EVS26
Los Angeles, California, May 6-9, 2012

Impacts of PHEV Charging on Electric Demand and Greenhouse Gas Emissions in Illinois

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Abstract

This study examined the impacts of plug-in hybrid electric vehicle (PHEV) charging scenarios in Illinois (IL) in the year 2030. We examined the impact of PHEV market penetration and charging scenarios on the electric utilities and transmission grid, and estimated the potential reductions in petroleum use and greenhouse gas (GHG) emissions due to displacing petroleum with electricity. Two charging scenarios were considered: (1) PHEVs start recharging upon arrival at home at the end of their last daily trip (arrival time charging), and (2) PHEVs recharging during overnight hours when the demand on the grid is the lowest (smart charging, with no needed investment in new capacity). The two charging scenarios produced distinct hourly load profiles, with increased load during the daytime for the arrival time charging scenario. Utility dispatch simulations for these charging scenarios predicted dissimilar marginal generation mixes and GHG emissions for the same PHEV total demand, with more dispatching of coal generation in the smart charging scenario. A well-to-wheel (WTW) analysis showed that PHEV10 and PHEV40 can reduce petroleum use by 46% and 63%, respectively. Depending on the vehicle's electric range and the hourly charging (load) profile, PHEVs in IL can reduce GHG emissions by 16% to 36% compared to conventional gasoline internal combustion engine vehicles (ICEVs).

Keywords: PHEV, LCA, charging, emissions, environment

1 Introduction

The transportation sector is totally dependent on petroleum fuels requiring U.S. to import over half of its petroleum needs [1]. Within the transportation sector, light duty vehicles account for 55% of its total energy use [2]. In order to reduce the nation's reliance on imported fuels, the U.S. government is supporting several initiatives. One of these initiatives is to diversify transportation energy sources by using electricity to drive the light duty vehicles.

The plug-in hybrid electric vehicle (PHEV) technology is aimed at transferring a part of light duty vehicle energy use to electricity, thereby reducing the transportation sector's heavy reliance on petroleum fuels. The technology involves storing electricity from a plug into a battery pack on board a vehicle and using it later to propel the vehicle. A PHEV also has an internal combustion engine that drives the vehicle when the energy in the battery pack is used up. Thus, a PHEV travels its initial miles on electricity and operates on fossil fuels once the battery is depleted. Because electricity is generated through use of coal, nuclear, natural gas, hydro, and wind sources, widespread acceptance of PHEVs could diversify energy sources. However, these PHEVs could be connected to the electricity grid at various times of the day, causing unexpected additional demand on electric utilities. Also, over half the electricity in the United States is presently generated by burning coal and additional electricity demand could result in increased carbon dioxide and other greenhouse gas emissions. Aside from reduced petroleum use, the impacts on electricity generation associated with the widespread use of PHEVs need to be evaluated.

While all previous studies predicted significant reductions in petroleum energy use by PHEVs, they predicted mixed results for GHG emissions of these vehicles. All past studies indicated that the marginal electricity generation mix for battery recharging was a major factor impacting the GHG emissions associated with PHEVs [3-11]. They examined the impact of the pattern and magnitude of charging on the generation mix. If consumers add load during the peak hours, the added load will require the construction of new power plants, which results in high marginal cost. One concern with recharging during late afternoon hours when the demand on the grid is the highest is the "avalanche" effect, in which all PHEVs charge at about the same time, delivering a pulse in power requirements to the grid [12]. The higher the power rating of the chargers chosen by PHEVs, the worse are the hypothetical effects, both in terms of causing needs for added generation units [3,8] and in terms of causing needs for transformer replacements [13] and household rewiring. Hadley and Tsvetkova [8] showed that if all PHEVs in an optimistically large fleet were to be plugged in upon arrival at home (with timing near the daily peak) and each had a 6 kW charger, a new higher and more pronounced summer daily peak would result, as well as a significant heightening of the winter daily peak. However, with Level 1 charging at 1.4 kW, there was no summer peak problem.

Elgowainy et al. [3] and Hadley and Tsvetkova [8] observed that "smart charging" that meets the idealized goals of the public utility commissions by scheduling charging during the low point of the overnight trough may lead to an increase in coal use in comparison to the "arrival time" charging scenario. Smart overnight charging has often been estimated to be the least-desirable strategy in terms of GHG emissions, because coal use is at a low point in the overnight trough in utility regions that have a significant share of coal in their generation mix, e.g., IL [3, 8]. Elgowainy et al. [3] conducted detailed least-cost dispatch modeling simulations in different U.S. utility service areas with different charging scenarios for PHEVs in 2020. This study showed that the electricity generation mix for recharging PHEVs in different utility regions results in a wide range of GHG emissions, which were comparable to the GHG emissions of conventional gasoline ICEVs when the power generation mix was dominated by coal, but were comparable to the GHG emissions of hybrid electric vehicles (HEVs) when the mix was dominated by natural gas. By observing these results, it was deduced that spreading the charge period by reducing the charge rate would thus reduce the amount of coal generation used in the trough and increase the use of low-GHG NGCC power plants, which are the type used in the "shoulders" of the trough and/or during partial peak periods [14]. Elgowainy et al. have estimated that when NGCC power plants provide electricity for PHEVs, GHG reductions by PHEVs relative to HEVs occur, but when coal power plants are used, GHG emissions increase [3].

This paper summarizes the results of a study in which PHEVs are assumed to capture a substantial share of the light duty vehicle fleet in IL by 2030. The PHEVs are assumed to be offered in cars and small sport utility vehicles. The powertrain characteristics of the PHEVs and their electric energy requirements are estimated by using Argonne's Autonomie simulation tool [15]. Autonomie is a tool that simulates fuel (and electricity) consumption on standard or customized driving cycle for different vehicle configurations. A utility simulation model is employed in which electricity generation and transmission systems in IL, in 2030, are represented with accounting for future renewable energy requirements, energy efficiency gains, as well as scheduled retirement of coal power plants. Alternative scenarios relating to the time of day PHEVs will be connected to the electricity grid are simulated and the resulting impacts are evaluated.

2 Analysis Methodology

We started our analysis by examining the potential markets for the large-scale deployment of PHEVs and estimate the market penetration of such vehicles. We selected Illinois for our analysis and used the VISION model, developed at Argonne National Laboratory (Argonne), to simulate a market profile of PHEVs up to the year 2050.The

VISION model is a tool to estimate potential energy uses, oil uses and emission impacts of highway transportation technologies [16]. Based on our research experiences, economic analysis, PHEV performance attributes and personal VMT attributes, we developed an optimistic new PHEV market penetration profile. When the resulting 2010-2030 new PHEV sales were input to the VISION model, that the model predicted a 10% share of on-road light duty vehicles to be PHEVs in 2030. Next, we analyzed travel data obtained from the 2009 National Household Travel Survey (NHTS) to develop the distribution and shares of PHEVs of different electric ranges [17]. We then calculated the electric energy required to recharge PHEVs of various electric ranges by using simulation results from Autonomie. We examined Level 1 and Level 2 charging rates in different scenarios of recharging the batteries of PHEVs accounting for various losses from the wall plug to the battery pack. These charging rates define the load of each PHEV type on the local grid. To establish the hourly load profile of PHEVs, we examined different scenarios for the time at which these vehicles would recharge their batteries. The PHEVs' load was then added to the system load in the selected utility region, and a detailed dispatch simulation was conducted to determine the mix of the electric generation units that will satisfy such marginal load. Finally, a well-to-wheels (WTW) analysis — which examines energy use and emissions from primary energy sources through vehicle operation — was conducted to examine the impact of the upstream mix of these electricity-generating technologies used for PHEV recharging and of the gasoline use in the non-electric operation of PHEVs. For the WTW analysis, we used the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by Argonne to compare the WTW energy use and GHG emissions associated with PHEVs to those associated with baseline gasoline ICEVs and HEVs. The following sections of the paper provide details of each step in the above-described methodology that we adopted for our analysis.

3 Electricity and Fuel Consumption by PHEVs

We examined the performance of compact cars, midsize cars, and small sport utility PHEVs. Two PHEV design configurations were considered for this analysis: a power-split design for PHEV10 (i.e., with 10 miles of electric range) and a series design for PHEV40 (i.e., with 40 miles of electric range). Some use the term extended range electric vehicles (EREVs) for the series PHEVs since they are capable of charge depleting (CD) in the electric mode under nearly all driving conditions. The power-split design is a parallel hybrid configuration in which the ICE and the electric motor are connected to a single mechanical transmission. The design incorporates a power-split device that allows for power paths from the engine to the wheels that can be either mechanical or electrical, thus decoupling the power supplied by the ICE from the power demanded by the driver. The series design is based on an ICE that powers a generator, which charges the battery or directly powers the electric motor to drive the drivetrain; thus, the gasoline engine never directly powers the vehicle in this configuration. For the power-split PHEV, the engine is sized to meet the gradeability requirement. The size of the engine in the series PHEV is similar to that in the power-split PHEV, but it has a higher power demand because of the added inefficiencies associated with the longer power path of the driveline in the series configuration. The battery power for all PHEVs is sized to meet the urban dynamometer driving schedule (UDDS) in the CD mode of operation, although the control strategy may limit the use of battery power to maximize the engine's efficiency during the blended-mode operation of the power-split PHEVs. The electric machine motor is sized to meet the UDDS load for the power-split PHEVs and to meet the US06 (a more aggressive, high-speed driving cycle) for the series PHEVs. The choice of the power-split configuration for PHEVs with shorter electric range is consistent with the limited energy and power ratings of the employed batteries, while the choice of the series design configuration for PHEVs with longer electric driving range is consistent with the bigger batteries and more powerful electric motors needed to extend the driving range all electrically.

A PHEV charges the battery to a high state-of-charge (SOC) (e.g., 90%). Then, the vehicle operates in a CD mode by using the stored electricity in the battery until it reaches a low SOC (e.g., 30%). Once the battery reaches the low SOC threshold, the PHEV operates in a charge-sustaining (CS) mode, which is similar to the operation of regular HEVs [18]. This strategy allows the vehicle to operate as a zero-emission vehicle in CD operation. However, battery cost and PHEV performance requirements have led some automakers to consider a "blended" CD mode, through which the engine is intermittently turned on, resulting in increase in the CD range by utilizing the electric powertrain and the engine simultaneously (blended operation). The blended operation of the engine and the electric motor allows for a more efficient utilization of the battery, especially in hot and cold weather operations.

Since different PHEV configurations are yet to be produced by the automotive industry or have been introduced only recently, the consumption of fuel and electricity by PHEVs is estimated by Autonomie. Autonomie predicts the fuel and/or electricity consumption of the selected vehicle technologies on the UDDS and the Highway Federal Emissions Test (HWFET) driving cycles. However, these (laboratory) driving cycles do not reflect the actual "on-road" fuel and electricity consumption that occurs during "real-world" driving. Limitations of these cycles include mild climatic conditions (24°C), modest acceleration rates, no use of fuel-consuming accessories (such as air conditioning), and a top speed of only 60 miles per hour for the highway test cycle. Thus, the actual "on-road" fuel and electricity consumption rates per unit distance travelled need to be adjusted to reflect the impact of typical driving behaviour, air-conditioning use, and cold-weather implications.

Autonomie produces three sets of fuel economy and electricity consumption (high optimism, medium optimism, and low optimism) representing 10%, 50%, and 90% chance of the technology being available at the time considered. We considered the high optimism scenario for PHEVs to reflect reasonable performance improvement in 2030 over today's Chevy Volt which is rated by the U.S. Environmental Protection Agency (EPA) at 94 miles per gallon equivalent (MPGe) in electric operation. Autonomie's projection of equivalent fuel economy for the electric operation of a midsize PHEV40 in 2030 is 105 MPGe (high optimism). The projected modest increase in MPGe over today's demonstrated performance reflects the focus of research and development on cost reduction rather than performance improvement of electric powertrains.

We examined the fuel economy adjustment factors for different vehicle technologies (i.e., adjusting the fuel economy and electricity consumption from the UDDS and HWFET values to the actual on-road estimates). We calculated the equivalent "on-road" fuel economy by using MPG-based formulas developed by EPA [19]. The reduction in fuel economy attributable to the "on-road" adjustment formula was capped at 30% for advanced vehicle systems (e.g., PHEVs and HEVs), as suggested by EPA and other experts in this area. Thus, we adjusted the electricity consumption of series PHEVs in CD operation on the basis of a 0.7 fuel economy degradation factor. However, we did not adjust the electricity consumption of the power-split PHEV design because the additional on-road load (above the cycle load) is assumed to be handled by the engine (in the blended CD mode of operation). In such a case, we assumed that the additional load (over the test cycle load) would result in an increase in fuel consumption similar to the one recorded during CS operation of the same vehicle for the same additional load. The composite city/highway fuel economy was calculated on the basis of new EPA proposed weighting factors of 43% for city driving and 57% for highway driving [20]. Table 1 shows the adjusted fuel economy and electricity consumption for PHEVs, as well as for baseline conventional ICEVs and regular HEVs for midsize vehicle class, in year 2030.

Table 1: Adjusted Fuel Economy and Electricity Consumption for Alternative Gasoline Vehicle Technologies

	Baseline Light-Duty Vehicles		PHEV10 (power-split)		PHEV40 (series)[1]	
	ICEV	HEV	CD	CS	CD	CS
Gasoline Fuel Economy (MPG)	36	51	133	54	N/A	44
Electricity Consumption[2] (Wh/mi)	N/A	N/A	166	N/A	270[*]	N/A

[1]Also known as EREV

[2]Electricity consumption does not include charging losses; charging efficiency assumed at 85%

[*]Equivalent to 123 MPGe, not including charging losses

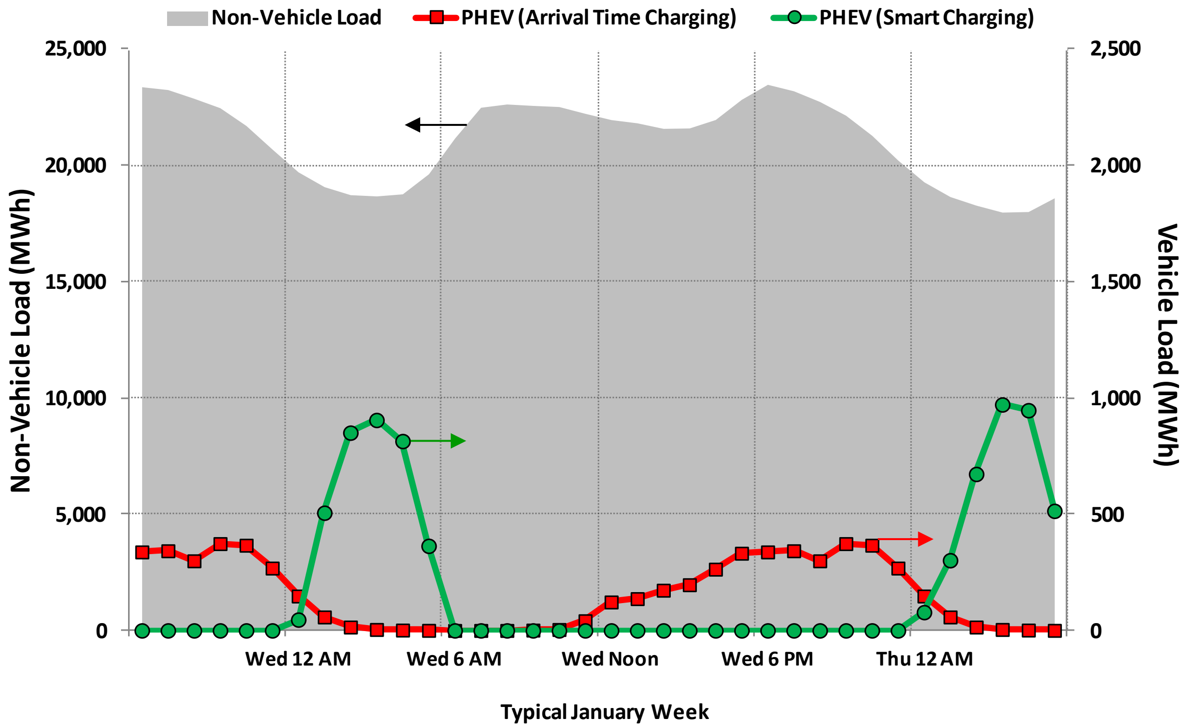

Figure 1: Electricity Demand of Two Charging Scenarios in Illinois (2030)

4 PHEV Electric Demand (Load) Profiles

We used light-duty vehicle projections by the Energy Information Administration (EIA) in its Annual Energy Outlook (AEO) 2010 to estimate the number of vehicles on the road in 2030 [21]. We first used driving age (16-84 year) population data from the U.S. Census Bureau [22] by state to allocate EIA's national vehicle projections to each state. However, the states have different vehicle ownership rates by driving age population. We analyzed the past vehicle registration data to estimate correction factors reflecting each state's propensity to own more or less light duty vehicles per driving age person. Then we used the state-level vehicle registration data to allocate vehicles by type based on the 2008 Highway Statistics [23]. Based on the VISION model results, PHEVs of various electric ranges were assigned a 10% share of all light-duty vehicles on road by 2030. The 2009 National Household Travel Survey (NHTS) data [17] were used to allocate the total number of PHEVs by their electric range. Further details on the allocation methodology are provided in Elgowainy et al. [24].

We used the one-day travel component in the 2009 NHTS to study the travel pattern of the potential PHEV drivers, but only focused on weekday travel. This study focuses on two PHEV charging scenarios: "arrival time charging" and "smart charging" as described earlier. Both level 1 (110 V/15 A, 110 V/20 A) and level 2 (220 V/20 A) charging facilities were assumed in this scenario, depending on vehicle type and PHEV electric range, to ensure that PHEVs with fully depleted battery packs can recharge within 6 hours.

PHEVs will draw electric energy from the grid. The hourly electricity demand by PHEVs can be estimated by analyzing the following four factors: (1) daily vehicle usage, (2) pattern of vehicle arrival at home at the end of the last trip and of vehicle departure from home at start of first trip, (3) number of PHEVs of different electric ranges that will be plugged in each hour and the useable capacity of their batteries, and (4) the charging rate by each PHEV and the total time required for full charging.

Figure 1 shows the baseline (non-vehicle) as well as PHEV loads (sustained over one hour, i.e., in MWh) for the "arrival time" charging and "smart charging" scenarios. The figure shows for the "arrival time" charging that the load of PHEVs peaks around 6 p.m. and drops to the lowest point around 3 a.m. In such scenario, the utility grid could face very high challenges at the early part of night, especially during the summer when air-conditioning units are typically turned on. In the "smart charging" scenario, PHEVs' peak demand happens around 3 a.m., with the lowest point occurring at 6 a.m. The sharper and much higher peak of the “smart charging” scenario may be of concern to electric utilities if causing a need for transformer replacements.

5 Electricity Dispatch Modelling

5.1 Model Representation and System Topology

The Electricity Market Complex Adaptive (EMCAS) model is used to simulate the hourly operations of the power systems [25]. The simulated power system includes detailed representation of generating units, transmission lines and aggregated bus-level loads. This configuration is similar to the power system used by Elgowainy et al. [3] and also in the original study for the Illinois Commerce Commission [26, 27]. However, there are several updates that have been made to the dataset. Historic simulations indicated that Illinois is a net exporter of energy and hence in this simulation we excluded non-Illinois generation. However, the external loads are included as price elastic loads. This facilitates export of nuclear and wind generation during low load periods, during which time the prices are very low. These price elastic external loads are required to avoid the infeasible operation of shutting down the nuclear units during night times.

5.2 Load Forecast

The non-vehicle electric load in Illinois is updated to 2030 based on the long-term projections of annual and peak load projections for ComEd and Ameren areas by the PJM Interconnections [28] and the MISO [29] respectively. The regulations in Illinois stipulate that the electric utilities implement cost-effective energy efficiency and demand-response measures to reduce the annual energy growth and peak demand respectively [30, 31]. These regulations are taken into consideration when projecting the load to 2030. A load shaping algorithm is applied to obtain an hourly load profile for these areas. The bus-level hourly loads from 2007 have been scaled to match the area hourly, annual and peak load profiles.

5.3 Vehicle Loads

In the “arrival time” charging scenario, drivers begin charging their vehicles immediately upon returning home from the last trip of the day. This profile is developed using the battery capacity of each type of vehicle, the electric range of those vehicles, the characteristics of the charging equipment used, and the time of the day at which the last trip home occurs. The “smart charge” scenario assumes that the utility company is able to control the delivery of power to recharge vehicles, and does so during overnight hours when system demand is the lowest. Vehicles are fully charged before the driver leaves for the first trip of the day. For a given penetration of vehicles, the arrival time and smart charging scenarios have the same amount of aggregate load and the difference is only in the hour-by-hour profile of when those loads occur. The total vehicle load for each area (ComEd and Ameren) is distributed on a bus-by-bus basis according to the proportion of system (non-vehicle) load at each bus.

5.4 Retirements

By 2030, several of the generating units in Illinois will far exceed their design lifetime. In addition, the pending legislations that aim to reduce emissions of carbon and other pollutants will impact the economic viability of the thermal units. The following general rules are applied to retire the existing generating units in Illinois:

1) Any coal or fuel oil or nuclear powered unit whose age will be 60 years or more by 2030
2) Any natural gas powered unit whose age will be 40 years or more by 2030

With these assumptions, the total capacity that will be retired by 2030 is 4032 MW, 5730 MW, 572 MW and 678 MW of bituminous, sub-bituminous, fuel oil and natural gas powered units respectively. None of the nuclear units will be retired by 2030.

5.5 Fuel Price Updates

The fuel prices used by the thermal units have been updated based on the EIA projection as used in annual energy outlook (AEO) [32] for the year 2030.

5.6 Renewable Portfolio Standards

The Illinois Public Act 095-0481 [33] that created the Illinois Power Agency (IPA) and subsequent amendments 096-0159 require that the electric utilities and alternate retail electric suppliers procure cost-effective renewable energy sources. As per the schedule under this law, 25% of electric sales by 2026 should come from renewable resources of which at least 75% should be from wind and 6% from solar resources. As the schedule ends in 2026, it is assumed that the same requirement will be applicable in the year 2030. To meet this renewable portfolio standard, it is estimated that a capacity of 13,100 MW of Wind-turbines would be required by 2030 and we distribute these resources in the model to several existing and proposed wind farm sites in Illinois. Similarly, a solar capacity of 1,620 MW would be required by 2030 and we distribute these resources across several brownfield sites as identified by EPA [34].

5.7 Solar and Wind Profiles

PV Watts [35] is a web based calculator developed by the National Renewable Energy Laboratory (NREL) that computes the hourly solar energy production considering the typical meteorological year and PV performance. Several such profiles were obtained across Illinois (Chicago, Rockford, Moline, Peoria and Springfield) to present the hourly generation from solar farms. Similarly, using the NREL wind dataset from the Eastern Wind Integration Study [36], a site with strong wind potential was chosen from each of four general geographic regions in Illinois to represent output from wind turbines in that region. NREL data showed hourly generation output at each site for a wind turbine of a specific size. The hourly wind profile from 2005 was used to project generation from wind for 2030.

5.8 Uprates

The design of every U.S. commercial reactor has excess capacity needed to potentially allow for an uprate, which can fall into one of three categories: 1) measurement uncertainty recapture power uprates, 2) stretch power uprates, and 3) extended power uprates. In the current simulation, it is assumed that only those uprates that have been filed by Exelon and approved by NRC will be in implemented by 2030. With these assumptions, a total of 1,115 MW [37] additional nuclear generation capacity would be available by 2030.

5.9 Capacity Expansion

Due to the load growth and retirement of existing generating units, additional generation capacity is needed in the system. The addition of substantial wind and solar capacity and the uprating of nuclear units are not sufficient to meet the needs of the system in 2030. A total of 5,500 MW of thermal capacity in IL is required to maintain a 15% reserve margin, which is a typical target reserve margin in power systems with huge thermal capacity such as Illinois. It is assumed that the availability of cheap natural gas and pending environmental regulations will make natural gas the primary choice for capacity expansion. With these assumptions, 12 combined cycle plants (400 MW each) and 3 gas turbines (230 MW each) were added. It is assumed that these plants will be located at the locations of other retired thermal plants. In the smart charging case the hourly vehicle loads do not add to the system peak loads, therefore no additional generating units are required beyond those present in the base case. However, the loads in the arrival time charging scenario add to the system peaks and so, this scenario required one additional gas turbine unit to maintain the aforementioned reserve margin.

5.10 Transmission Capacity Upgrades

The changes in the unit inventory because of retirements of thermal units, uprates to nuclear units, installation of wind and solar farms require upgrades to some transmission lines in order to avoid excessive amounts of congestion. The transmission capacity of few transmission lines have been increased from the Phase 2 of this study.

5.11 Planned Maintenance and Forced Outage Schedule

EMCAS has built-in algorithms to generate planned maintenance and forced outages. The planned maintenance algorithm schedules the generating units by maximizing the minimum reserve margin in each month and the forced outages occur at random as a result of component failures. The number and length of these schedules is technology specific and consistent with Generating Availability Data Systems (GADS) statistics [38].

5.12 Utility Simulation Results

The simulations are carried out for four typical weeks (the second weeks of January, April, July, and October) in 2030 representing winter, spring, summer and autumn seasons. However, simple scaling to annual level will not result in representative yearly results because of the varying maintenance schedule of the generating units across these four seasons. Therefore, scaling factors that take into account the maintenance schedule throughout the year are developed by generating technology and fuel type. The Figure 2 shows the base case capacity and annual generation based on these scaling factors. In the base case (without vehicle load), most of the energy is produced by nuclear units, followed by renewables, coal, and natural gas. When electric vehicle load is present, the additional energy comes mostly from natural gas and coal, and exports from Illinois are reduced. The higher loads also make it possible to utilize more of the generation in-state rather than export it. The smart charging profile, with most of its load occurring in early morning hours, facilitates the use of more nuclear and wind generation which would have otherwise been exported.

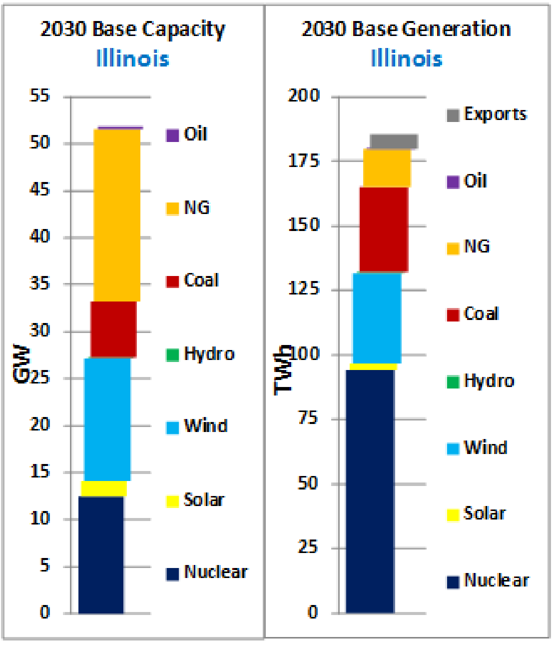

Figure 2: Base Case Capacity and Generation Projections for Illinois in 2030

6 WTW Analysis of PHEVs

Since a PHEV consumes fuel and electricity, its pathway consists of two parallel paths for these two energy sources. The fuel path includes the recovery of the feedstock (e.g., crude), the transportation of the feedstock, the production of the fuel (e.g., refining of crude to gasoline), and the transportation of the fuel to the pump. The electricity path includes the recovery, processing, and transportation of the fuel used for electricity generation (e.g., natural gas and coal); the technology used for electric power generation (e.g., steam power plant, gas combustion turbine, etc.); the transmission of the electricity to the wall outlet; and the charging of the vehicle's battery. The fuel and electricity production and transmission represent the well-to-pump (WTP) stage of the pathway, while the vehicle's consumption of fuel and electricity represents the pump-to-wheel (PTW) stage. Our results reflect 4% transmission losses in IL [39].

We used Argonne's GREET model to examine the WTW energy use and GHG emissions for PHEVs, as well as regular HEVs and conventional gasoline ICEVs. WTW results are examined for CD operation of PHEVs for the arrival time charging and smart charging scenarios. The combined WTW results of CD and CS PHEV operations (using the utility factor method [3]) were also examined.

Figure 3 shows the WTW results of gasoline PHEVs, in addition to gasoline ICEVs and gasoline regular HEVs. The figure includes WTW results for the marginal generation mix in IL for the two charging scenarios shown in Table 2. The WTW petroleum energy use and GHG emissions of HEVs and PHEVs are normalized by the per-mile petroleum energy use and GHG emissions of the baseline conventional gasoline ICEV. Figure 3 includes the WTW results for CD-only operation and for the combined CD and CS operations of PHEVs. The results for the combined CD and CS operations are the weighted average of the electricity and fuel consumption in these two modes of operation by the share of mileage driven in each mode. The combined results reflect 23% and 52% shares of miles travelled in CD operation (based on the utility factor method and using the adjusted CD driving range) for PHEV 10 and 40, respectively.

Table 2: Marginal Electricity Generation Mix for Two Charging Scenarios in Illinois

Fuel	Technology	Charging Starts at Arrival Time (arrival time charging)	Charging Occurs During Lowest Demand (smart charging)
Coal	Utility Boiler	27%	69%
Natural Gas	Combined Cycle	60%	30%
	Combustion Turbine	13%	0%
Renewable	Wind/Solar	0%	1%
Total		100%	100%

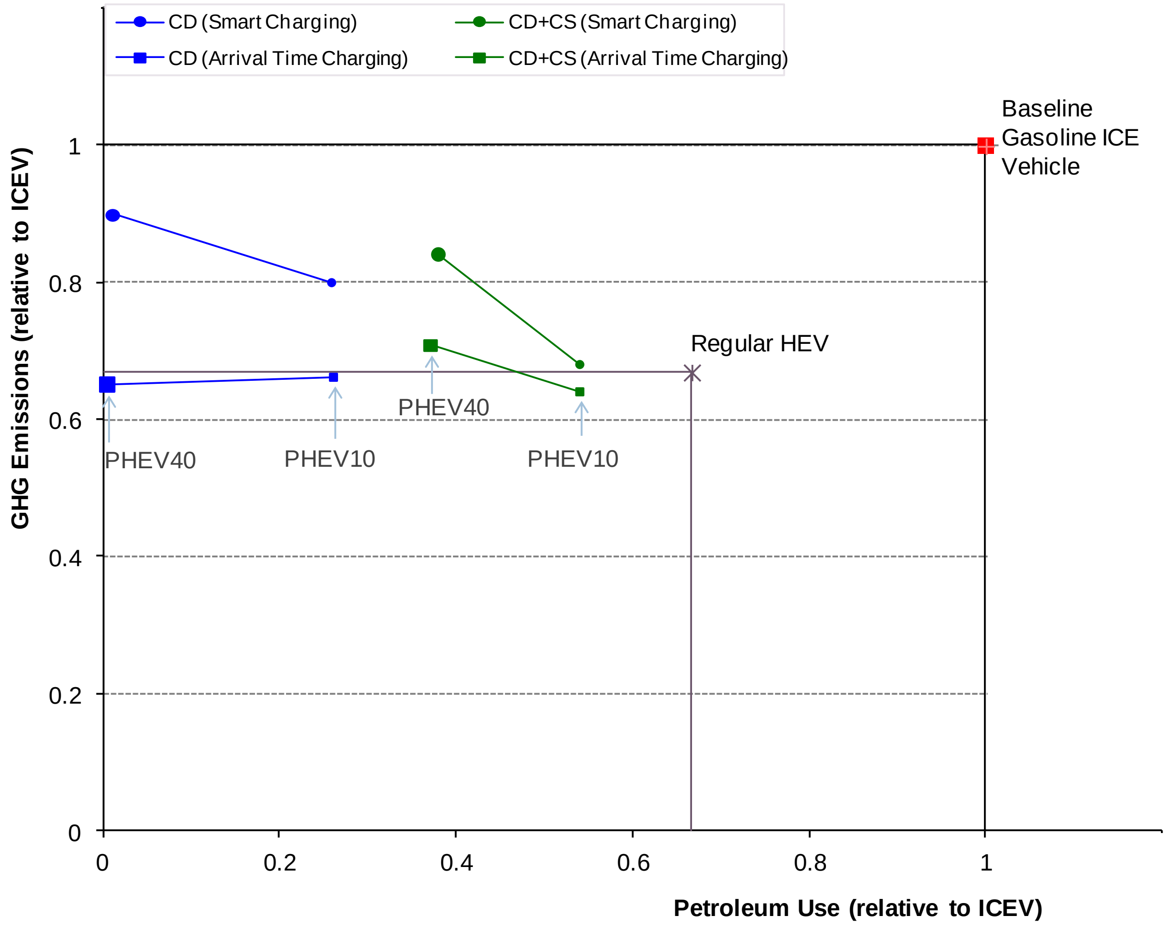

Figure 3: WTW Petroleum Use and GHG Emissions for Gasoline PHEVs Recharging in IL Relative to Baseline Gasoline ICEV

The WTW results for the Illinois region were distinctively different among the two charging scenarios mainly because of the availability of more (low cost) coal generation capacity during night hours compared to day hours. While wind is readily available to northern Illinois, it is estimated to mainly serve the baseload and not to be a marginal supplier to PHEVs because our modeling assumes wind is non-dispatchable. In the event that PHEVs were able to accept wind that would otherwise have to be curtailed because of a lack of demand (negative residual load), then under these circumstances it could be credited for some clean wind generation. This can happen in overnight troughs in demand if the supply of renewables under a renewable energy standard exceeds the demand at that time (see smart charging scenario in Table 2). Our estimate for wind power share in that scenario is rather small (~1%). The vast majority of energy still comes from fossil sources (i.e., coal and natural gas). A more aggressive renewable energy standard can increase the share of wind power for PHEV recharging [12].

Figure 3 also shows that the CD operation of PHEVs provides a 36% reduction in GHG emissions relative to the conventional ICEV, slightly outperforming the HEV, in the arrival time charging scenario. These reductions hold true regardless of the PHEV's electric range or its design configuration (i.e., power-split or series). However, recharging the same vehicles through the smart charging scenario provides modest GHG savings (10% for PHEV40 and 20% for PHEV10, relative to ICEV). The petroleum reduction in CD operation is a strong function of the vehicle's electric range and design, with a reduction in petroleum use of 63% for PHEV10 and 46% for PHEV40.

The WTW results for the combined CD and CS operations of PHEVs in Figure 3 reflect less petroleum savings due to the gasoline use in CS operation. The figure also highlights the impact of PHEV design on the WTW GHG emissions.

While the power-split design of PHEV10 produces GHG emissions comparable to regular HEVs, the series (EREV) design of PHEV40 produces higher GHG emissions compared to HEVs. This result is attributed to the added inefficiencies of the driveline in the series configuration when operated in CS mode. The utility factor method that we used for allocation of travelled distance between CD and CS assumes only one charge per day. EREVs charging more than once per day would approach the petroleum savings and GHG emissions of the CD operation. Analysis of opportunity charging of PHEVs is discussed in details by Santini et al. [40].

7 Conclusions

We examined the impact of various PHEV charging choices in Illinois, which has traditionally depended heavily on coal for baseload and intermediate load. The charging choice directly impacts the additional PHEV load that is added to the baseline system load in that region. We incorporated future renewable energy requirements, energy efficiency gains, and scheduled retirement of coal power plants in modeling the utility system in IL in the year 2030. Charging PHEVs upon arrival (i.e., starting at end of last daily trip) adds significant load in the late afternoon hours, which partially overlaps with the system load peak hours. Smart charging of PHEVs (i.e., during overnight's lowest demand periods) fills the overnight trough in the daily demand profile. The smart charging of PHEVs resulted in more dispatching of coal power plants compared to the arrival time charging (69% vs. 27% share of coal generation in the marginal mix for the smart charging and arrival time charging scenarios, respectively). These shares of coal generation for PHEV recharging in 2030 are significantly lower compared to those in 2020 in our earlier study [3] due to the retirement of coal generation and addition of natural gas generation. Our well-to-wheel analysis estimated that PHEVs can reduce GHG emissions by 16% to 36% compared to conventional ICEVs in IL, depending on the vehicle's electric range and the hourly charging profile.

Acknowledgments

This work was supported by the Vehicle Technology Program of Office of Energy Efficiency and Renewable Energy of the United State Department of Energy under contract DE-AC02-06CH11357. We would like also to thank the Autonomie group at Argonne for providing vehicle simulation results for this analysis.

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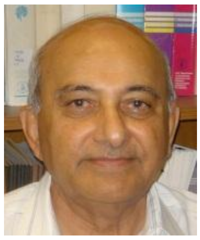

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