

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

Amgad Elgowainy, Andrew Burnham, Michael Wang, John Molburg and Aymeric Rousseau
Center for Transportation Research, Argonne National Laboratory

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ABSTRACT

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model incorporated 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). Based on PSAT simulations of the blended charge depleting (CD) operation, grid electricity accounted for a share of the vehicle's total energy use ranging from 6% for PHEV 10 to 24% for PHEV 40 based on CD vehicle mile traveled (VMT) shares of 23% and 63%, respectively. Besides fuel economy of PHEVs and type of on-board fuel, the type of electricity generation mix impacted the WTW results of PHEVs, especially GHG emissions.

For an all-electric range (AER) between 10 to 40 miles, PHEVs employing petroleum fuels (gasoline and diesel), a blend of 85% ethanol and 15% gasoline (E85), and hydrogen were shown to offer 40-60%, 70-90%, and over 90% reduction in petroleum energy use, and 30-60%, 40-80%, and 10-100% reduction in GHG emissions, respectively, relative to an internal combustion engine vehicle (ICEV) using gasoline. In addition, PHEVs offered reductions in petroleum energy use as compared to 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 AER, except when the marginal grid 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 AER increased. GHG emissions benefits may not be realized for PHEVs employing biomass-based fuels, e.g., biomass-E85 and -hydrogen, over regular HEVs if the marginal mix is dominated by fossil sources.

INTRODUCTION

Currently, PHEVs are being developed for mass production by the automotive industry and promoted with a promise to reduce transportation's petroleum consumption and GHG emissions by utilizing off-peak excess electricity generation capacity and increasing the vehicle's energy efficiency relative to gasoline ICEV. The U.S. Department of Energy's (DOE's) Vehicle Technology Program examines the pre-competitive, 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 the freedom of mobility or vehicle choice [1]. PHEVs are similar to regular HEVs except that the battery utilizes 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, e.g., 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 battery chemistry, amount of grid electricity that can be stored in the battery, and the powertrain and fuel choices, which could impact the environment significantly. 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 co-sponsored by U.S. automakers and the DOE while Japanese automakers introduced commercial HEVs that provided significant fuel consumption benefits as compared to similar ICEVs [2]. In 2001 as a response to these developments, both the Electric Power Research Institute (EPRI) and the DOE's national laboratories began evaluating PHEVs [3,4]. While these evaluations examined vehicles with nickel metal hydride (Ni-MH) batteries, the recent interest in PHEVs has been spurred by the improvements in the energy density and cost of lithium ion (Li-Ion) batteries.

While PHEVs offer the potential for significant reduction in 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 electricity generation needed for the electric VMT share. The implications of the upstream marginal electricity generation mix as well as the PHEV's powertrain technology, fuel source and AER rating can be fully understood through a WTW assessment of energy use and GHG emissions as provided by this analysis.

APPROACH

With funding from the DOE, the Center for Transportation Research of the Argonne National Laboratory (ANL) developed the GREET model to estimate the full fuel cycle energy use and emissions for alternative transportation fuels and advanced vehicle systems [5]. In estimating the 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, which is referred to 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 of a vehicle with one powertrain system that can utilize different fuels with minor modifications or the same fuel with different feedstock sources. However, in order to estimate the full implications of PHEVs, both the fuel for the engine and the grid electricity powering the electric drive system need to be examined. The engine/fuel combinations examined in this analysis are: a spark ignition (SI) engine using reformulated gasoline (RFG), a SI engine using a blend of 85% ethanol and 15% reformulated gasoline (E85), a compression ignition (CI) 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 centralized 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%)
		Corn
	Ethanol (E85)	Herbaceous Biomass
Compression Ignition	Low-Sulfur Diesel	Conventional Crude (82%) and Oil Sand (18%)
Fuel Cell	Hydrogen	Natural Gas (SMR)
		Electricity (Electrolysis)
		Herbaceous Biomass

A conventional gasoline ICEV and regular HEV powertrains employing ICE and fuel cells are considered and compared with PHEVs using the same fuels to examine their relative benefits with regards to energy use and greenhouse gas emissions. However, Santini and Vyas argued that it is more appropriate to compare regular HEVs and PHEVs to ICEVs, but not to each other, since they will compete against the ICEV in different niche markets [6]. Regular HEVs are expected to be more advantageous than PHEVs when operating at low average speeds and shorter daily driving distances, e.g. congested urban areas, where there are a lower percentage of single-family homes with garages. In contrast, PHEVs are expected to have an advantage over regular HEVs at higher speeds with less congestion, e.g. suburban areas where there are 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 in 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 which have not been commercially produced. Therefore, external models and data are used to characterize the important determinants of the WTW performance, which are the marginal electricity mix for charging PHEVs, fuel consumption and electricity use on a per-mile basis, and vehicle miles traveled on grid electricity. A recent study by Oak Ridge National Laboratory (ORNL) on region-specific marginal generation mixes for PHEVs is used in this analysis to calculate the WTP energy use and GHG emissions associated with the electricity used for EVs. PSAT is used to simulate the vehicle's fuel economy, and



electricity use, which are key inputs for the calculation of the 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. Detailed analysis and discussion of these key determinants are provided by Elgowainy, et al. [7].

MARGINAL 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 projection of generation mix for a target year so that we could realistically examine how PHEVs will perform. 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 provide projections of the charging demand of PHEVs and match this demand to estimates of available generation. These studies vary according to the regional scope and intent. Several nationwide studies have been completed, providing results for all North American Electricity Reliability Corporation (NERC) regions (Figure 1), while other studies are limited to specific regions. The generation mix at the time of charging becomes increasingly uncertain as the time to large-scale PHEV deployment increases, 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 provide some guidance for projecting future plant inventories and their dispatch. By estimating the change

in generating plant utilization associated with PHEV charging, these studies have been used to estimate the effects on reserve margins, fuel use, emissions, and costs.

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, and load growth patterns and the associated generation expansion in the years prior to the charging event of interest. Impact of the time of day, as well as time of year and geographic climate region are discussed by Elgowainy et al. [7]. 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, the last unit brought online, and when that unit reaches full capacity, another unit is brought online as the marginal unit and so on. Therefore, when a large number of PHEVs are added to a system, several additional units may be required to meet the charging load, and the energy use and emissions of those units would be allocated to PHEV charging. 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 2 displays an example of fuels on the margin during each hour of one day on the entire PJM Interconnection [8]. The PJM Interconnection includes parts of Regions 1 (ECAR), 3 (MAAC), and 9 (SERC). The height of the bars represents the percentage contribution from each fuel.

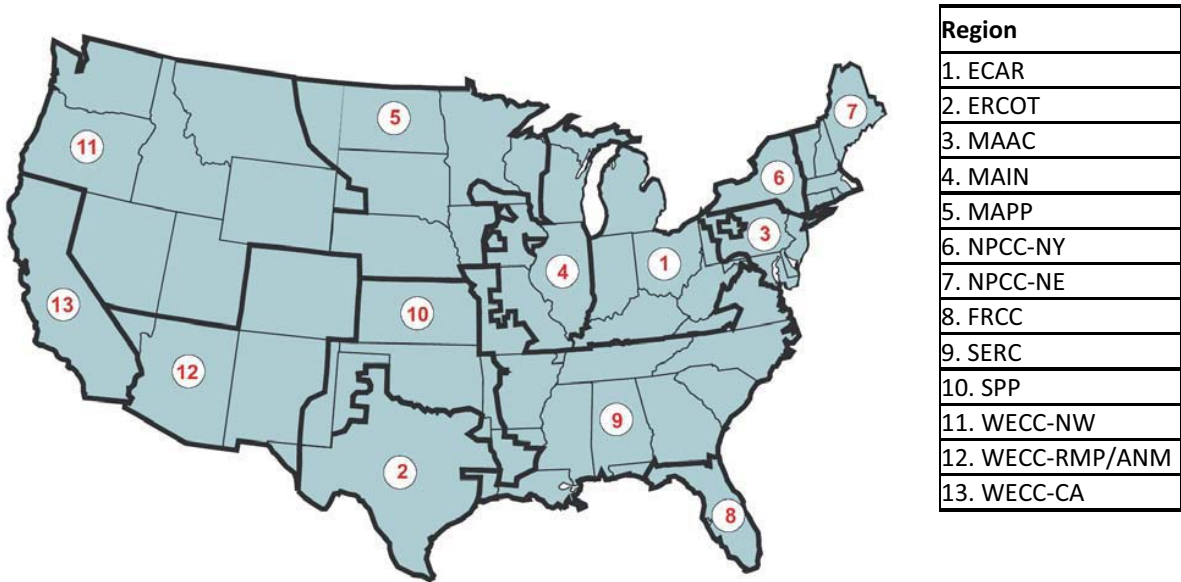


Figure 1 – NERC Regions from the Annual Energy Outlook 2007 [Source: Energy Information Administration, 2007]

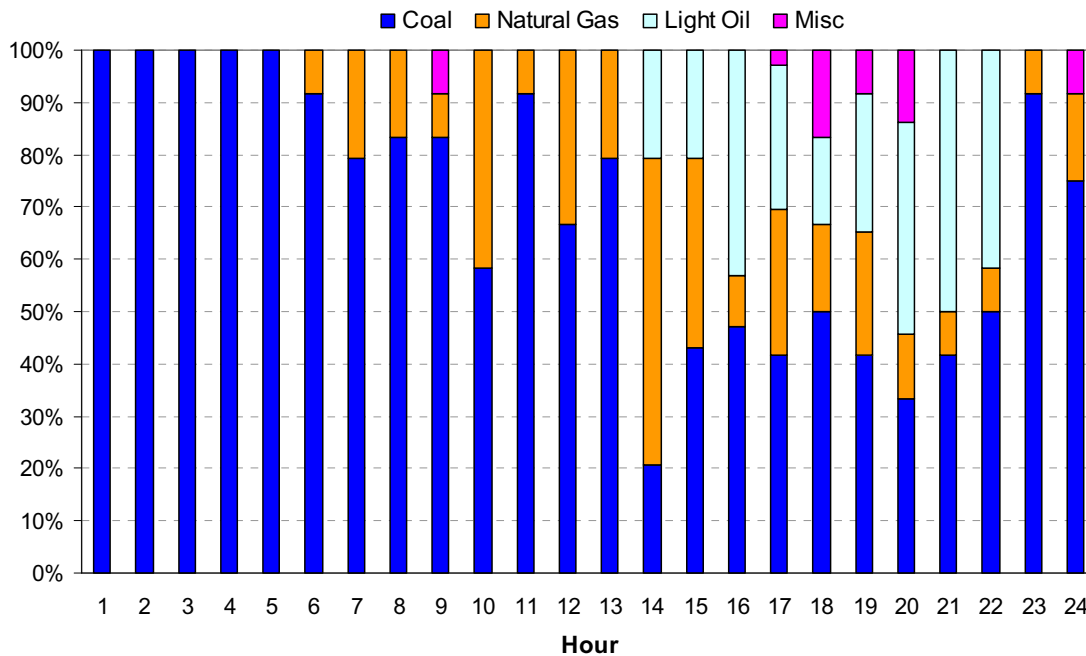


Figure 2 – Example of Hourly Marginal Fuels Data by Time of Day [Source: PJM, 2008]

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 the vehicle weight. It is most commonly assumed that the charger will operate at normal household power levels, typically 110 volts and no more than 20 amps. An SUV style PHEV may require larger batteries than a compact or sedan style 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 volts at 30 amps. Single phase 220 volt 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.

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 online. In 2006, there was 986,000 megawatts (MW) of generating capacity in the US, including both utility and non-utility capacity and 275 generators were 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 [9]. While 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 is used to optimize 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 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 is useful as an indicator of the potential PHEV charging capacity, 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, projections of transportation demand become linked to generation expansion projections. In the Annual Energy Outlook 2008, the EIA reference case is based on the historical (1980 to 2006) growth rate for transportation energy use [10]. The revised growth rate of 0.7% leads to an increase from the current 28.2 quadrillion Btus (quads) per year to 33 quads per year in 2030. This rate takes into account population growth, fuel prices, fuel economy standards, and general economic growth.

ADOPTION OF MARGINAL MIX IN GREET

The 2008 ORNL report by Hadley and Tsvetkova was found to be the best publicly available source for providing region-specific default marginal generation mixes for PHEVs as it reflected AEO 2007 projections for generation capacity expansion and load growth through 2020, and employed a region-specific dispatch model [11]. The following is a discussion of some of the major assumptions of that study, which addressed the following questions: how is the PHEV load determined, when is the charging taking place, and where is the charging taking place?

Hadley and Tsvetkova assumed PHEV penetration consistent with an EPRI base case assumption that PHEVs could achieve greater than 25% for the light duty vehicle market. They assumed that the PHEV market share would start at 0% in 2010 and grow to reach a plateau at 25% by 2020, with each vehicle retiring after 10 years. This might appear to be an aggressive assumption but fits with the goal of this analysis to examine the effect of significant demand from PHEVs on the electric grid. They assumed four vehicle classes of PHEVs to be sold, all with 20 mile AER, ranging from a compact sedan (5.1 kilowatt-hour [kWh] battery) to a full-size SUV (9.3 kWh battery). Hadley et al. examined two charging scenarios: an evening case, which initiates charging at 5 pm, and a night case which initiates charging at 10 pm. Three charging rates were evaluated, 1.4 kilowatt (kW), 2 kW and 6 kW. The charging rate along with the battery size determined how many hours are required for charging. For our analysis, the night case was chosen due to its potential for lower electricity cost, even though the true off-peak is probably close to midnight. The 2 kW charging rate was chosen, since it would minimize any additional cost for rewiring the household's electrical system. Such rewiring would likely be required for the 6 kW charging rate.

The study by Hadley et al. covers the 13 NERC regions identified in the AEO 2007 generation expansion plan. The regional power plant inventory for 2020 is taken from the AEO 2007. That inventory reflects 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 et al. 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. PHEV loads at the assumed vehicle penetration level will not have a significant effect on capacity expansion by 2020. As evidence of this, a study by Kintner-Meyer, which took a very broad look at the ability of the existing US mix to serve PHEV load,

estimated that up to 73% of the current LDV usage could be accommodated by the existing power infrastructure [12]. 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 is developed with the Oak Ridge Competitive Electricity Dispatch Model (ORCED). The ORCED determines 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) as they encompass large metropolitan areas and provide significant variation of marginal generation mixes. In addition, we examine a US 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 2. Note 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 is mostly relying on the natural gas combined cycle (NGCC) technology may consider the WTW results of this analysis for California. Similarly, a marginal mix that is heavily relying on conventional coal or residual oil for power generation may consider the WTW results of this analysis for Illinois and New York, respectively. Note that this study is not meant to provide interregional comparison or as 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 are directly reflecting the impact of these mixes.

PSAT VEHICLES' FUEL ECONOMY SIMULATION

PSAT is designed to serve as a tool to meet the requirements of automotive engineering throughout the development process, from modeling to control [13,14]. PSAT is a forward-looking model that uses the driver outputs to send commands to the different components in order to follow a specified drive cycle, and has been validated within 5% for several vehicle powertrain configurations on a number of driving cycles [15].

Table 2 – Generation mixes for recharging PHEVs (for use in GREET)

Mix	Coal	Oil	Natural Gas	Nuclear	Other
US 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

When analyzing the performance of PHEVs, the amount of electricity used by the vehicle compared to 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 (e.g. 90% SOC), then the vehicle would operate in a CD mode using only the stored electricity until it reached a low SOC (e.g. 30% SOC). 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 [16]. This operation strategy allows the vehicle to operate as a zero emission vehicle (ZEV) 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 have been 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 (battery and electric machine, e.g., 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% 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 detailed explanation on the assumptions and methodology of PSAT for evaluating fuel economy of advanced vehicle configurations (including ICEVs, HEVs, PHEVs, and electric vehicles [EVs]) for model years 2010 to 2045 [17]. The vehicle assumptions for the PSAT simulations, which are incorporated in this study, are shown in Table 3.

Table 4 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 energy use of the electric motor during the same CD VMT distance. Note that the per-mile energy use from 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 in Table 4. Furthermore, the fuel economy data for the engine in CD operation should be correlated with the actual CD VMT range shown in Figure 3 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.