTS data became available, Vyas et al. updated the UF and examined the blended-mode strategy, which was not considered in the original calculations. The UF partitioned the average national miles driven into VMT that could be met by the PHEV's CD mode and VMT that exceeded the rated CD range.

Table 7 shows the share of national VMT contributed by vehicles traveling various ranges per day and the maximum percentage of VMT that could be substituted by all-electric operation of a PHEV. If a PHEV has an AER rating equal to or larger than the daily VMT, it could travel all those miles on electricity. However, if the vehicle is driven longer than the AER, only the first miles driven up to the AER can be electrified. Figure 8 shows a curve fitted to these results. Furthermore, if the PHEV does not operate all-electrically in CD mode and employs some type of blended-mode strategy, the miles to deplete the battery will be extended beyond the AER rating. When a PHEV that operates under a blended CD mode travels a distance shorter than or equal to its rated electric range, the battery will not be depleted and fewer miles will be displaced by electricity, as compared with a PHEV that uses 100% electricity in the CD mode.

TABLE 7 Share of National VMT Available for Substitution by a PHEV Using 100% Grid Electricity in CD Mode until Depletion

Daily Travel Range of Vehicle	VMT Share in NHTS 2001	One Charge/Day – % "Electric" VMT by PHEV Type				
		10 EV mi	20 EV mi	30 EV mi	40 EV mi	60 EV mi
Up to 10 mi	3.3%	3.3%	3.3%	3.3%	3.3%	3.3%
10-20 mi	8.1%	5.3%	8.1%	8.1%	8.1%	8.1%
20-30 mi	10.0%	3.9%	7.9%	10.0%	10.0%	10.0%
30-40 mi	10.0%	2.8%	5.7%	8.5%	10.0%	10.0%
40-60 mi	16.8%	3.4%	6.7%	10.1%	13.5%	16.8%
Over 60 mi	51.8%	4.5%	8.9%	13.4%	17.9%	26.7%
PHEV sum	100.0%	23.2%	40.6%	53.4%	62.8%	74.9%

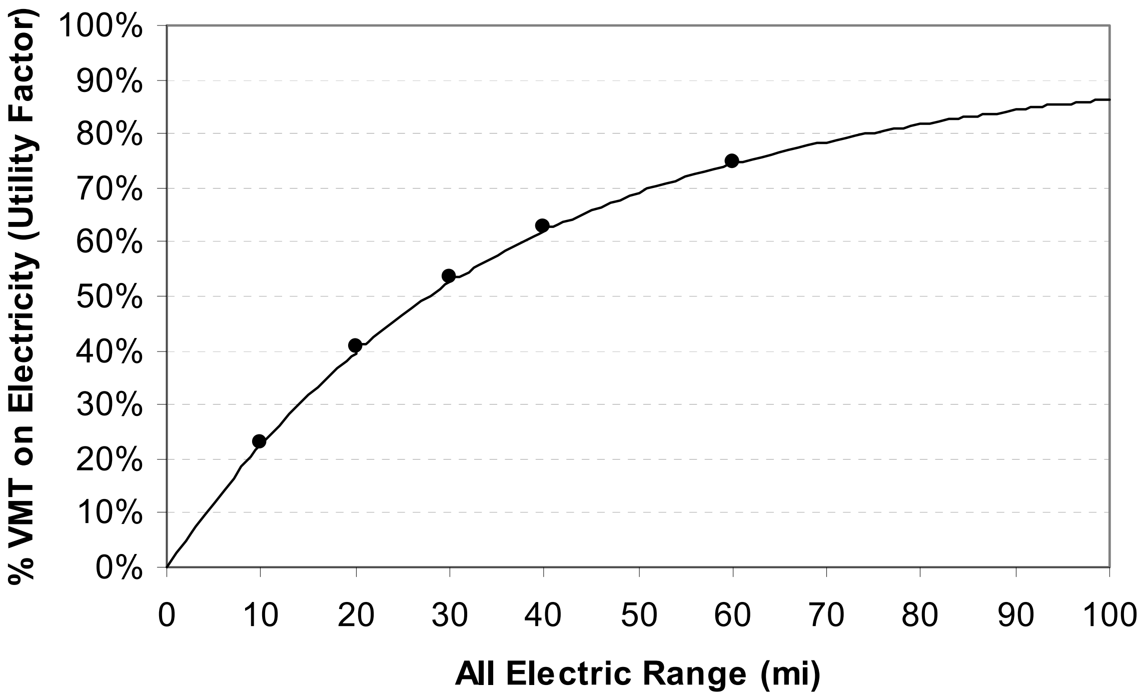


FIGURE 8 National VMT Available for Substitution by a PHEV Using 100% Electric CD Mode

When estimating the potential of national savings in petroleum energy use and GHG emissions, an estimate of the electrifiable VMT share based on Figure 8 is complicated further by the following issues, according to Santini and Vyas (2008):

- Slow fleet turnover (~7-8%/year) will require time to accomplish large-scale change.
- PHEVs will not be purchased by everyone.
- PHEVs will likely complement rather than displace HEVs, thus expanding the long-term hybrid drivetrain market (i.e., PHEVs may not become a universal powertrain).
- Various control strategies for utilizing the engine and the electric machine could result in a myriad of extended VMT shares driven in CD mode.
- PHEVs will vary in their AER capability and will have different configurations of the electric machine, battery, and engine.
- PHEVs purchased with a nominal range capability (AER rating) will not exactly realize that rated value in practice.
- Batteries for PHEVs may be charged more than once every day.

Due to the above issues and the methodological differences in estimating the VMT displaced by electricity, our analysis employed the UF method to evaluate the share of VMT driven in CD mode, based on the AER of the vehicle and data in Figure 8. Furthermore, because of the uncertainties in estimating that share and in order to simplify the analysis, the rated AER (rather than the extended miles driven in CD operation, as shown in Figure 7) was used to determine the UF. Then the UF was used to combine the WTW results of the CD and CS operations, as explained in Section 5.

5 GREET WELL-TO-WHEELS ENERGY USE AND GREENHOUSE GAS EMISSIONS CALCULATIONS

5.1 OVERVIEW

To perform WTW energy and GHG emissions calculations in GREET, the PSAT (on-road adjusted) fuel economy results for different fuel/vehicle systems were processed for inclusion in GREET. The first step in the processing of PSAT simulation results was to convert the electricity use and the fuel economy values of the engine (ICE or fuel cell) to per-mile fuel consumption in consistent units (e.g., Btu/mi), as shown in Table 8. The electricity consumption at the wall outlet was calculated from the grid electricity use in CD operation by assuming a charger efficiency of 85%. The average fuel consumption of the engine in the CD and CS operational modes was calculated based on weighting factors of 55% and 45% for the fuel consumption in UDDS and HWFET driving cycles, respectively. Thus, Table 8 includes three types of fuel consumptions for each PHEV system: grid electricity consumption in CD operation, engine fuel consumption in the blended CD operation, and engine fuel consumption in the CS operation. The first two columns in Table 8 represent the fuel consumption of the corresponding conventional gasoline ICEV and regular HEV (AER 0) systems, respectively. They are provided to allow the comparison of fuel consumption between the existing and future powertrain systems.

The data in Table 8 are plotted in Figures 9 and 10 for different fuel/vehicle systems. Figure 9 reveals two qualitative features of the PSAT fuel consumption results for PHEV powertrains that use blended mode operation: the ICEs consume more (fuel) energy than the electric motor at the lower AER range, while the opposite trend is observed for the fuel cell. It should be noted that the conversion efficiency of the electric energy to mechanical energy (powering the wheels) is several times higher than the conversion efficiency of fuel energy in the engine, since the electric energy has already been upgraded in the upstream process of power generation. The impact of this issue will become evident in the WTW results presented in Section 5.2. Figure 9 also reveals the effect of the control strategy on the contribution of the engine relative to that of the electric motor in blended CD operational mode. Such an effect is evident in Figures 5 and 6 at AER 30, where the fuel consumption of the fuel cell exceeded the electricity consumption of the electric motor, thus significantly extending the distance in CD operation for the H2 FC PHEV 30. The observed buckling shown in Figure 9 for the H2 FC PHEV 30 is mainly due to the control strategy parameters in PSAT, which are tuned to obtain a CD range within 20% of the rated AER. The 20% (±10%) allowance in the CD range may allow additional usage of the engine (or fuel cell) at the expense of the electric motor, which impacts the trend of fuel and electricity consumption in CD operation.

TABLE 8 Fuel Consumption Calculated from PSAT Simulated Fuel Economy Results (Btu/mi)

		AER 0	AER 10			AER 20			AER 30			AER 40		
Fuel	ICEV	Regular Hybrid	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine
Gasoline	3,790	2,680	520	1,135	2,590	560	1,010	2,600	670	725	2,620	670	750	2,645
E85		2,840	515	1,200	2,740	560	1,050	2,750	665	760	2,780	665	780	2,810
Diesel		2,470	535	1,080	2,435	575	955	2,450	690	680	2,470	685	710	2,490
Hydrogen		1,890	760	510	1,895	745	595	1,915	650	795	1,940	735	670	1,960

Figure 10 shows the differences in fuel consumption in CS and CD operational modes for various PHEV powertrains. The markers shown on the vertical axis represent the fuel consumption of the gasoline ICEV and the regular HEVs (AER 0) to compare the fuel consumption of these powertrains with those of PHEV systems. Figure 10 indicates that the vehicle's energy consumption in the CD operation is much lower than that in the CS operation, mainly due to the implication of the electric energy use in the CD operation, as discussed above. Overall, the vehicle's energy consumption trend exhibits a small change with increasing AER for both CS and CD operations.

5.2 RESULTS OF WELL-TO-WHEELS SIMULATION

The WTW analysis of PHEVs in GREET is separated into three distinct parts: grid electricity use in CD operation, fuel use in CD operation, and fuel use in CS operation. It should be noted that the combined operation of the electric motor and engine contribute to the VMT in CD blended mode; thus their per-mile energy use and emissions must be added to properly characterize the PHEV CD operation. The data shown in Table 8 represent only the energy use in the PTW (vehicle operation) stage. The PTW GHG emissions are calculated based on the carbon content of the fuel and the engine's emissions characteristics. The electricity use by the vehicle does not produce any GHG emissions, since all emissions have already occurred upstream of the vehicle during the electric power generation and transmission stage (WTP). Thus, the WTP energy use and emissions must be calculated to account for their occurrences during electricity generation and transmission, as well as during fuel production and transportation to the vehicle's point of use. For each of the WTP and PTW stages, GREET calculates total energy use, fossil energy use (combining petroleum, natural gas, and coal), petroleum energy use, and carbon dioxide (CO_2)-equivalent GHG emissions. The GHG emissions calculation combines CO_2, methane (CH_4), and nitrous oxide (N_2O) with their global warming potentials, which are 1, 25, and 298, respectively, as recommended by the latest Intergovernmental Panel on Climate Change for a 100-year time horizon (IPCC 2008).

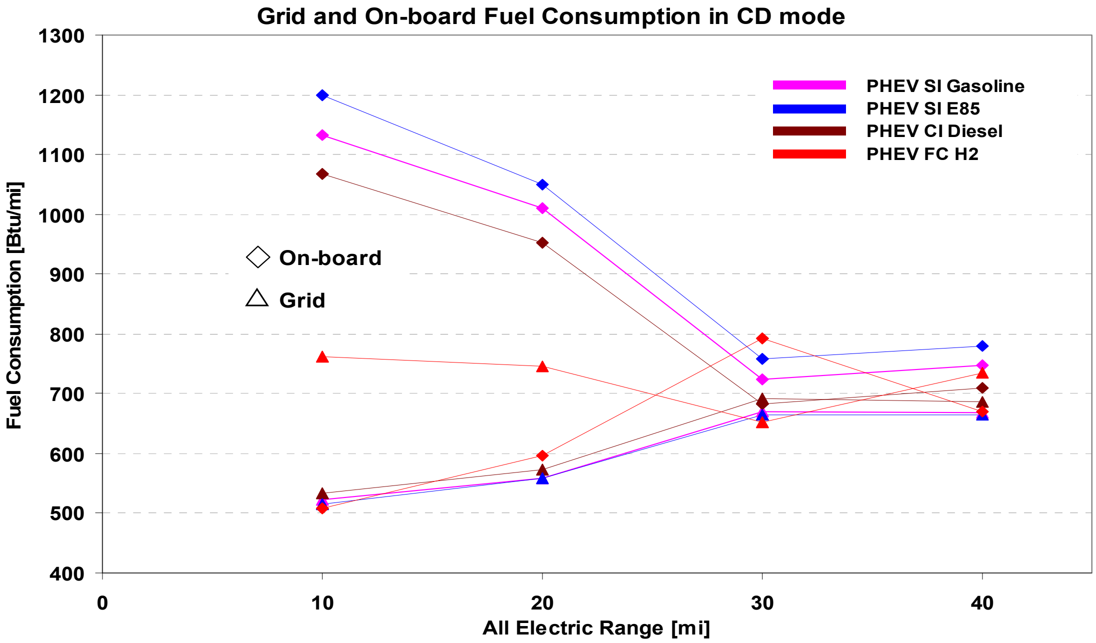


FIGURE 9 Fuel Consumption in CD (blended mode) Operation

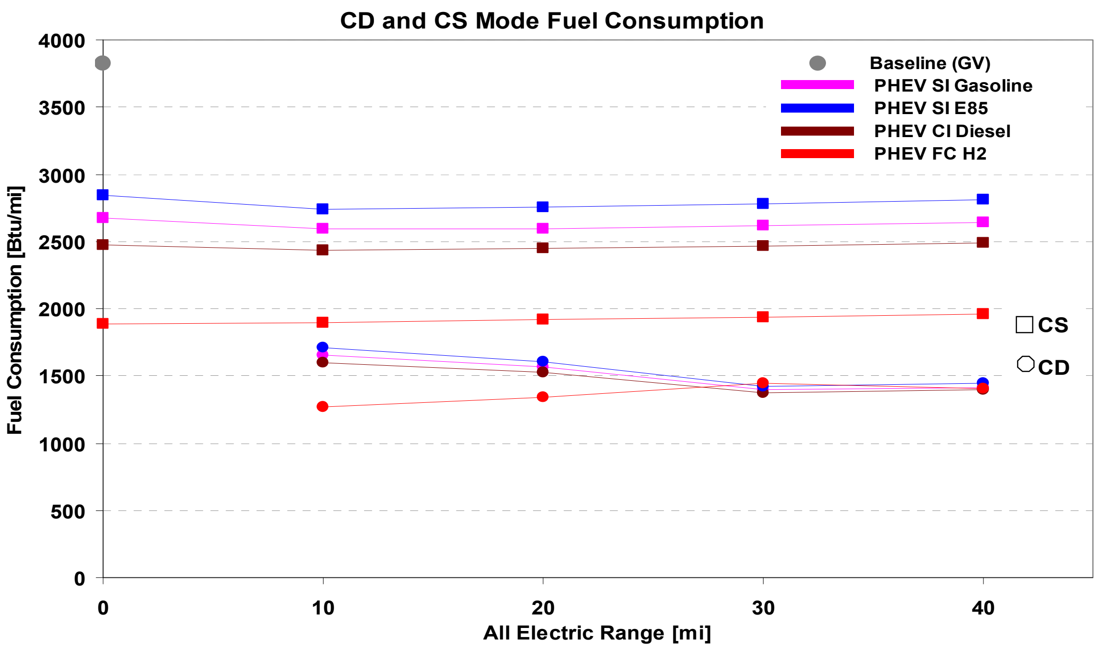


FIGURE 10 Fuel Consumption in CD (blended mode) and CS Operations

The vehicle technologies and fuels considered in this analysis, as well as the feedstock sources for these fuels, are provided in Table 1. The selected vehicle platform is the mid-size vehicle, and the examined AERs for PHEV technologies are AER 10, 20, 30, and 40. The marginal electricity generation mixes considered in this WTW analysis include those in NERC regions 4, 6, and 13 (representing Illinois, New York, and California, respectively), as well as electricity generation from the U.S. average mix and renewable sources. As shown in Table 4, the California marginal mix is almost entirely powered by natural gas, which is a fuel of low carbon intensity, while the marginal mixes in Illinois and New York are dominated by coal and oil, respectively, which are fuels of higher carbon intensity. The WTW results of this analysis should be correlated to the underlying generation mix, rather than to the specified region or state, as discussed above.

Figures 11(a–d) show the WTW energy and GHG emissions results for various PHEV technologies at AER 20, utilizing the California (NERC Region 13) marginal mix for charging the vehicle overnight. As shown in Table 4, the marginal generation mix for that region is almost entirely from natural gas (99%) — the majority of which (83%) is provided by the NGCC technology. GREET calculates an average efficiency of 53% for the marginal electricity generation from NG in California for the year 2020 and assumes 8% losses for electricity transmission and distribution activities. It should be noted that the emission rates during the vehicle's operation will deteriorate over time. Thus, the data of the lifetime mileage midpoint for a typical MY vehicle should be applied for the simulation. Since, on average, the midpoint for U.S. light-duty vehicles is about five years, the fuel economy values in GREET are based on a MY five years earlier than the calendar year targeted for simulation. Therefore, fuel economy values of MY 2015 vehicles are employed in the simulations of calendar-year 2020.

Two stacked bars for CD and CS and operations are shown in Figures 11(a–d) for each vehicle technology. The stacked bar on the left represents the CD blended mode operation and consists of four components, which are (from bottom to top) the vehicle's (PTW) fuel and electricity use, followed by the upstream (WTP) stages of electricity generation and fuel production, respectively. The stacked bar at the right represents the CS operation of the vehicle and consists of the engine's fuel consumption, followed by the upstream stage of the fuel production, from bottom to top, respectively.

Figure 11(a) shows the WTW total energy use for CD (blended mode) and CS operations of different PHEV 20 technologies using the California marginal mix. The total energy includes fossil energy (e.g., petroleum, natural gas, and coal) and non-fossil energy (e.g., nuclear and renewables). Of interest is the second component from the bottom in the stacked CD bar of Figure 11(a), which represents the amount of electricity purchased from the grid to charge the batteries of PHEVs. Although electric energy use is expected to dominate the CD operation, it is remarkable that the electric energy use appears small relative to the fuel energy use in that mode of operation. However, it should be noted that the contribution of electric energy to power the wheels through the electric motor is several times higher than that of the fuel energy through the engine. Thus, most of the energy that reaches the wheels is provided by the electric motor in the CD operation. Figure 11(a) also shows that the CD operation provides significant energy savings compared with the CS operation for all vehicle technologies using the California marginal mix.

Figure 11(b) shows that fossil energy use exhibits a trend similar to that of total energy use, except for E85 and hydrogen from herbaceous biomass (switchgrass), where the CS operation consumes less fossil fuel compared with the CD operation. This is attributed to the biomass renewable energy that dominates the total energy embedded in ethanol and hydrogen fuels for CS operation, as opposed to the natural gas that dominates the electricity generation for CD operation.

Figure 11(c) shows the petroleum energy use for the different PHEV 20 technologies. The electricity use in the CD operation reduces petroleum use relative to CS operation for RFG, LSD, and E85 PHEVs. The E85 PHEV exhibits lower dependence on petroleum energy than RFG and LSD PHEVs due to the high percentage of bio-ethanol in the blend. All hydrogen PHEV systems almost eliminate the dependence on petroleum energy sources.

As expected, the WTW GHG emissions shown in Figure 11(d) exhibit a similar trend to that of fossil energy use for all PHEV fuel/vehicle systems. The negative GHG emissions shown for the biomass-based fuels represent the CO_2 sequestered from the atmosphere by the biomass, which is deducted from the top of the GHG emissions bars to calculate the net WTW GHG emissions for these fuels, as shown by the vertical arrows. It should be noted that the use of biomass-based fuels in PHEVs produces higher GHG emissions in CD operation compared with CS operation, even with the efficient and low carbon intensity marginal generation mix of California. Thus, PHEVs that use fuels produced from biomass sources and operate in CD mode may generate less GHG emissions relative to CS operational mode only if the source of electricity is non-fossil (e.g., nuclear, biomass, or renewable energy sources).

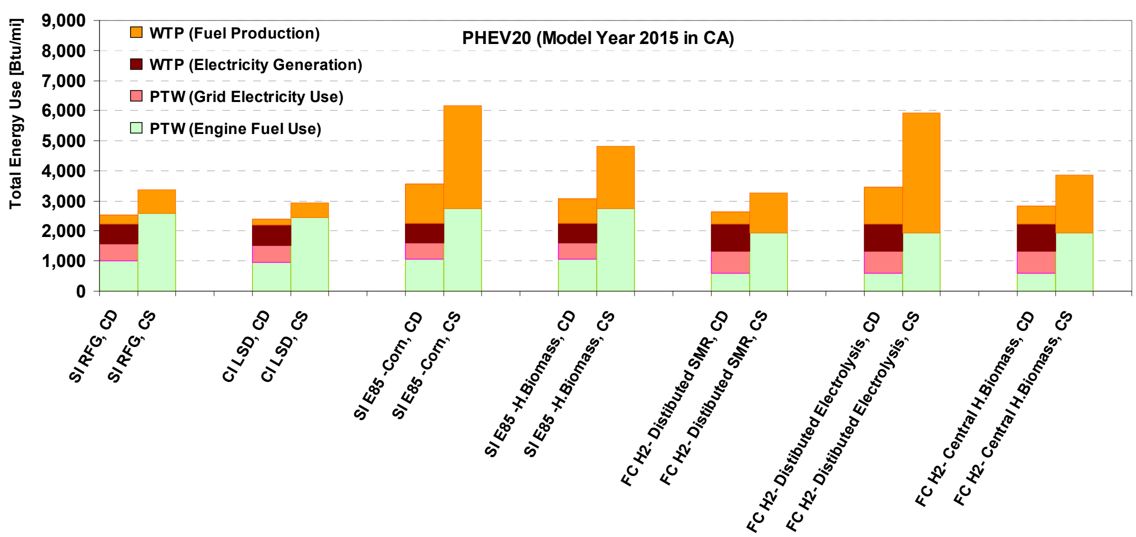


FIGURE 11(a) WTW Total Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the California Marginal Mix

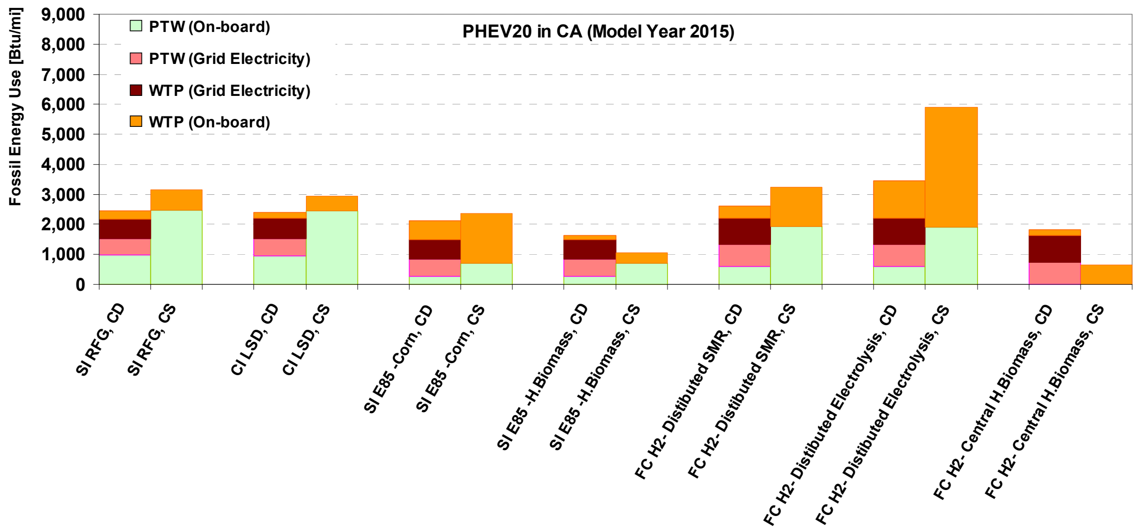


FIGURE 11(b) WTW Fossil Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the California Marginal Mix

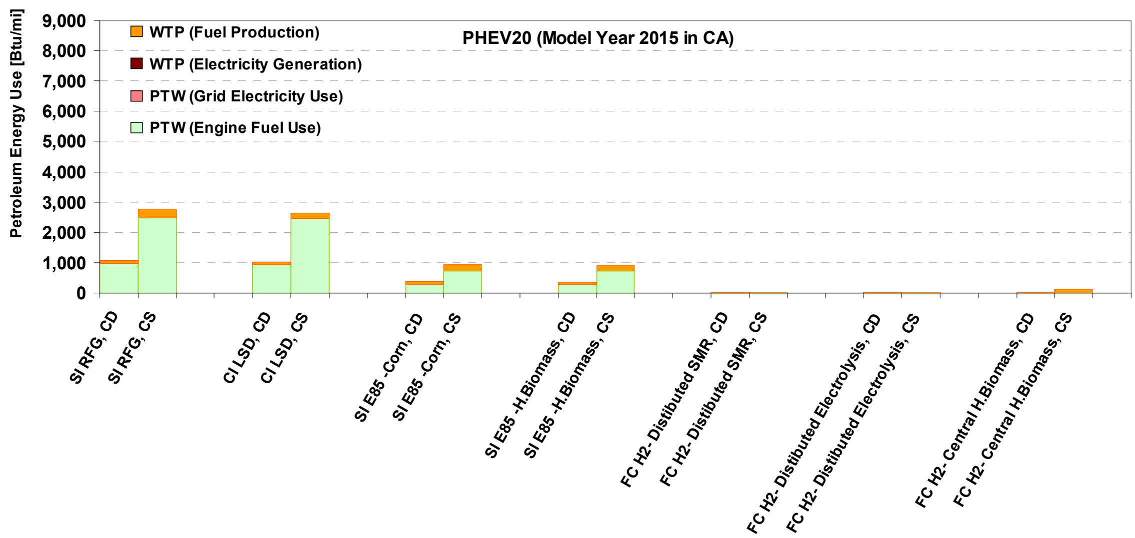


FIGURE 11(c) WTW Petroleum Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the California Marginal Mix

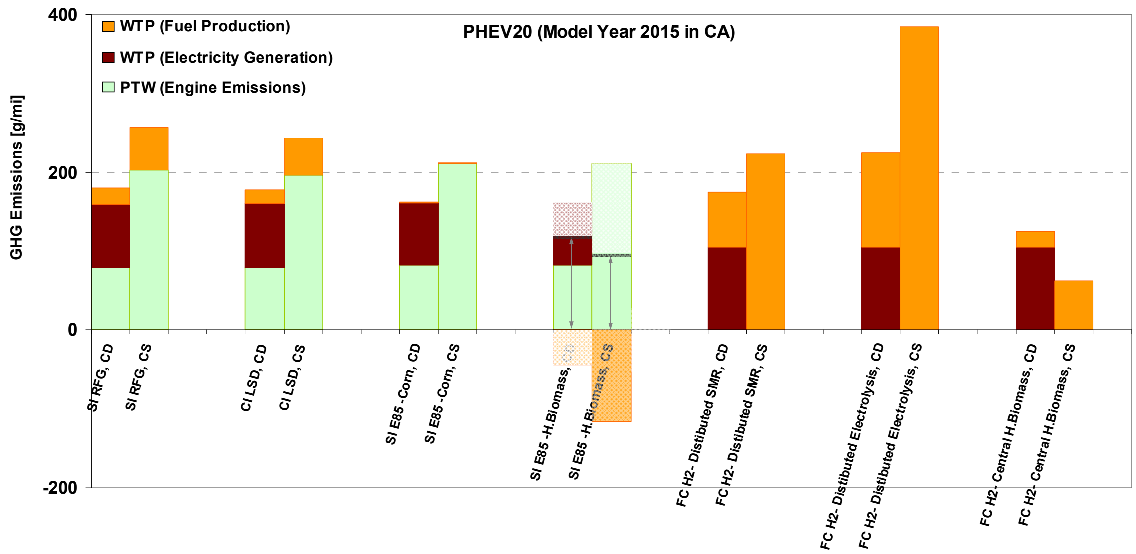


FIGURE 11(d) WTW GHG Emissions for CD (blended mode) and CS Operations of PHEV 20 Using the California Marginal Mix

To study the effect of the electricity marginal generation mix on the WTW analysis of PHEV technologies, two sets of graphs, Figures 12(a–d) and Figures 13(a–d), have been generated for the U.S. average mix and the Illinois marginal mix, respectively. The significance of the marginal generation mixes mostly lies in the electricity generation (WTP stage). Close examination reveals that the only difference between the graphs in Figures 11(a–d) for the California mix and the corresponding graphs in Figures 12 and 13 for the U.S. and Illinois mixes is the size of the electricity WTP component in CD operation (the third component from the bottom of the CD bars).

The electricity WTP energy use and GHG emissions increase successively as the marginal mix becomes less efficient and dominated by a larger share of coal, such as the cases of the U.S. and Illinois mixes, respectively. The U.S. and Illinois generation mixes do not affect petroleum energy use because they incorporate little or no petroleum sources in their portfolio. The reduction in total energy consumption in CD relative to CS operation progressively diminishes as the electricity generation mix changes from the California to the U.S. and Illinois mixes, respectively. Furthermore, the WTW GHG emissions advantage of CD over CS operation disappears by moving from the California to the U.S. generation mix, and it is even reversed by moving to the Illinois marginal generation mix, thus surrendering the potential GHG emissions benefit of PHEVs (except for the case of hydrogen when produced via electrolysis). In other words, the improved energy efficiency and GHG emissions of PHEVs over regular HEVs could be entirely negated by the energy penalty and GHG emissions associated with the electricity generation in power plants. Such implications underscore the significance of the employed electricity generation mix for charging PHEVs.

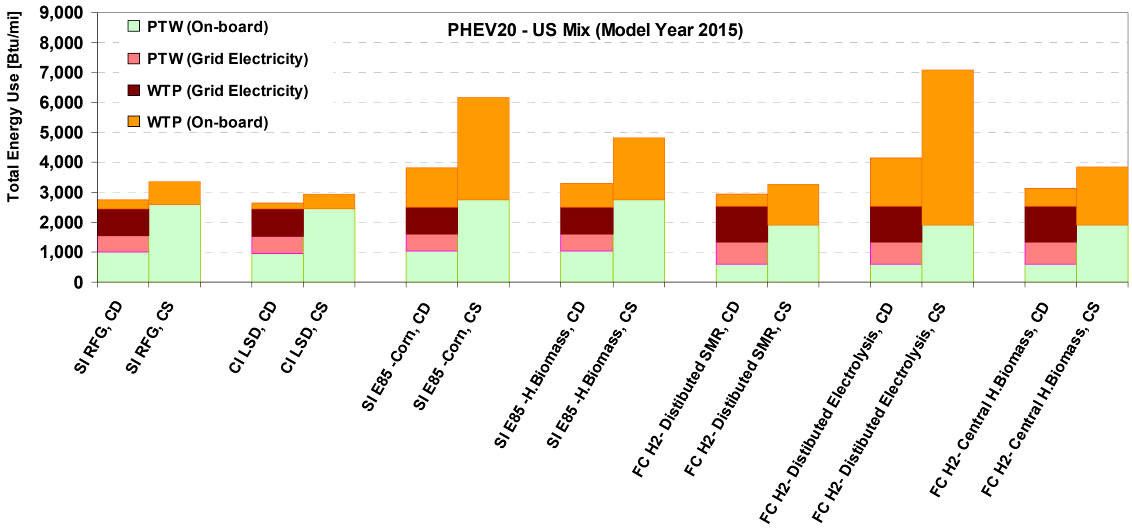


FIGURE 12(a) WTW Total Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the U.S. Mix

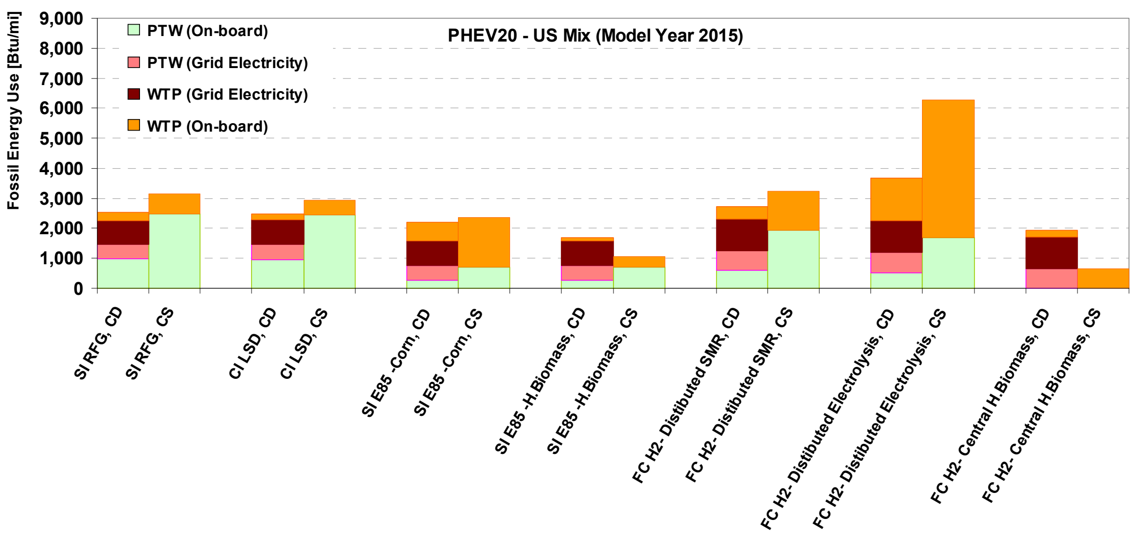


FIGURE 12(b) WTW Fossil Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the U.S. Mix

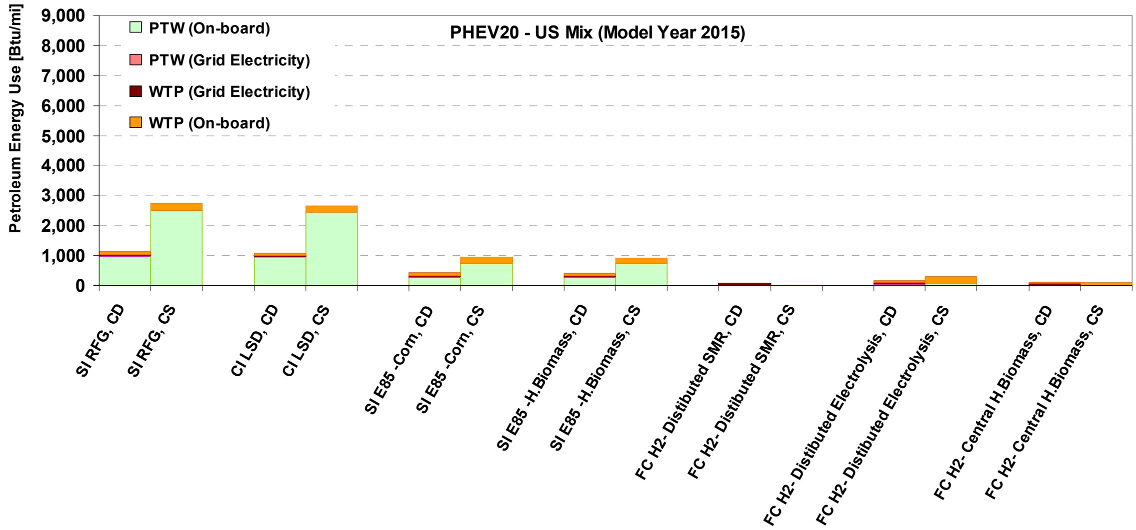


FIGURE 12(c) WTW Petroleum Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the U.S. mix

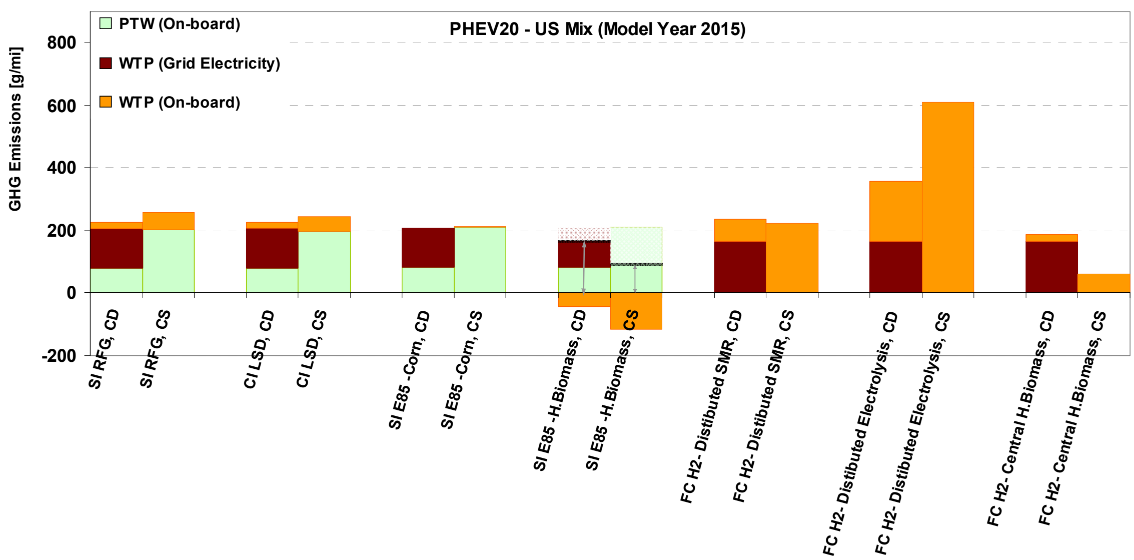


FIGURE 12(d) WTW GHG Emissions for CD (blended mode) and CS Operations of PHEV 20 Using the U.S. Mix

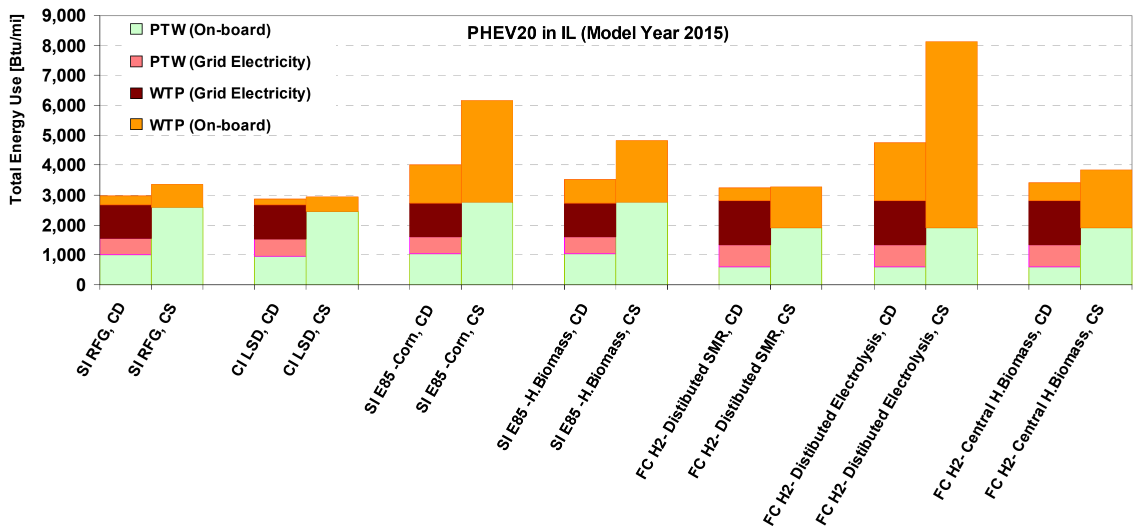


FIGURE 13(a) WTW Total Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the Illinois Marginal Mix

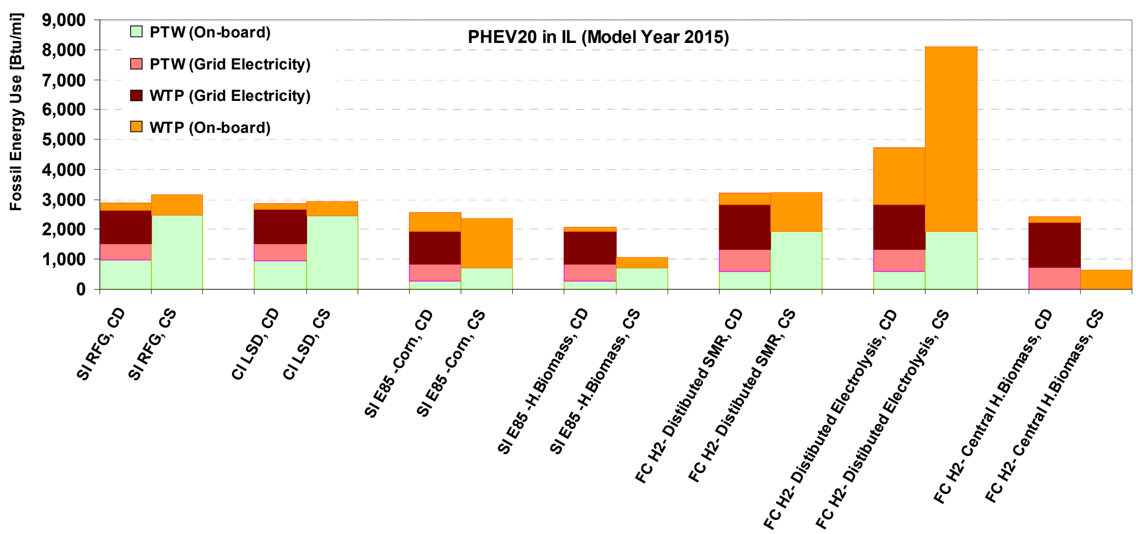


FIGURE 13(b) WTW Fossil Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the Illinois Marginal Mix

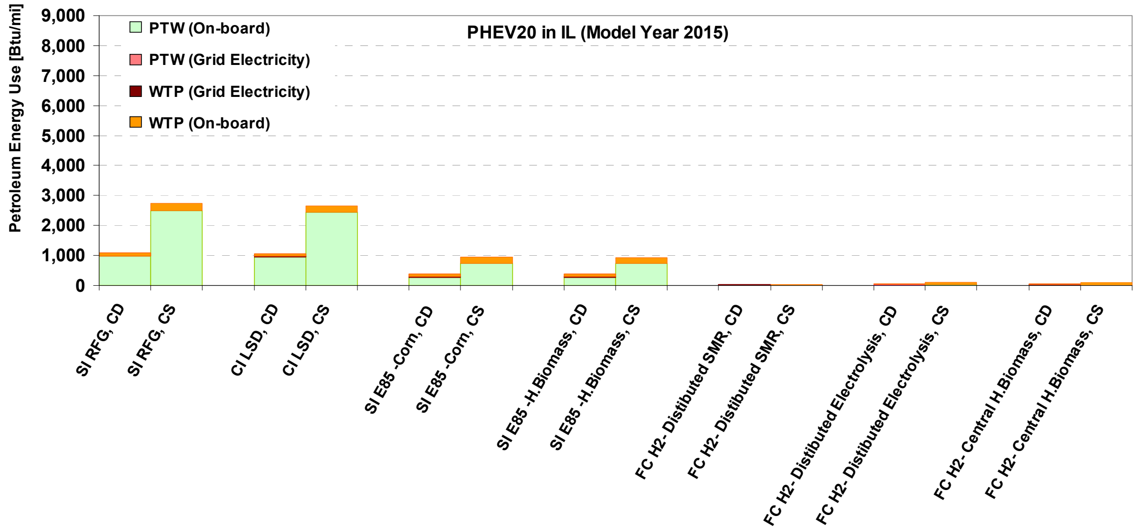


FIGURE 13(c) WTW Petroleum Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the Illinois Marginal Mix

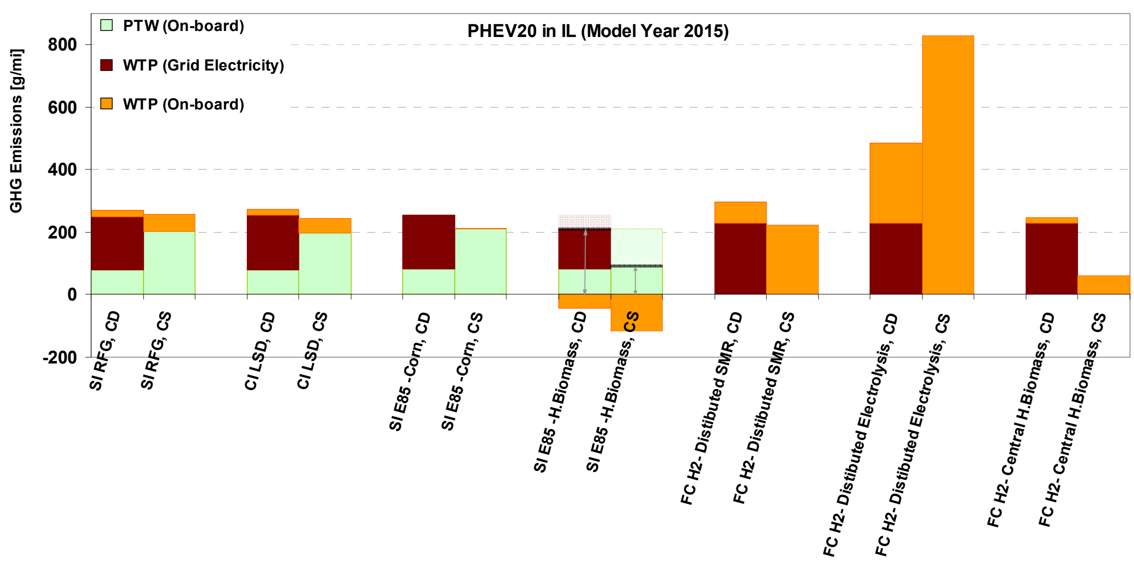


FIGURE 13(d) WTW GHG Emissions for CD (blended mode) and CS Operations of PHEV 20 Using the Illinois Marginal Mix

GREET calculates the weighted average energy use and GHG emissions of CD and CS operational modes by using the VMT share in each mode. The UF at the rated AER of the PHEV (Figure 8) combines the PHEV's average fuel consumption (AFC) in CD and CS operational modes according to the following formula:

$$AFC_{combined} = (AFC_{Grid} + AFC_{Engine})_{CD}*UF + AFC_{CS}*(1\text{-}UF). \quad (1)$$

The UF for PHEV 20 is 40%, as shown in Table 7. The UF serves as a weighting factor to average the CD and CS WTW energy use and emissions of PHEVs. Thus, the combined AFC is always bounded by the height of the CD and CS AFC, as shown in Figure 14. A UF of 100% yields a combined AFC identical to the CD AFC, which signifies pure CD operation, while a UF of 0% yields a combined AFC identical to the CS AFC, which signifies pure CS operation (similar to the operation of a comparable regular HEV.

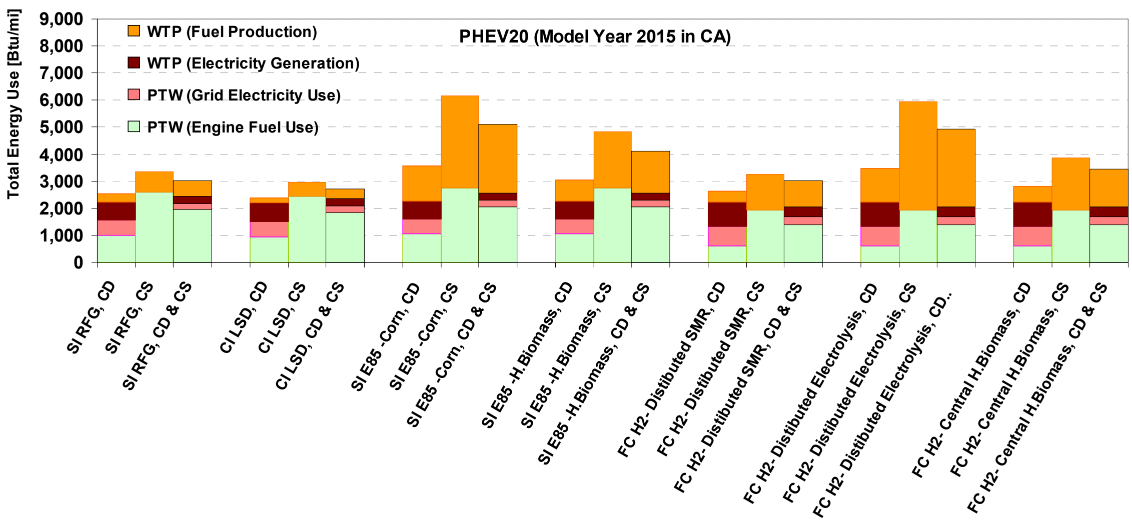


FIGURE 14 WTW Total Energy Use for CD (blended mode) and CS Operations of PHEV 20 Using the California Marginal Mix

Figures 15(a–d) show the WTW results for various PHEV technologies at AER 20, utilizing the California (NERC Region 13) marginal mix by combining the CD and CS results and applying a UF of 40%. Figure 15(a) shows a relatively small grid electricity energy use by PHEV 20 with respect to its total vehicle energy use. On average, the grid electricity energy share is 6%, 12%, and 24% of the total PHEV energy use for AER 10, 20, and 40, using a UF of 23%, 40%, and 63%, respectively. The small share of electricity use is due to the significant amount of fuel use by the engine in the CD blended mode of operation. The fuel use in CS operation further dilutes the share of grid electricity, as implied by the above equation. However, it is expected that, on a Btu/mi basis, a larger fraction of the electric energy would power the PHEV wheels in CD operation, compared with the fuel energy, due to the much lower energy conversion efficiency of the engine relative to the electric motor, as discussed above.

Figure 15(b) indicates that PHEVs using fuels from bio-feedstock sources — such as hydrogen from switchgrass and E85 from corn and switchgrass — consume less fossil energy relative to other PHEV fuels. Figure 15(c) shows that PHEVs that employ hydrogen as a fuel almost eliminate the dependence on petroleum energy. The PHEVs that employ E85, which is blended with a small percentage of gasoline, demonstrate a small dependence on petroleum energy. The PHEVs that employ hydrogen and E85 from switchgrass exhibit the least GHG emissions, followed by PHEVs that employ E85 from corn and hydrogen from SMR, as shown in Figure 15(d). The PHEVs that employ hydrogen produced via electrolysis exhibit the highest fossil energy use and GHG emissions, despite the high efficiency and low carbon intensity of the California marginal generation mix. This suggests that PHEVs that use hydrogen produced via electrolysis may provide GHG emissions benefits over other PHEVs only if the electricity is generated from non-fossil sources.

Figure 16 shows the WTW petroleum energy use as a function of the PHEV's AER. The AER 0 represents the regular HEVs. As expected, the petroleum energy use decreases significantly with a corresponding increase in AER for petroleum-based fuels (e.g., RFG and LSD), due to the displacement of petroleum fuels with electricity generated from non-petroleum sources. A PHEV 40 that uses either RFG or LSD provides a 60% reduction in petroleum energy use compared with a conventional gasoline ICEV. It should be noted that the trends shown in Figure 8 are insensitive to the marginal generation mix as long as the mix of fuels for electricity generation is from non-petroleum sources, such as the case of the California, Illinois, and U.S. mixes (see Table 4). The reduction of petroleum energy use with the increase in AER is less significant for the E85 PHEVs because of the small share of gasoline in the E85 blend. All hydrogen PHEVs are nearly independent of petroleum energy, since the feedstock sources of the hydrogen fuel are non-petroleum based. For all AER ratings, including AER 0 (regular HEV),

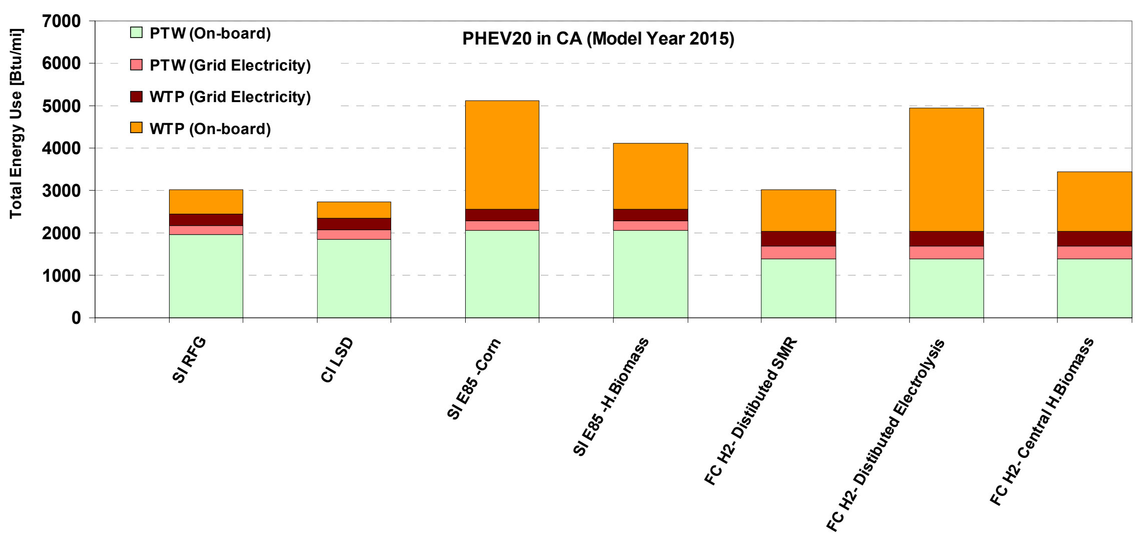


FIGURE 15(a) WTW Total Energy Use for Combined CD and CS Operations of PHEV 20 Using the California Marginal Mix (UF=40%)

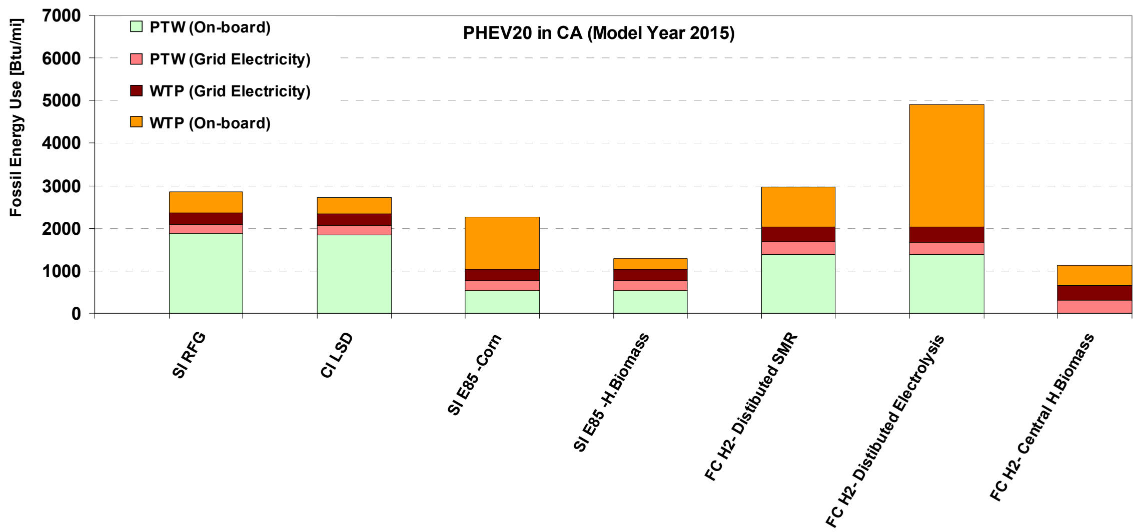


FIGURE 15(b) WTW Fossil Energy Use for Combined CD and CS Operations of PHEV 20 Using the California Marginal Mix (UF=40%)

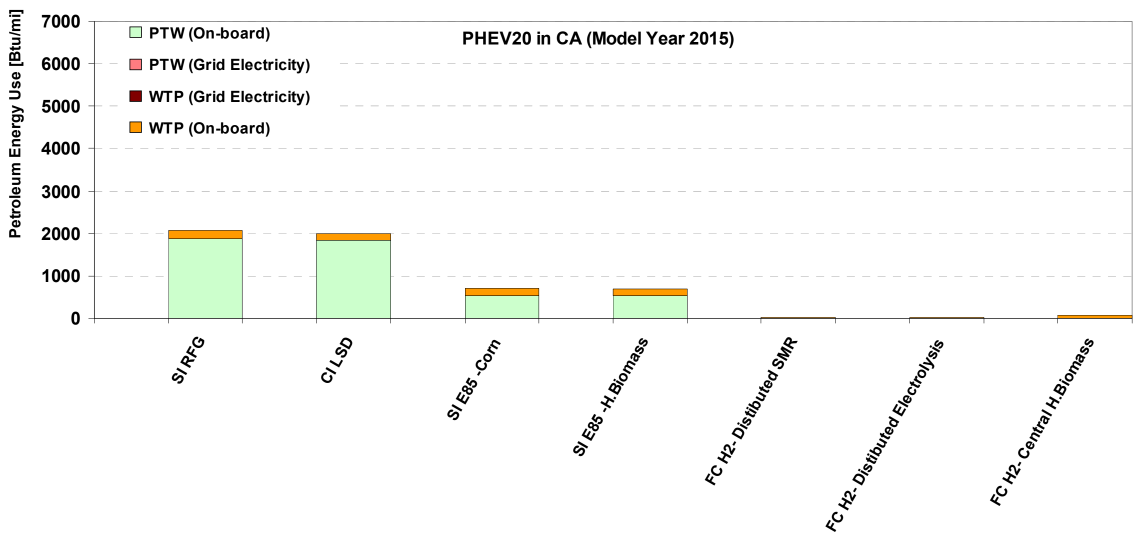


FIGURE 15(c) WTW Petroleum Energy Use for Combined CD and CS Operations of PHEV 20 Using the California Marginal Mix (UF=40%)

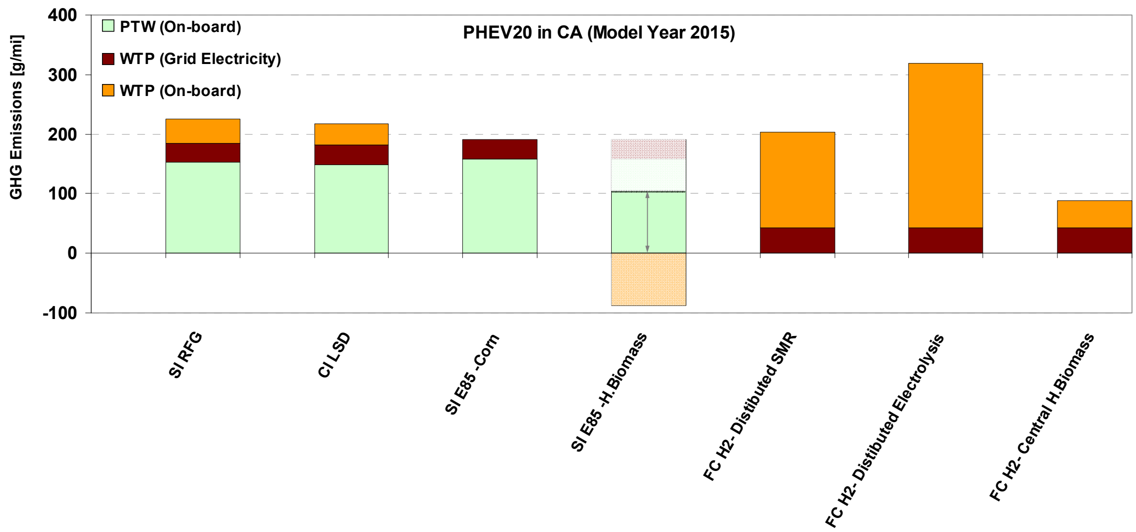


FIGURE 15(d) WTW GHG Emissions for Combined CD and CS Operations of PHEV 20 Using the California Marginal Mix (UF=40%)

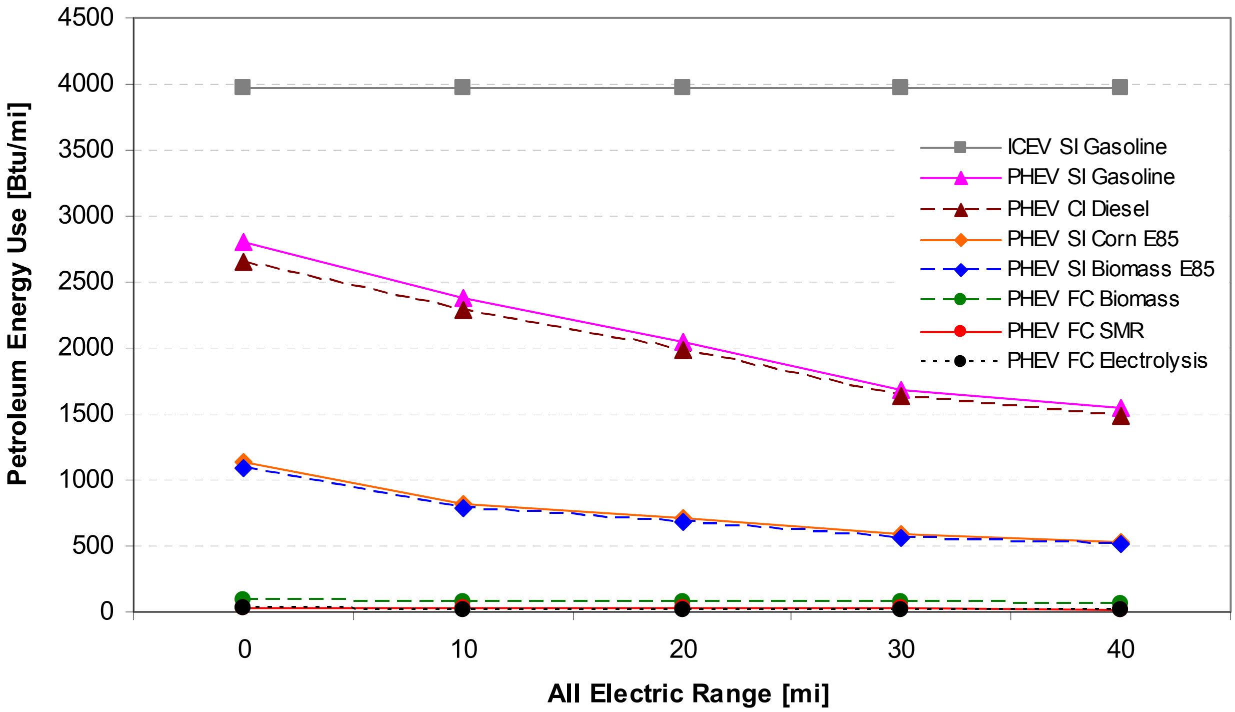


FIGURE 16 WTW Petroleum Energy Use for Combined CD and CS Operations as a Function of AER

the petroleum use is significantly reduced relative to the gasoline ICEV. The UF for combining the CD and CS petroleum energy use is 23%, 40%, 53%, and 63% for PHEV 10, 20, 30, and 40, respectively.

Figures 17, 18, and 19 show the WTW GHG emissions as a function of AER for the California, U.S., and Illinois marginal generation mixes, respectively. The PHEVs that employ fuels produced from biomass sources (e.g., E85 and hydrogen produced from switchgrass) exhibit a proportional increase in GHG emissions with increasing AER because of the significant contribution of fossil fuels to the electricity generation in the California, U.S., and Illinois mixes, as shown in Figures 17–19. Thus, PHEVs that employ biomass-based fuels (e.g., biomass-E85 and -hydrogen) may not realize GHG emissions benefits over regular HEVs if the marginal generation mix is dominated by fossil sources.

Figure 17 shows a significant decrease in the WTW GHG emissions, with a corresponding increase in AER for all PHEVs that use the California marginal generation mix (except for fuels produced from biomass sources), due to the displacement of fossil fuels by the highly efficient electricity generation with low carbon intensity. Figure 19 shows an opposite trend for the Illinois mix because of its high dependence on carbon-intensive coal for the marginal generation. All PHEVs, regardless of the AER rating, significantly reduce the GHG emissions relative to a conventional gasoline ICEV, except for PHEVs that employ hydrogen produced via electrolysis from carbon-intensive electricity generation, as shown in Figures 18 and 19 for the U.S. and Illinois marginal generation mixes, respectively.

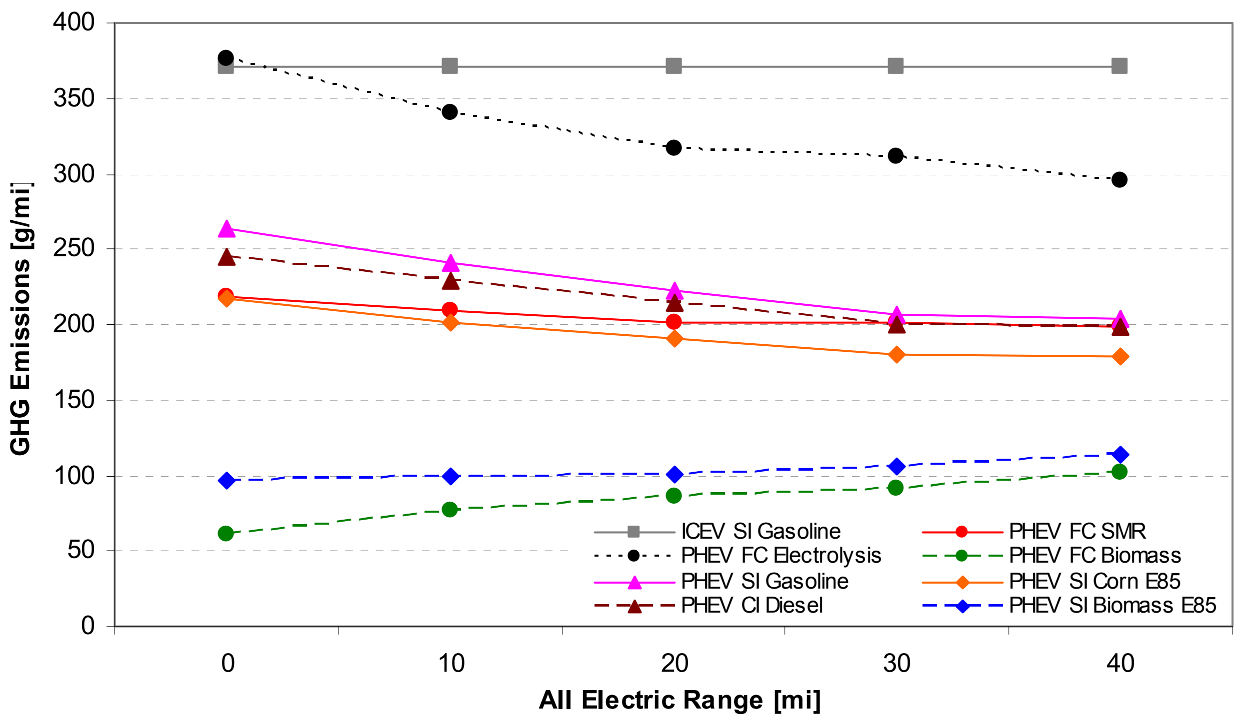


FIGURE 17 WTW GHG Emissions for Combined CD and CS Operations as a Function of AER Using the California Marginal Generation Mix

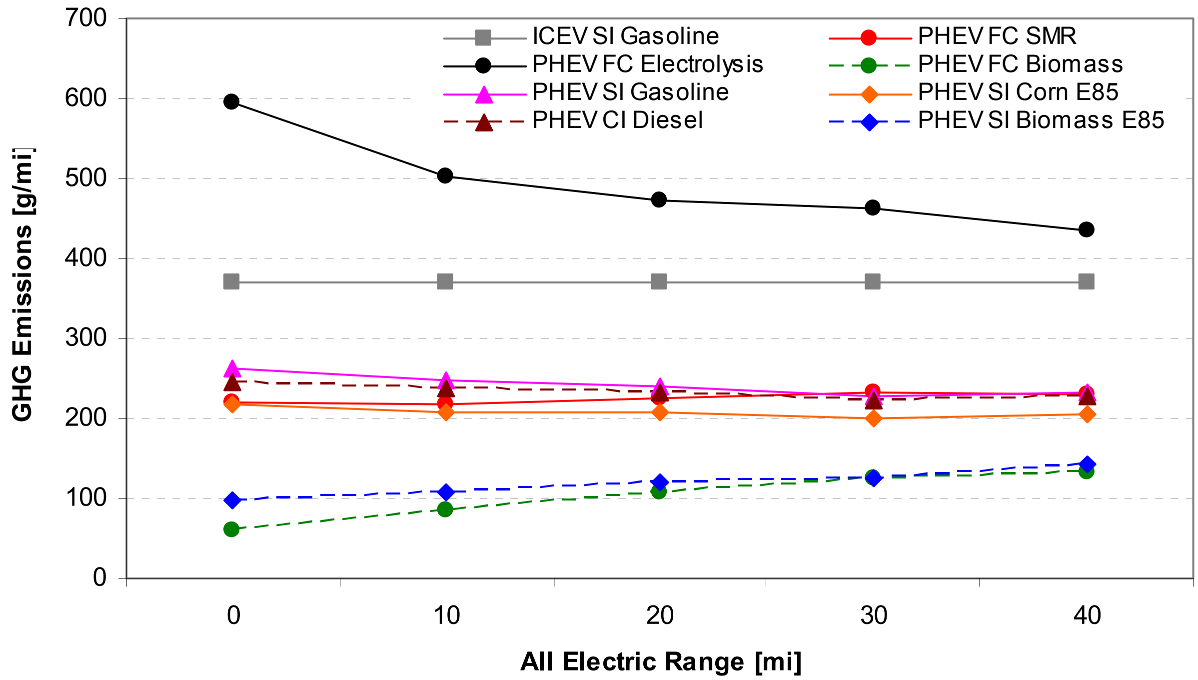


FIGURE 18 WTW GHG Emissions for Combined CD and CS Operations as a Function of AER Using the U.S. Generation Mix

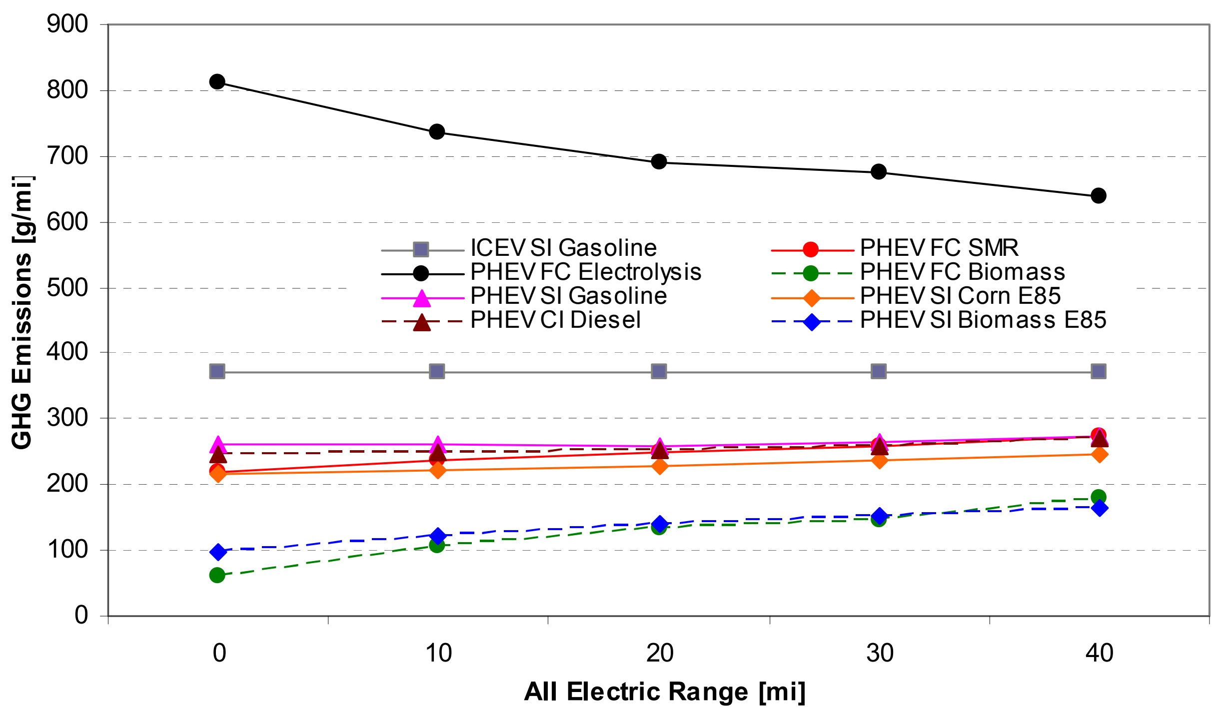


FIGURE 19 WTW GHG Emissions for Combined CD and CS Operations as a Function of AER Using the Illinois Marginal Generation Mix

Figures 20–23 show side-by-side comparisons of the WTW results of analyses for the alternative PHEV 20 systems using U.S., California, Illinois, and renewable marginal generation mixes. The WTW results combine the CD and CS operations, on the basis of a UF of 40% for AER 20. The first bar on the left represents the WTW result of a conventional gasoline ICEV, which is provided as a baseline for comparison with the alternative PHEV fuel/vehicle systems. The graphs show a similar trend across all PHEVs for the different generation mixes. The only exception is the disappearance of the fossil, petroleum, and GHG emissions bars for the PHEV that employs hydrogen when produced from renewable electricity via electrolysis. In general, the energy use and GHG emissions decline progressively in the following order of marginal generation mixes: Illinois, U.S., California, and renewable. As shown in Figure 22, petroleum energy use is insensitive to the marginal generation mixes because the main sources for these mixes are non-petroleum fuels (e.g., coal, natural gas, and renewables). Figure 23 shows that all PHEV systems provide GHG emissions benefits over the conventional gasoline ICEV, except for PHEVs that employ hydrogen via electrolysis when the electricity is produced from a less-efficient and more carbon-intensive generation mix (e.g., U.S. and Illinois).

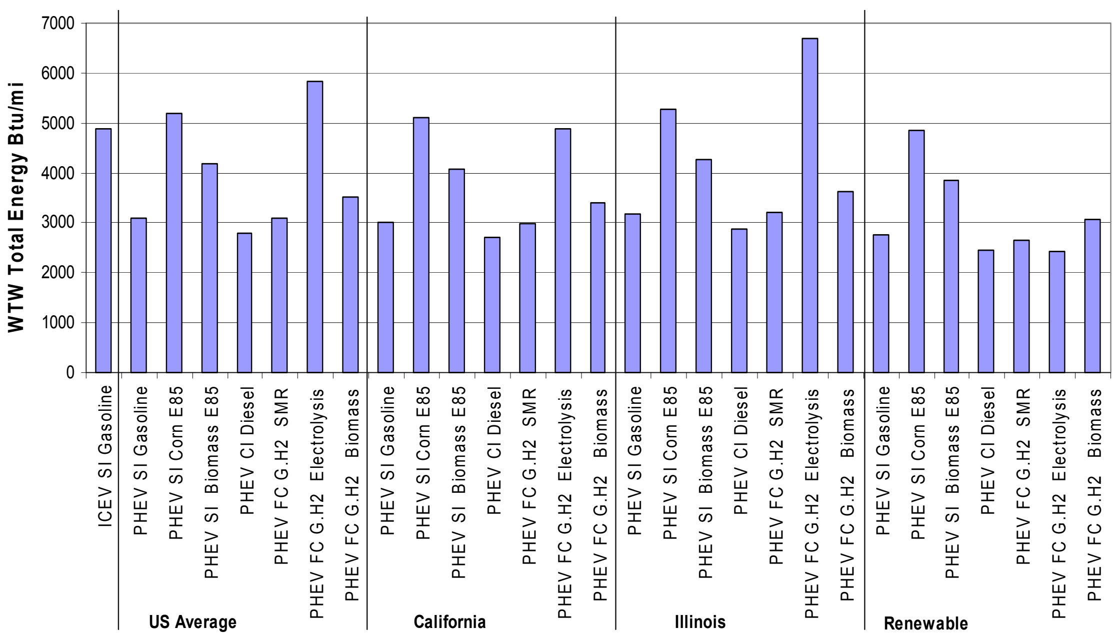


FIGURE 20 WTW Total Energy Use for PHEV 20 Vehicle/Fuel Systems Using Different Marginal Electricity Generation Mixes

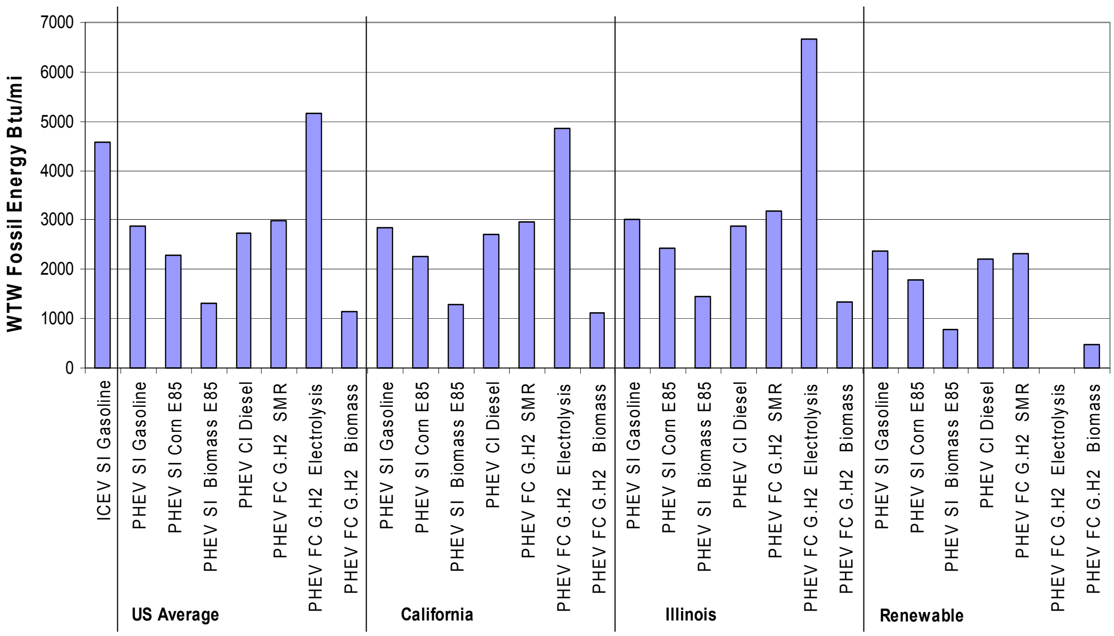


FIGURE 21 WTW Fossil Energy Use for PHEV 20 Vehicle/Fuel Systems Using Different Marginal Electricity Generation Mixes

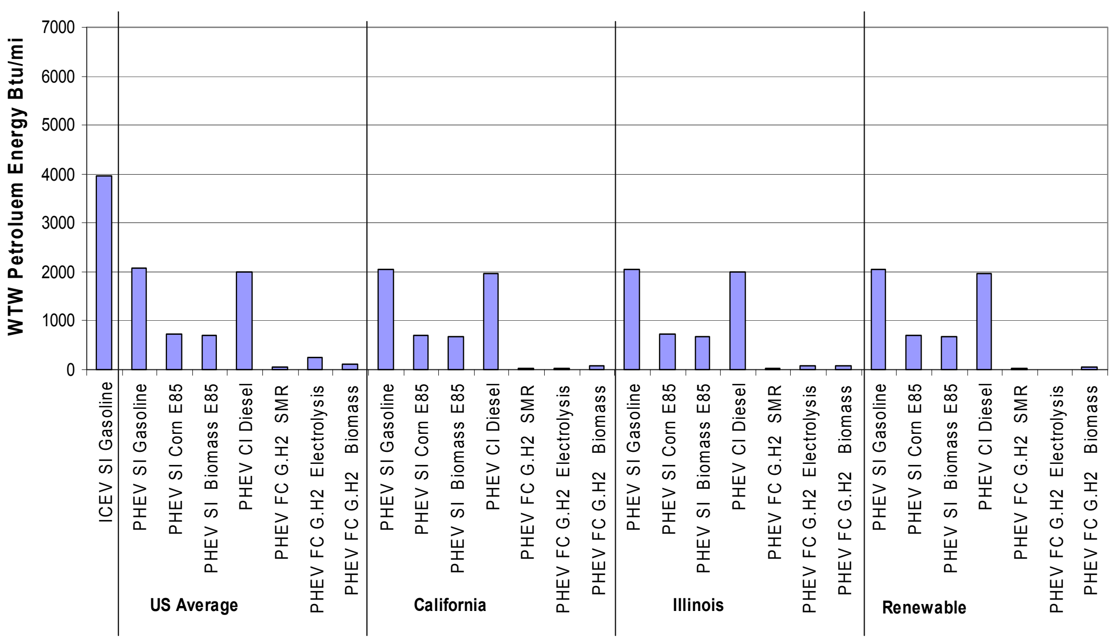


FIGURE 22 WTW Petroleum Energy Use for PHEV 20 Vehicle/Fuel Systems Using Different Marginal Electricity Generation Mixes

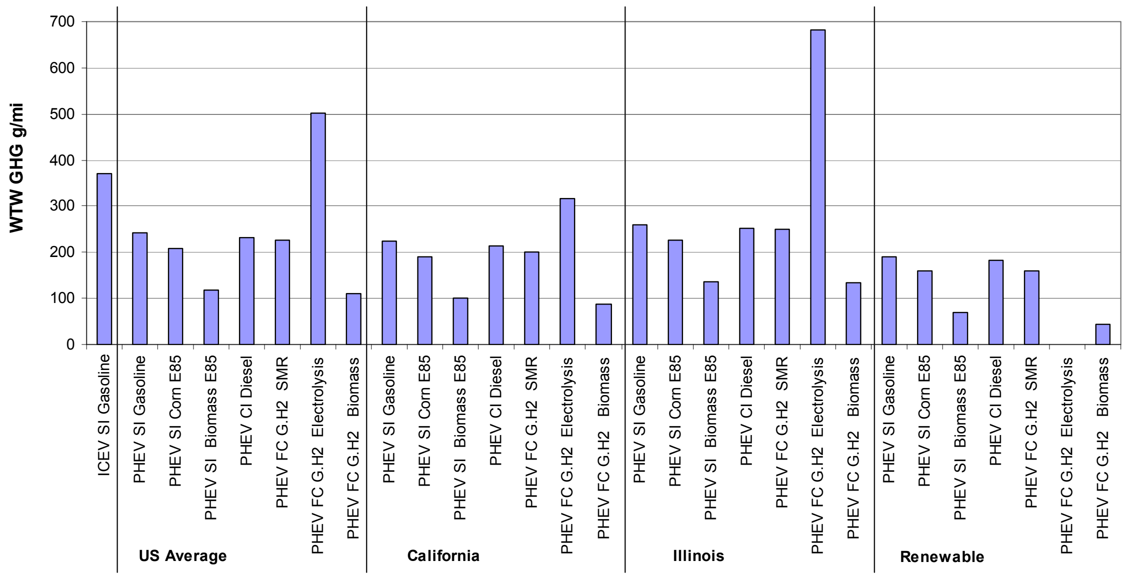


FIGURE 23 WTW GHG Emissions for PHEV 20 Vehicle/Fuel Systems Using Different Marginal Electricity Generation Mixes

Figure 24 summarizes the most significant WTW results for all considered PHEV fuel/vehicle systems, AER ratings, and marginal generation mixes by calculating the per-mile ratio of the petroleum energy use and GHG emissions of the PHEVs relative to those of the baseline conventional gasoline ICEV. It is worthwhile to provide a few guidelines to facilitate an easy interpretation of Figure 24. The reference point for comparison with all PHEVs is (1,1), which represents arbitrary units for the baseline conventional gasoline ICEV's petroleum energy use and GHG emissions. The color of the marker represents a particular PHEV fuel/vehicle technology, while the size of the marker represents the AER rating of that PHEV (a smaller marker for PHEV 10 and a larger marker for PHEV 40). The shape of the marker represents the marginal generation mix used for recharging the batteries of PHEVs.

Figure 24 notes that the WTW results for the combined CD and CS operations employ 23% and 63% UF for the PHEV 10 and PHEV 40, respectively. All PHEV/grid mix technology combinations that fall inside the frame bounded by the two points (0,0) and (1,1) provide a reduction in per-mile petroleum energy use and GHG emissions relative to the conventional gasoline ICEV. Conversely, all technology combinations that lie outside that frame represent an increase in petroleum energy use or GHG emissions, or both. The closer the marker is to the vertical coordinate, the less dependent the technology is on petroleum energy. Similarly, the closer the marker is to the horizontal coordinate, the lower the GHG emissions are from the technology.

The markers for a particular PHEV technology are connected from PHEV 10 to PHEV 40. The position of the PHEV 40 marker relative to that of PHEV 10 indicates the relative change in petroleum energy use and GHG emissions as the AER increases from 10 mi to 40 mi. Quantitatively, the relative change in petroleum energy use and GHG emissions with AER can be represented by the respective horizontal and vertical components of a vector extending from the PHEV 10 marker to the PHEV 40 marker.

Figure 24 indicates that all PHEV/grid mix technologies provide a significant reduction in petroleum energy use and GHG emissions, except PHEVs powered by hydrogen produced via electrolysis, where the electricity mix is dominated by oil or coal. For example, using the U.S. average, New York, or Illinois marginal generation mix for hydrogen production via electrolysis creates the only outliers in Figure 24 due to the high percentage of oil or coal in these mixes. However, using renewable generation of electricity for hydrogen production via electrolysis entirely eliminates petroleum use and GHG emissions. Thus, the implication of the marginal generation mix resides in the electricity generation stage (WTP). In general, the electricity WTP energy use and GHG emissions increase progressively as the marginal mix becomes less efficient and dominated by a larger share of oil or coal. It should be noted that use of the U.S. or Illinois generation mix leads to a reduction in petroleum energy use, since these mixes incorporate insignificant petroleum sources in their portfolio. The following discussion focuses on PHEVs with a significant potential for petroleum energy savings and GHG emissions reduction.

Figure 24 shows three distinct zones of petroleum energy use and GHG emissions for PHEVs powered by petroleum, E85, and hydrogen fuels. The PHEVs that employ petroleum fuels, E85, and hydrogen offer a 40–60%, 70–90%, and more than 90% reduction in petroleum energy use, respectively, compared with the conventional gasoline ICEV. The corresponding reductions in GHG emissions for PHEVs that employ petroleum fuels, E85, and hydrogen are 30–60%, 40–80%, and 10–100%, respectively. For the same fuel, the spread of the WTW GHG emissions among the different fuel production technologies and grid mixes is much higher compared with the spread of petroleum energy use. This is particularly true for E85 and hydrogen because of the diverse production technologies and feedstock sources considered for these fuels in this analysis.

Overall, more petroleum energy savings are realized at a higher AER, except when an oil-intensive grid mix is used. Similarly, more GHG emissions reductions are realized at a higher AER, except when an oil- or coal-intensive grid mix is used. (In Figure 24, notice the trend from the smaller to larger diamond- and circular-shaped markers for most PHEVs). The U.S. mix provides a slight reduction in GHG emissions as the AER increases for PHEVs that employ petroleum and corn-E85 fuels, but significantly increases the GHG emissions for PHEVs powered by biomass-E85 and SMR- and biomass-hydrogen fuels for the same increase in AER. (In Figure 24, see the trend of connected disc-shaped markers). Certainly, PHEVs that use electricity from renewable sources would realize the most reduction in petroleum energy use and GHG emissions as the AER rating increases. (In Figure 24, see the trend of connected square-shaped markers). Using the California marginal mix for PHEV charging provides a significant reduction in petroleum energy use as well as GHG emissions, except for biomass-based fuels (e.g., biomass-E85 and biomass-hydrogen). (In Figure 24, notice the trend of connected triangular-shaped markers). These favorable characteristics of PHEVs in California are attributed to the highly efficient NGCC technology that dominates its marginal mix.

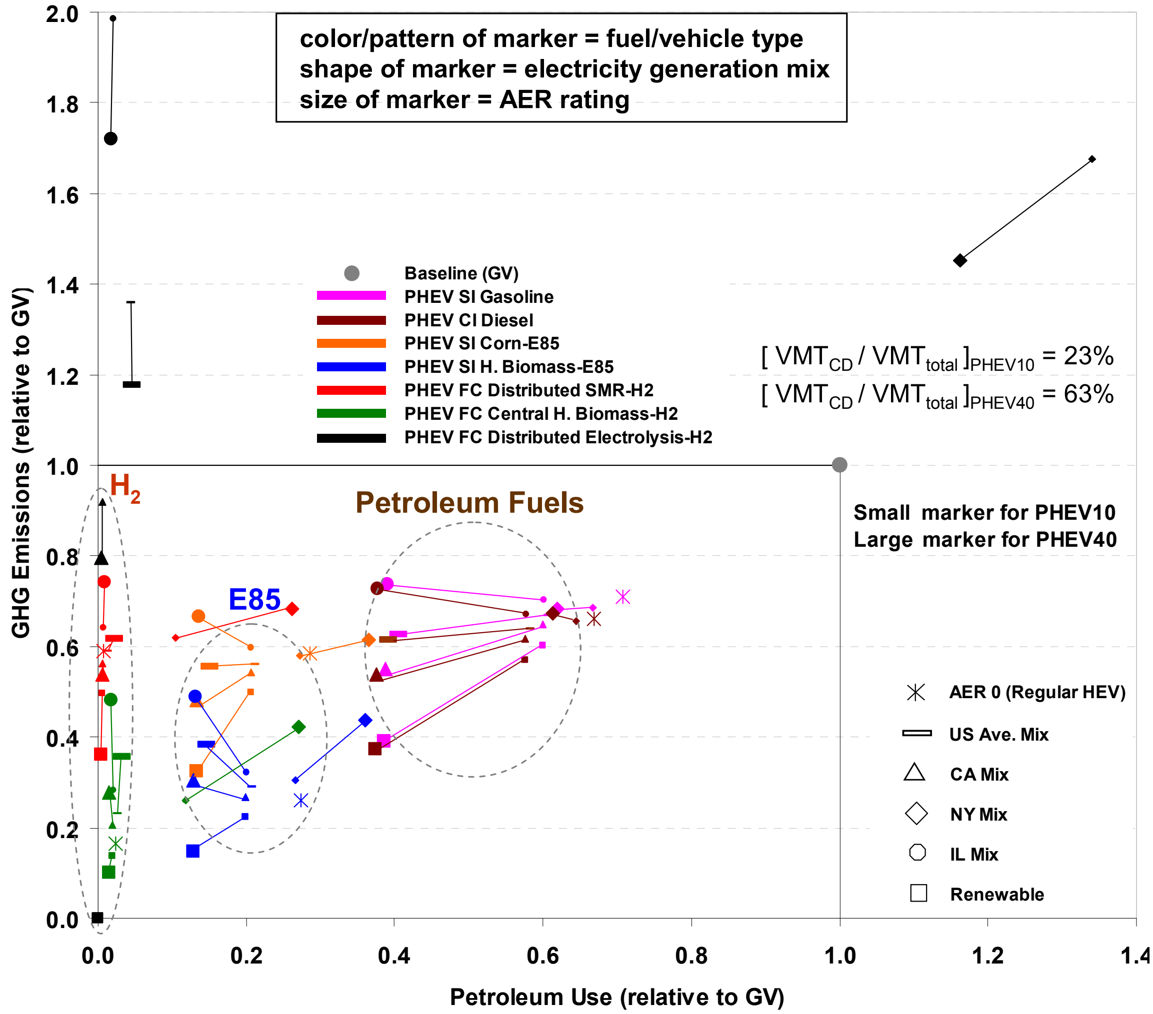


FIGURE 24 Summary of WTW Petroleum Energy Use and GHG Emissions for Combined CD and CS Operations Relative to Baseline Gasoline ICEV

The isolated markers in Figure 24 represent the regular HEVs (AER 0). The positions of these isolated markers relative to the baseline conventional gasoline ICEV marker indicate the reduction in petroleum energy and GHG emissions due to the (grid-independent) hybridization technology (CS operation) of these vehicles. In addition, the position of these markers relative to the PHEV markers represents the change in relative petroleum energy use and GHG emissions because of the partial displacement of VMT from the CS operation of the regular HEV to the CD operation of the PHEV. The displaced CS VMT in this case is represented by the UF (23% for PHEV 10, and 63% for PHEV 40). For a carbon-intensive generation mix, such as that of Illinois, Figure 24 shows that PHEVs produce more WTW GHG emissions compared with regular HEVs for most fuels. Such implication becomes more pronounced as the AER increases from 10 mi to 40 mi, especially for E85 and hydrogen fuels, which highlights the significance of the electricity generation mix for charging PHEVs.

6 IMPLICATIONS FOR FUTURE RESEARCH

The WTW results documented in this report are influenced by Argonne's PSAT simulation results for the per-mile electricity use and fuel consumption of alternative vehicle technologies. The WTW results are also influenced by the ORNL predictions of the marginal electricity generation mix for PHEVs charging in different U.S. regions. Further investigation and research are required in these two significant areas to better understand how the penetration of PHEVs into the transportation market will be able to transfer miles to electricity. For example, various configurations of the electric machine, battery, and engine, as well as the various control strategies for the combined operation of the electric motor and engine, could significantly affect the performance in CD operational mode. The lack of an approved testing standard for rating various PHEV configurations adds to these complications.

The market penetration of the PHEVs, their total electric load, and their role as complements rather than replacements of regular HEVs are also uncertain. In addition, various generation expansion paths, which determine available marginal units, should be included to represent policy options and other factors in grid expansion. The effects of the number of daily charges, the time of charging, and the charging capacity have not been evaluated in this study. A more robust analysis of the VMT share of the CD operation is also needed.

7 CONCLUSIONS

GREET incorporated PSAT simulation of the fuel economy and electricity use of PHEVs to perform a WTW energy use and GHG emissions analysis. The WTW results were separately calculated for the CD and CS modes of PHEV operation, and then combined by using a UF that represented the CD VMT share. Based on PSAT simulations of the blended CD mode of operation, grid electricity accounted for a share of the total energy use of the vehicle, ranging from 6% for PHEV 10 to 24% for PHEV 40, by using a UF of 23% and 63%, respectively.

The electricity generation mix significantly impacted the WTW results, especially GHG emissions. Three NERC regions (4, 6, and 13) were selected for this analysis because of their significance. These regions represented marginal generation mixes dominated by coal, oil, and natural gas, respectively. Results were also reported for the U.S. generation mix and renewable electricity to examine cases of “average” and “clean” mixes, respectively. The PHEVs that employed petroleum fuels, E85, and hydrogen, with an AER between 10 mi and 40 mi, were shown to reduce petroleum energy use by 40–60%, 70–90%, and more than 90%, and GHG emissions by 30–60%, 40–80%, and 10–100%, respectively, compared with those of a conventional gasoline ICEV. The spread of the WTW GHG emissions among the different fuel production technologies and grid generation mixes was wider than the spread of petroleum energy use, mainly due to the diverse fuel production technologies and feedstock sources for the fuels considered in this analysis.

In addition, PHEVs offered more savings of petroleum energy use than regular HEVs. More petroleum energy savings were realized as the AER increased, except for the case of a marginal grid mix dominated by oil fuel. Similarly, more GHG emissions reductions were realized as the AER increased, except when the marginal grid mix was dominated by coal or oil. Electricity from renewable sources realized the most reduction in petroleum energy use and GHG emissions for all PHEVs as the AER increased. The PHEVs that employ biomass-based fuels (e.g., biomass-E85 and -hydrogen) may not realize GHG emissions benefits over regular HEVs if the marginal generation mix is dominated by fossil sources.

8 REFERENCES

Delorme, A., A. Rousseau, and S. Pagerit, 2008, "Fuel Economy Potential of Advanced Configurations from 2010 to 2045," Proceedings of Les Rencontres Scientifiques de l'IFP — Advances in Hybrid Powertrains, November 25–26.

EIA: Energy Information Administration

EIA, 2008, "Annual Energy Outlook 2008 with Projections to 2030," DOE/EIA-0383 (2008), U.S. Department of Energy, Washington, D.C., June.

EIA, 2007, "Electric Power Annual 2006," DOE/EIA-0348(2006), U.S. Department of Energy, Washington, D.C., October.

Gaines, L., A. Burnham, A. Rousseau, and D. Santini, 2007, "Sorting Through the Many Total-Energy-Cycle Pathways Possible with Early Plug-in Hybrids," Proceedings of the Electric Vehicle Symposium 23, Anaheim, CA, December 2–5.

Graham, R., et al., 2001, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options," 1000349, Electric Power Research Institute, Palo Alto, CA, July.

Hadley, S, 2006, "Impact of Plug-in Hybrid Vehicles on the Electric Grid," ORNL/TM-2006/554, Oak Ridge National Laboratory, Oak Ridge, TN, October.

IPCC: International Panel on Climate Change

IPCC 2008, 2008, Climate Change 2007: Technical Summary, Cambridge University Press, Cambridge, UK.

Pagerit, S., A. Rousseau, and P. Sharer, 2006, "Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains," SAE Paper 2006-01-0665, SAE World Congress, Detroit, MI, April.

Plotkin, S., D. Santini, A. Vyas, J. Anderson, M. Wang, J. He, and D. Bharathan, 2001, "Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results," ANL/ESD-02-2, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, October.

Roach, C., S. Rein, and K. Gottshall, 2008, "2007 State of the Market Report Southwest Power Pool, Inc." Boston Pacific Company, Inc., Washington, DC, April.

Rousseau, A., P. Sharer, and F. Besnie, 2004, "Feasibility of Reusable Vehicle Modeling: Application to Hybrid Vehicles," SAE paper 2004-01-1618, SAE World Congress, Detroit, MI, March.

Santini, D., and A. Vyas, 2008, "How to Use Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains," presented at the 8th International Advanced Automotive Battery and Ultracapacitor Conference, Tampa, FL, May 12–16.

Shelby, M., and S. Mui, 2007, "Plug-in Hybrids: A Scenario Analysis," presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 22.

Shidore, N., T. Bohn, M. Duoba, H. Lohse-Busch, and P. Sharer, 2007, "PHEV 'All Electric Range' and Fuel Economy in Charge Sustaining Mode for Low SOC Operation of the JCS VL41M Li-Ion Battery Using Battery HIL," Proceedings of the Electric Vehicle Symposium 23, Anaheim, CA, December 2–5.

Vyas, A., D. Santini, M. Duoba, and M. Alexander, 2007, "Plug-In Hybrid Electric Vehicles: How Does One Determine Their Potential for Reducing U.S. Oil Dependence?" Proceedings of the Electric Vehicle Symposium 23, Anaheim, CA, December 2–5.

Wang, M., 1999, "GREET 1.5 — Transportation Fuel-Cycle Model," ANL/ESD-39, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, August.

APPENDIX: RECENT GRID IMPACT STUDIES

Some recent studies on plug-in hybrid vehicle (PHEV) grid impact are summarized below. The summaries identify the assumed PHEV market share, the generator inventory, and the resulting dispatch to meet the charging load.

A.1 LEMOINE ET AL. (2008)

This is a study of the capability of existing generators to support PHEV charging in the California Independent System Operator (CAISO) region. The current generator inventory is used to meet the charging load for arbitrary levels of PHEV penetration. The study concludes that the current grid mix is capable of supporting a PHEV fleet much larger than what might reasonably be anticipated in the current planning period. The analysis estimates how many vehicles could economically charge at various gasoline price levels in the range of $0.50 to $3.00 per gallon.

A.1.1 PHEV Performance and Market Assumptions

The performance assumptions were adapted from a 2002 Electric Power Research Institute (EPRI) study (Duvall et al. 2002). The PHEVs are compact sedans with an all-electric range (AER) of 20 mi, an on-board fuel economy of 52.7 mi per gallon gasoline equivalent, and electrical consumption of 249 watt-hours per mile (Wh/mi), including charging losses. Rather than postulate a market share and growth for PHEVs, this analysis examines the grid impacts associated with a fleet of 1 million, 5 million, and 10 million PHEVs under several charging scenarios and for an electricity demand determined by the relative cost of gasoline and electricity.

A.1.2 Charging Demand and Aggregate Load

All scenarios assume a 1.2 kW demand from each charger as sport utility vehicles (SUVs) are charged for longer periods rather than at higher power. Three scenarios are evaluated: optimal charging at times of minimum demand, evening charging that has some overlap with peak hours, and twice-per-day charging. These charging demands are aggregated for 1, 5, and 10 million PHEV scenarios in the CAISO region.

A.1.3 Generating Capacity Mix

The current capacity mix for the CAISO region is assumed with no generation expansion.

A.1.4 Generating Capacity Dispatch

Rather than explicitly represent or model unit dispatch, this analysis overlays charging demand on the system load curves to obtain a graphical representation of the impact on peak loads. Any increase in peak load is an indication that additional capacity would be required. Under optimal charging (timed to fill the valleys in the load curve), no additional capacity is required.

A.1.5 Key Results

If the timing of charging is controlled by appropriate mechanisms, even the current CAISO generating capacity could meet the charging demand from millions of PHEVs. However, on-peak or on-shoulder charging would result in a total demand that exceeds the available capacity. These results are interesting, but they do not provide information applicable to the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model enhancement, since they do not identify the nature of marginal units used to meet the charging demand. Also, our preference is for a generating mix that represents 2020 or some time at which significant PHEV penetration is more likely.

A.2 MILLER (2007)

This is a limited analysis of a possible synergy between nuclear generation and PHEV charging. This analysis concludes that if the current coal capacity in Ontario were replaced with nuclear, the off-peak energy available from the new nuclear capacity could supply more than one-third of the Ontario light-duty vehicle miles traveled (VMT) if PHEVs or electric vehicles (EVs) were used.

A.2.1 Charging Demand and Aggregate Load

Vehicles are assumed to be small light-duty vehicles that obtain 90% of their energy requirement from the grid.

A.2.2 Generating Capacity Mix

In Ontario, the generation mix includes run-of-river hydro, dammed hydro, nuclear, coal, and natural gas. The availability of natural river resources, including the Niagara Falls, has long defined and will continue to define the Ontario capacity mix. Continued operation or expansion of nuclear capacity will be determined by several factors, such as policy decisions and public acceptance. This study assumes that new nuclear capacity is an acceptable generation expansion option.

A.2.3 Generating Capacity Dispatch

The base load is served first by nuclear and then by run-of-river hydro, such as the Beck plant on the Niagara Falls. Variable loads are served by dammed hydro, coal, and natural gas.

A.2.4 Key Results

One goal of large-scale PHEV deployment is a reduction of carbon dioxide (CO_2) emissions. This goal is best served if a low carbon generation alternative is used for charging. Nuclear is one such option, but nuclear plants must be run continuously. This makes them a poor candidate for off-peak valley filling operation. However, if nuclear capacity is employed to displace the existing coal capacity used for variable load, it would be available off-peak to serve a substantial PHEV charging demand. The author estimates that one-third of Ontario's light-duty VMT could be met with this new nuclear capacity.

A.3 DUVALL ET AL. (2007)

This is a sensitivity analysis intended to identify the possible net environmental impacts of the broad distribution of PHEVs by 2050. High, medium, and low PHEV market-share cases are evaluated under future generation mixes that are high, medium, and low with respect to carbon emissions. All cases resulted in GHG reductions, but the range of reductions varies by a factor of four between the best and worst combinations of PHEV market share and generation mix; the range through 2050 is 3.4 to 10.3 billion metric tons of CO_2. The results are based on a marginal approach, which estimates the change in emissions from a base case to a PHEV penetration scenario.

A.3.1 PHEV Performance and Market Assumptions

Overall, the vehicle inventory includes internal combustion engine vehicles, HEVs, and PHEVs with three AER options: 10 mi, 20 mi, and 30 mi. The onboard power for these vehicles is either diesel or gasoline. The PHEV technology is applied only to light-duty vehicles and to heavy-duty vehicles with less than a 19,500-pound gross vehicle weight rating. The HEV fuel consumption is 35% less than a comparable conventional vehicle, while the PHEV fuel economy in charge-sustaining mode is assumed to be the same as the fuel economy of a comparable HEV.

By the year 2050, the low, medium, and high penetration assumptions result in a 20%, 62%, and 80% market share of new vehicle sales, respectively. In the non-PHEV case, the market share of regular HEVs increases to 30%, 63%, and 75%, respectively, as a baseline for each of these scenarios.

A.3.2 Charging Demand and Aggregate Load

Vehicle charging is assumed to match a demand profile where charging ramps up after 6 p.m., maintains a sustained peak from 11 p.m. until 3 a.m., and declines after 3 a.m. to a minimum at 8 a.m. A modest mid-day charging increase extends from 11 a.m. through 3 p.m. Utilities may use controls to impose charging restrictions on large fleets.

A.3.3 Generating Capacity Mix

The National Electric System Simulation Integral Evaluation (NESSIE) model, developed by EPRI, is used to simulate generation expansion and generation dispatch at five-year intervals from 2010 to 2050. The National Energy Modeling System (NEMS), developed by the Energy Information Administration (EIA), is used to obtain fuel prices and emission allowances. The generating unit inventory at year 2030 resulting from the NESSIE model simulations is very similar to that reported in the AEO 2006, which used the NEMS Electricity Market Module for generation expansion and dispatch. The analysis is nationwide, with regional disaggregation based on the NEMS regions. However, only aggregate national results are provided in the report.

A.3.4 Generating Capacity Dispatch

The NESSIE model is also used for dispatch of the expanded capacity. Details are not discussed in the report. It is noted that, since charging is largely off-peak, base load coal units will provide most of the charging power.

A.3.5 Key Results

The regional generation mixes were not given explicitly in this report, so we were unable to apply the results to GREET. However, if regional results were available, this study would provide a useful validation of other dispatch modeling results.

A.4 KINTNER-MEYER ET AL. (2007)

This analysis seeks to estimate the maximum PHEV fleet size that could be charged by filling the so-called "valley" in the diurnal load curve with regards to 12 North American Electric Reliability Corporation (NERC)-based regions.

A.4.1 PHEV Performance and Market Assumptions

The AER assumed was a PHEV 33, which was based on a national annual average daily VMT of 33 mi per day per vehicle. The electrical consumption of these PHEVs ranged from 260 Wh/mi for a compact sedan to 460 Wh/mi for a full-size SUV.

A.4.2 Charging Demand and Aggregate Load

The vehicle charging rate was not specified. However, the battery capacity for the PHEVs ranged from 8.6 kWh to 15.2 kWh, depending on vehicle class. The aggregate load is actually calculated from the available capacity to fill the load curve valley for each region. This aggregate load divided by the battery capacity yields the number of vehicles.

A.4.3 Generating Capacity Mix

The analysis is restricted to the existing generation and transmission and distribution infrastructure. This yields a conservative capacity result, since it allows for no generation expansion.

A.4.4 Generating Capacity Dispatch

All charging is simply applied to fully utilize available capacity, so no dispatch modeling was used.

A.4.5 Key Results

The analysis concludes that as much as 73% of U.S. light-duty VMT could be supported by the existing electric power infrastructure, with an overall reduction in net GHG emissions. This analysis is not directly applicable to GREET calibration, but it shows the potential for PHEVs to reduce petroleum use.

A.5 HADLEY AND TSVETKOVA (2008)

In this regional analysis, the distribution and use of PHEVs are based on region-specific populations of vehicle types and AEO 2007 projections of total sales of light-duty vehicles. The make-up of the generator fleet used for charging is also region-specific. The 13 regions are based on the 10 NERC regions within the continental United States (as defined before 2006), with the Western Electricity Coordinating Council split into three regions for this analysis and the Northeast Power Coordinating Council split into two regions. The PHEV market penetration assumptions yield a PHEV inventory for 2020 and 2030. The charging load for these vehicles is met by an expanded generation inventory from EIA projections. Electricity costs and emissions from power production are projected for each region for a base case with no PHEVs and for the case with PHEVs. The emissions and costs associated with the PHEVs can be taken as the difference between these values. Fuel use and emissions for the PHEVs are compared in this analysis with those from charge-sustaining HEVs, which are regarded as the alternative vehicles being displaced by the plug-in technology.

A.5.1 PHEV Performance and Market Assumptions

National new vehicle sales projections from the AEO 2007 were distributed among regions and vehicle types (all light duty) according to current vehicle registrations. The PHEV market share is assumed to increase from zero before 2010 to 25% of new car sales by 2020 and hold steady after that. With these assumptions and expected vehicle retirement at 10 years, the fleet inventory is constructed. The AER is assumed to be 20 mi.

A.5.2 Charging Demand and Aggregate Load

Several charging rates are evaluated (1.4 kW, 2 kW, and 6 kW). The 6 kW requires a 240-V, 30-A circuit. The aggregate load is based on the assumption that each PHEV will require daily charging of a battery capacity sized for 20 mi of operation. This corresponds to a charge from 20% to 100% of the battery packs. These packs range in capacity from 5.1 kWh for a compact sedan to 9.3 kWh for a full-size SUV. Because the number of PHEVs of various types is known from the market assumptions, the aggregate daily demand can be calculated for each region. Several alternative charging strategies are analyzed. “Evening” charging starts at 6 p.m. or 7 p.m. One-half of the PHEV fleet begins charging at each of these hours. “Night” charging starts at 10 p.m. or 11 p.m.

A.5.3 Generating Capacity Mix

The regional generator inventory for 2020 and 2030 is taken from the AEO 2007, and that inventory reflects necessary expansion to meet growth, anticipated unit retirements, and fuel and technology choices on the basis of capital costs, projected fuel costs, and regulatory restrictions. However, since the AEO 2007 does not anticipate PHEV market growth, PHEV charging demand is not incorporated in the generation expansion planning.

A.5.4 Generating Capacity Dispatch

The PHEV charging demand has been superimposed on the demand patterns from the AEO 2007 projections. This changes the diurnal load pattern by adding load during the evening or nighttime hours selected for charging. The loading of generators to meet this new demand pattern is developed with the Oak Ridge Competitive Electricity Dispatch Model. This model determines which units will be brought on-line or ramped up to meet the PHEV charging demand and, consequently, what associated emissions will result.

A.5.5 Key Results

Our interest is in obtaining an estimate of the generation mix employed on the margin to meet the PHEV generating load. GREET uses that mix to estimate the electricity generation portion of the WTW results for PHEV operation. From that perspective, the results of this study are very informative. Results for six cases, including three charge rates (1.4 kW, 2 kW, and 6 kW) and two charging times (evening and night), are presented. It should be noted that the high-charge-rate case (6 kW) results in some unserved load with evening (5 p.m. or 6 p.m.) charging. This is a reflection of the facts that the original generation expansion included in the AEO 2007 did not anticipate PHEV charging demand and that the charging start time occurs during a high load period. Similar results are presented for each of the 13 regions.

A.6 REFERENCES

Duvall, M., E. Knipping, M. Alexander, L. Tonachel, and C. Clark, 2007, "Environmental Assessment of Plug-in Hybrid Electric Vehicles; Volume 1: Nationwide Greenhouse Gas Emissions," 1015325, Electric Power Research Institute, Palo Alto, CA, July.

Duvall, M., et al., 2002, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles," 1006892, Electric Power Research Institute, Palo Alto, CA, July.

Hadley, S., and A. Tsvetkova, 2008, "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation," ORNL/TM-2007/150, Oak Ridge National Laboratory, Oak Ridge, TN, Jan.

Kintner-Meyer, M., K. Scheider, and R. Pratt, 2007, "Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids; Part 1: Technical Analysis," Pacific Northwest National Laboratory, Richland, WA, Nov.

Lemoine, D., D. Kammen, and A. Farrell, 2008, "An Innovation and Policy Agenda for Commercially Competitive Plug-in Hybrid Electric Vehicles," 014003, Environmental Research Letters Volume 3(1), Feb.

Miller, A., 2007, "A Historic Perspective on the Future Cost of Off-Peak Electricity for EVs," Plug-in Highway PHEV2007 Conference, Winnipeg, MB, Canada, Nov.

Argonne
NATIONAL LABORATORY

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov

U.S. DEPARTMENT OF
ENERGY

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC