IMPACT OF PLUG-IN HYBRID ELECTRIC VEHICLES ON CALIFORNIA'S ELECTRICITY GRID

by

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ABSTRACT

Several automakers are preparing for the next generation of passenger transportation, Plug-in Hybrid Electric Vehicles (PHEVs). These vehicles are slated to be commercially available starting in 2010. PHEVs operate similar to Hybrid Electric Vehicles (HEVs) which utilize a significant portion of energy from the battery for drive; however PHEV batteries have the capability of recharging through most standard electrical outlets. For these vehicle owners, the demand for gasoline will be offset and replaced by an increased demand in electricity. Using data from the California Independent Systems Operator (CAISO), this report sought to understand how different charging scenarios for PHEVs could impact electricity demand in California. Furthermore, this study aimed to understand how the additional demand from plug-in hybrid vehicles would affect the supply price of generating electricity.

The results from this study estimated that PHEVs would require between 2% of California's summer peak capacity for a low market penetrations and 8% for a high market penetrations of PHEVs. At most, a $5/MWh increase in electricity price can be expected for a 5% market penetration of PHEVs charging under a normal distribution scenario in the evening. Under the same scenario, a 20% market penetration of plug-ins will result in a maximum supply price increase of $20/MWh. Nighttime charging of these vehicles can help level the load curve up to 25% during peak generation days and can decrease the price impact by an average of 30%. Furthermore, the introduction of plug-ins onto CAISO's grid can increase the amount of electricity needed to meet the minimum load demand, requiring more baseload generation. Under a scenario in which PHEVs are allowed to charge during peak hours, the additional demand can lead to constraints on the existing "peaking units" in California.

INTRODUCTION

As gasoline prices rise and the nation's reliance on foreign oil becomes a more pressing concern, efforts are being made to reduce the economic impacts on U.S. citizens. Laws to improve the Corporate Average Fuel Economy (CAFE) standards on passenger vehicles have been passed to increase average gas mileage for cars. Furthermore, automakers are looking at new technologies to boost vehicle miles per gallon (mpgs) at the same time, mitigating air pollution and greenhouse gas emissions. Hybrid electric vehicles (HEV), which combine an internal combustion engine with a battery for improved energy efficiency, have made their way into the market and have grown in popularity. In 2007, HEVs accounted for around 2% of all U.S. light duty vehicle sales (Lamberson 2008) and the government is encouraging the use of these vehicle by providing tax credits averaging $2,000 per new 2009 hybrid model purchased (Electric Drive Transportation Association 2009). The next generation of transportation technology, Plug-in Hybrid Vehicles (PHEVs), plan to build on the success of HEV vehicles and will begin to gain market penetration starting in 2010 (Maynard 2008). Although not currently available for commercial use, these passenger vehicles allow for greater efficiency by allocating a substantial amount of drive to the lithium-ion (Li-ion) battery. Automakers and battery designers promise to introduce plug-in hybrids that can achieve over 100 miles per equivalent gallons (mpegs)[1]. As a trade-off, these vehicles must be charged through electrical outlets, requiring the use of electricity. Linking the electricity sector with transportation could be a major step in establishing an energy independent nation; however the impact to electric utilities could prove to be substantial without proper planning.

Charging the PHEV batteries can occur through dedicated electrical outlets in a household, through specific charging stations designed for personal use, or charging stations designed for public use in high traffic areas, such as shopping malls and work offices. One scenario for charging plug-in hybrids is during nighttime, or off-peak, hours where electricity demand is typically much lower than during the middle of the day. For baseload electricity generators, such as nuclear plants that must maintain certain heat rates throughout the days in order to

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[1] The miles per energy equivalent gasoline gallon (mpeg) of a Plug-in Hybrid Electric Vehicle is estimated by using the all electric range of the vehicle and assuming 33.44 kWh per gallon of gasoline.

operate efficiently, unused electricity could potentially be utilized to charge these vehicles. Also, electricity is cheaper during off-peak hours, costing much less on a mile per equivalent gasoline gallon (The California Cars Initiative 2009) than a typical gallon of gasoline, creating a win-win scenario for both utilities and plug-in owners. However, in the absence of technology that controls electricity flow to the vehicle at the most economically feasible time, PHEV charging may occur at the discretion of the customer, potentially during peak hours where electricity demand is already high. Additional demand during these hours could lead to a significant strain on available resources of electricity, increasing the cost of electricity and impacting planned generation. Therefore, the relationship dynamics between electricity supply and additional demand from plug-in hybrids vehicles need be adequately addressed.

The first objective of this study was to understand how plug-in hybrid vehicle charging might impact the electricity grid under different scenarios for the state of California. The second objective of this project sought to estimate how variations in the charging time, vehicle design, and circuit sizes change these scenarios. A final objective was to determine how the additional demand might affect electricity supply prices.

Literature Review

Since 1999, the Hybrid Electric Vehicle Working Group (WG), assembled by the Electric Power Research Institute (EPRI), has spearheaded much of the technical work on defining and characterizing PHEV technology. From this working group, two technical reports serve as the basis for much of the research on PHEV grid impacts. <u>Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options</u> (EPRI 2001), published by the EPRI in 2001, provides technical specifications for mid-sized sedan plug-in hybrid vehicles. The follow-up report in 2002, <u>Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles</u> (EPRI 2002) provides specifications for other potential PHEV classes with the 20 and 60 miles all-electric range. The technical parameters of different plug-in vehicles from these two reports are summarized in Table 1 of this report. It is important to note the assumptions accompanying these parameters as this information provides a basis for this project. Furthermore, it should be noted that the technical parameters of PHEVs from the EPRI WG reports may not necessarily represent those of PHEVs that ultimately reach the market. Major vehicle manufactures are likely doing their own work on battery and vehicle design which may differ from the EPRI reports. However, since this information is not readily available to the public, the technical parameters from the EPRI reports are used to analyze grid impacts from plug-in hybrid vehicles.

Table 1. Charging Times for Different PHEV-20s Vehicle Classes under Various Circuit Voltage and Amperage Levels

Vehicle Type	Pack Size (kWh)	Rated Pack Size (kWh)[2]	Charging Circuit	Charging Size (kW)[3]	Charger Rate (kWh/hr)[4]	Time to Charge Empty Pack (hours)[5]
Compact Car	5.1	4.1	120 V 15 Amp	1.4	1.0	4.0
			120 V 20 Amp	1.9	1.3	3.0
			240 V 40 Amp	7.7	5.7	0.7
Mid-Sized Sedan	5.9	4.7	120 V 15 Amp	1.4	1.0	4.7
			120 V 20 Amp	1.9	1.3	3.5
			240 V 40 Amp	7.7	5.7	0.9
Mid-Sized SUV	7.9	6.3	120 V 15 Amp	1.4	1.0	6.3
			120 V 20 Amp	1.9	1.3	4.7
			240 V 40 Amp	7.7	5.7	1.1
Full-sized SUV	9.3	7.4	120 V 15 Amp	1.4	1.0	7.4
			120 V 20 Amp	1.9	1.3	5.6
			240 V 40 Amp	7.7	5.7	1.3

While studies have used the EPRI WG reports to analyze greenhouse gas (GHG) impacts and displacement of petroleum from PHEVs, there are four studies summarized here that assess the grid impacts of such vehicles. Each study takes a different approach in terms of charging scenarios and PHEV vehicle designs to analyze the impacts on specific regional electric systems.

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[2] Rated pack size assumed to be 80% nominal pack size.

[3] An 80% required safety factor for continuous charging is used.

[4] Charger efficiency assumed to be 82% for 120 V chargers and 87% for 240 V chargers.

[5] Battery efficiency assumed to be 85%.

However, each study finds that the existing electric system is capable of charging a large fleet of PHEVs without the need of additional generation, transmission, or distribution infrastructure.

A study conducted by the Pacific Northwest National Laboratory (PNL) developed two 24-hour load profiles for each of the 12 North American Electric Reliability Council regions, one representing a typical summer day and another representing a typical winter day. The two load profiles were used to estimate the unused generating capacity in each region, which in turn was used to calculate the number of PHEVs that could be charged. The study did not include peaking plants in the analysis, since they are designed for short-run times and would likely be uneconomic to have running for extended periods to charge PHEVs. The study also assumed a PHEV all-electric range of 33 miles, the estimated average daily commute, and a vehicle population of 217 million. The PNL study concluded that, nationwide, 73 percent of energy for the light-duty vehicles (LDV) fleet could be supported on the existing US electric power infrastructure. The power sector would be running at near full capacity most hours of the day under this scenario. Another scenario was analyzed in which PHEVs could only charge for 12 hours of the day, between 6 pm and 6 am. Under this scenario, 43 percent of the energy of the nation's LDC fleet could be supplied by the existing infrastructure.

The study identified regional differences regarding the electric power systems' ability to charge a fleet of plug-in hybrids. For example, the potential of the California and Southern Nevada region is estimated to only be 23 percent of the energy requirements for the LDV fleet. In contrast, the Northeast Power Coordination Council region, which contains New York and six New England States, is estimated to support 80 percent of the LDV fleet, which equates to about 20 million vehicles (Kintner-Meyer, Schneider and Pratt 2007).

The National Renewable Energy Laboratory (NREL) study by Denholm and Short in 2006 looked at different penetration scenarios to assess the demand that PHEVs would place on regional grids. The study analyzed six regional electric grids and each PHEV scenario assumed that the utility controlled the charging, therefore eliminating the need for additional generation beyond the existing infrastructure. The study further assumed that 40 percent of the daily vehicle miles come from electricity. Under these scenarios and assumptions, vehicle penetration rates as high as 50 percent of the regional light duty vehicle fleet could be met by the existing regional generation capacity. The addition of these PHEVs would increase the annual energy demand by 6 to 12 percent, depending on the region. The study also identified additional benefits of the PHEVs, such as increased loading of baseload power plants and reduced cycling of intermediate generation resources; both of which could lower operating costs (Denholm and Short 2006). Another NREL study took a more geographic focus by analyzing electricity demand impacts in Xcel Energy Colorado's power grid. Xcel Energy provides electricity to roughly 3.3 million customers in eight states and serves almost 40 percent of its customers (1.3 million) in Colorado. A PHEV-20 vehicle configuration was used with an assumed penetration rate of 30 percent (500,000 vehicles). Four recharging scenarios were analyzed in the study and are summarized below:

- **Uncontrolled Charging:** Vehicle owners recharge their vehicles at home in an uncontrolled manner.
- **Delayed Charging:** Vehicle owners recharge their vehicles at home, however the initial charge is delayed until 10 pm.
- **Off-peak Charging:** Vehicle owners recharge their vehicles at home; however the initial charge is controlled by the utility and occurs at the most optimal time (lowest cost) overnight.
- **Continuous Charging:** Vehicle owners recharge their vehicles whenever parked. This assumes that public charging stations are available.

(Parks, Denholm and Markel 2007 pp.7-10)

The uncontrolled and continuous charging added considerable load during both the summer and winter months. The additional demand represented 2.5 percent of the system peak demand in the uncontrolled scenario, and 4.6 percent for the continuous charging scenario. The 500,000 PHEVs assessed would add 3 percent to the total energy required annually. The authors also conclude that substantial penetrations of PHEVs could be accommodated by Xcel Colorado's electric system, if modest steps towards optimal charging were encouraged (Parks, Denholm and Markel 2007).

A study from the University of Vermont Transportation Center used similar scenarios to that of the Parks, Denholm, and Merkal 2007 study and analyzed the impacts of the three different penetrations of PHEVs on Vermont's electricity grid. The market penetrations rates used included 50,000, 100,000 and 200,000 PHEV-20s, representing 7.6 percent, 15 percent and 30 percent of the light duty fleet respectively. Hourly load data for the entire state of Vermont were acquired. The data represented demand at the transmission level, and thus the PHEV load was adjusted to account for line losses through the distribution network. For this study, 6 percent line losses were assumed. Peak summer and winter season days were identified and used to assess PHEV load impacts on days of high generation. The four different recharging scenarios represented four possible situations in terms of consumer and electric utility charging preferences in Vermont. The scenarios are described below:

- **Uncontrolled Evening Charging:** Vehicle owner recharges once home from work. Charging start times are evenly distributed between 6:00 pm, 7:00 pm and 8:00 pm. Each PHEV-20 recharges from 6 continuous hours
- **Uncontrolled Evening Charging/Twice per Day Charging:** Each PHEV is assumed to be plugged in to charge fully at the end of each commute leg, therefore being recharged two times per day. The evening recharge start times are the same as above. The daytime charging start times are evenly distributed between 8:00 am and 9:00 am.
- **Delayed Nighttime Charging:** The charging entire fleet of PHEV is delayed until 12:00 am.
- **Optimal Nighttime Charging:** Vehicles are charged in a pattern that smoothes demand as much as possible by charging during periods of lowest demand, and vehicles need not charge continuously during the late evening and early morning hours.

The results of the study estimated that the low penetration of PHEVs (50,000) would require 7% to the summer and winter peak capacity. Furthermore, the medium (100,000) and high penetration (200,000) would require over 14% and 28% to summer and winter peak capacities, respectively. The existing grid could support 100,000 PHEVs chraging during nighttime hours and charging during peak hours could cause a significant increase in peak generation (Letendre, Watts and Cross 2008).

The results of these four studies are summarized in Table 2 below.

Table 2. Summary Table of Literature Review Studies

Title	**Authors Affiliation**	**Summary of Results**
Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids	Pacific Northwest National Laboratory	• 73 %of energy for the light-duty vehicle (LDV) fleet could be supported by existing US electric power infrastructure. • Significant differences in regional analysis.
An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles	National Renewable Energy Laboratory	• 50% of the light vehicle fleets can be met by the existing generation capacity in each of the study areas. • Annual energy demand increases of 6% to 12%.
Costs and Emissions Associated with Plug-In Hybrid Electric Charging in the Xcel Energy Colorado Service Territory	National Renewable Energy Laboratory	• 4 different charging scenarios • Uncontrolled recharging adds 2.5% to peak demand • Continuous charging adds 4.6% to peak demand.
Plug-In Hybrid Electric Vehicles and the Vermont Grid: A Scoping Analysis	University of Vermont Transportation Center	• Existing Vermont electric grid could support 100,000 PHEVs recharging during off-peak (nighttime) hours. • Charging during peak hours could cause a significant increase in peak generation.

The approach taken in this study is similar to the last three studies where charging scenarios representing different behaviors were created and used with electricity data to analyze potential impacts. The details regarding this approach are specified in the "Methods" section of this document.

Regional Focus: California

The regional focus of this analysis is California. In 2007, California's electricity consumption per capita was one of the lowest in the nation (ranked 49th); however their consumption of motor gasoline was the highest according to the Energy Information Administration (EIA State Profiles). Since California is one of the states on the forefront of tackling energy efficiency and greenhouse gas emission issues through state-driven policy, it is a likely candidate for high adoption rates of PHEVs. One such policy, California's Zero Emissions Vehicle (ZEV) mandate, maintains a goal of ZEVs sold in the state. The mandate translates into a minimum of 60,000 PHEVs being sold in the years 2012-2014 (California Air Resources Board 2008).

The other basis for choosing California for this study is the State's high electricity prices. Retail electricity prices averaged 12.11 cents per kilowatt-hour (kWh) in 2008 compared to the U.S. average of 9.64 ¢/kWh (EIA Average Retail Electricity Price). Since the cost of generating electricity is reflected in retail prices and California's retail electricity prices are relatively high, supplying power onto its grid is more expensive for utilities in this region. Requiring more electricity to meet the additional demand of charging plug-in hybrid vehicles will likely yield higher energy prices if plug-in hybrid vehicles are allowed to freely charge.

California operates in a deregulated market and has an Independent Systems Operator (ISO) which controls 80% of the electricity and makes this data publically available (California Independent Systems Operator 2009). California's Independent Systems Operator, CAISO, matches electricity demand with supply through active monitoring of load demand, energy prices, and forecasting. Load data represents the aggregate amount of electricity on the transmission lines in megawatts (MW). CAISO also maintains average hourly energy prices which represent the average price a generating unit would be paid for a given hour for supplying electricity onto the grid, in dollars per megawatt-hour (MWh). The data from the ISO is to determine the supply of electricity in California during different months and to estimate potential changes in electricity prices from adding PHEVs onto the CAISO electricity grid.

Battery Design and Charging

The electric potential for plug-in hybrid electric vehicles depends on the rate at which electricity can be drawn and the amount of time needed to fully charge the battery. As described earlier in the literature review, the Electric Power Research Institute has conducted several studies on PHEV battery design and requirements. This section provides a background on battery design and vehicle charging taken from these EPRI studies.

The amount of energy it takes to charge a battery through an electrical outlet depends on the circuit size and the capacity of the battery. At 120V AC, a 15 amp circuit would result in approximately 1.4 kW load per hour, while a 20 amp circuit would result in a charging rate of 2.0 kW per hour (Duvall 2006). Current PHEV vehicle designs are expected to have battery capacities between 6 kWh and 18 kWh and can travel several miles at relatively low speeds using only electric drive. Most PHEV vehicle battery designs have range-based goals, in which a specific number of miles can be driven purely on battery power. Proposed battery specifications include 20, 40, and 60 miles of all-electric range. For example, a PHEV-20 is expected to travel 20 miles on the battery before the gasoline engine is turned on to assist in vehicle drive. These high-capacity batteries are said to be in charge depleting (CD) mode when draining to a specific State of Charge (SOC), after which the battery enters charge sustaining (CS) mode, where the internal combustion engine is used in conjunction with the battery to provide power. The duration the battery is in CD mode varies, but the goal for lithium-ion batteries is to have CS mode occur at no less than 20% SOC.

In charge sustaining mode the battery is still utilized but to a lesser degree, usually by providing short bursts of power to the drive train. Regenerative braking and energy from the combustion engine help charge the battery while in CS mode, until the next charge by way of the electricity grid. While most designs follow the example above with respect CD and CS modes, some PHEV designs utilize both the internal combustion engine and battery power throughout the duration of the trip to optimize battery life. Various forms of lithium-ion (Li-ion) and nickel-metal hydride (NiMH) batteries will likely provide the electric drive for plug-in hybrids. Although NiMH battery technology is currently used HEVs, lithium-ion batteries provide the most potential for PHEVs and therefore were assumed to be used in all PHEVs reaching the market. For the purposes of this study, it is assumed that all lithium-ion batteries are at a SOC of 20% before charging begins and therefore 80% of the rated battery capacity is needed to be recharged. Since PHEV-20s have an all-electric range of 20 miles and the average commute distance a vehicle owner in California in 2003 was 26.5 miles (BTS 2003), it is assumed that the battery is in CS mode and ready for a full recharge before connecting to the grid. Due to efficiency losses, not all of the energy drawn from an electrical outlet is converted into stored energy in the Li-ion battery. To account for this, battery and charging efficiencies are included per the EPRI 2001 report.

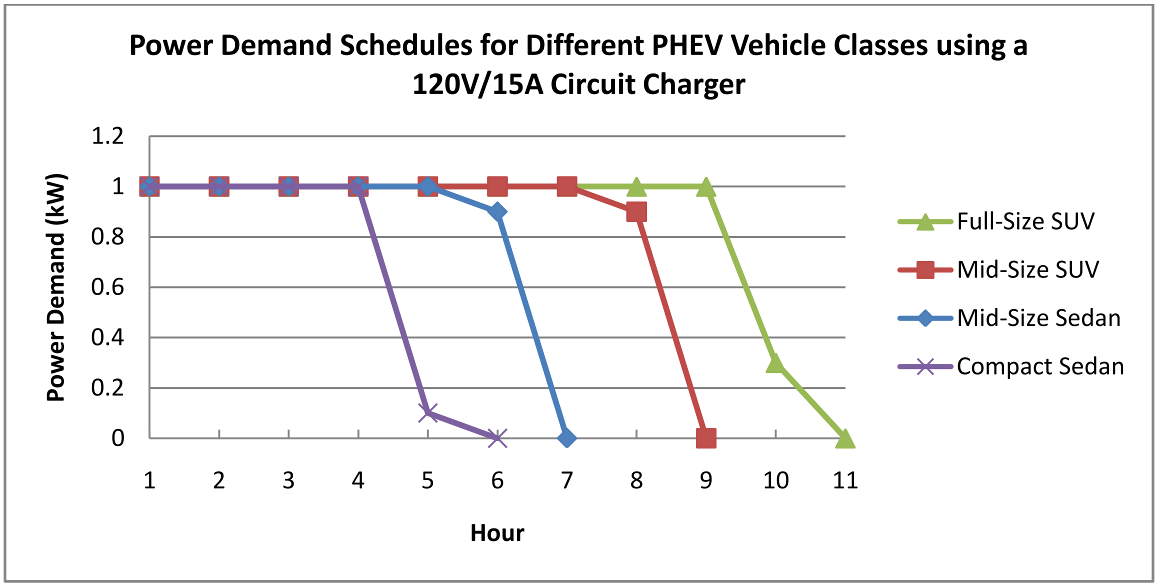
METHODS

The approach in this step involved four basics steps: The first included creating baseline charging scenarios for plug-in hybrid vehicles. The second step included acquiring hourly load data from CAISO and using it to construct 24-hour load profiles. These profiles were then combined with the baseline PHEV charging scenarios to estimate potential impacts. The third step included using average hourly energy price data from CAISO to construct supply price curves. These curves were used to estimate changes in price from adding PHEVs onto the electric grid. The final step involved applying variations to the baseline scenarios with respect to time of day for recharging, the PHEV vehicle type, and the charger size. The impacts on the electric grid and supply price were analyzed for the different variations. Details for the methodology of each step are provided in the subsections below.

Plug-in Hybrid Vehicle Charging Scenarios

As previously stated in this document, the Electric Power Research Institute has performed studies regarding the energy requirements for potential PHEV vehicle designs. This information, which is summarized in Table 1, provided a basis for the charging scenarios. Figure 1 shows the power demanded for different PHEV-20 vehicle classes using a standard household electrical circuit of 120 volts and 15 amperes.

Figure 1. Power Demand Schedules for Different PHEV Vehicle Classes using a 120V/15A Circuit Charger.



The power demand schedules in Figure 1 show a consistent draw of power for the first few hours and then a partial power demand during the last hour of charging. For example, the Compact Sedan PHEV-20 requires 4.1 kWh of energy to fully recharge the battery from a 20% SOC. 1.0 kW of power is needed over the first 4 hours, and 0.1 kW during the 5th hour. This compact sedan therefore would require 4.1 hours to recharge at a rate of 1.0 kW per hour. Since most household outlets already contain 120 volt/15 amp outlets, it was assumed that most PHEVs that reach the market will charge through these circuits. Mid-sized sedan plug-in hybrids with all-electric ranges of 20 miles were used as the standard in the baseline scenarios. Variations to the electric range were used later in this study. Using the information on charging rates and battery capacity, PHEV power demand curves were generated based around three types of charging scenarios.

The three scenarios representing how vehicle owners might charge their vehicles in the course of a day are summarized below:

- **Simultaneous Charging:** All PHEV owners charge their vehicles at a specified time. This scenario is an adequate upper limit since recharging all the vehicles at one time maximizes the power demanded by plug-in hybrids.
- **Continuous Charging:** A random percent of PHEVs are connected to the grid throughout the day, requiring a continuous demand of power. A random value between 1% and 50% were established for each hour, representing the percent of PHEVs that are connected to the grid. This scenario represents a lower limit for this study.
- **Normal Distribution Charging:** PHEV charging follows a normal distribution around a specific hour of the day (or mean hour). This represents a scenario between the two limits.

For the simultaneous and normal distribution charging scenarios, an evening charge time of 6 pm is used for the baseline. In the simultaneous charging scenario all PHEVs plug in at 6 pm. For the normal distribution recharge, most of the PHEVs begin charging between the hours of 4 pm and 8 pm (mean hour of 6 pm and standard deviation of 2 hours). Combining the charging scenarios above with the time of day charge and charging circuit size provided the baseline scenarios for this study. Each of these is scenarios are summarized in Table 3 below.

Table 3. Description of Baseline Scenarios

Scenario 1	All mid-sized sedan PHEV-20s begin charging at 6 pm using 120V/15A charging circuits.
Scenario 2	A random percent between 1% and 50% of mid-sized sedan PHEV-20s charge throughout the day, using 120V/15A charging circuits.
Scenario 3	Mid-sized sedan PHEV-20s charge as a normal distribution about mean hour 6 pm, with a standard deviation of 2 hours, using 120V/15A charging circuits.

Different market penetrations of plug-in hybrids were used with each of the charge scenarios above. The PHEVs market penetrations represented 5%, 10%, 15%, and 20% of the number of registered vehicles in California. The Bureau of Transportation Statistics determines the number of vehicles in California to be approximately 30 million in 2005 (BTS 2003). Since CAISO data represented only 80% of California’s electricity data, it was assumed that 80% of the registered vehicles would equal the total number of vehicles that could have access to the grid. Even though the total number of vehicles in California was reduced to almost 25 million, the estimated market penetrations of PHEVs, which ranged between 1.2 to almost 5 million vehicles, were still large enough to create significant changes in power demand. These baseline scenarios were then added to 24-hour load profiles described in the next section.

Electricity Load Data

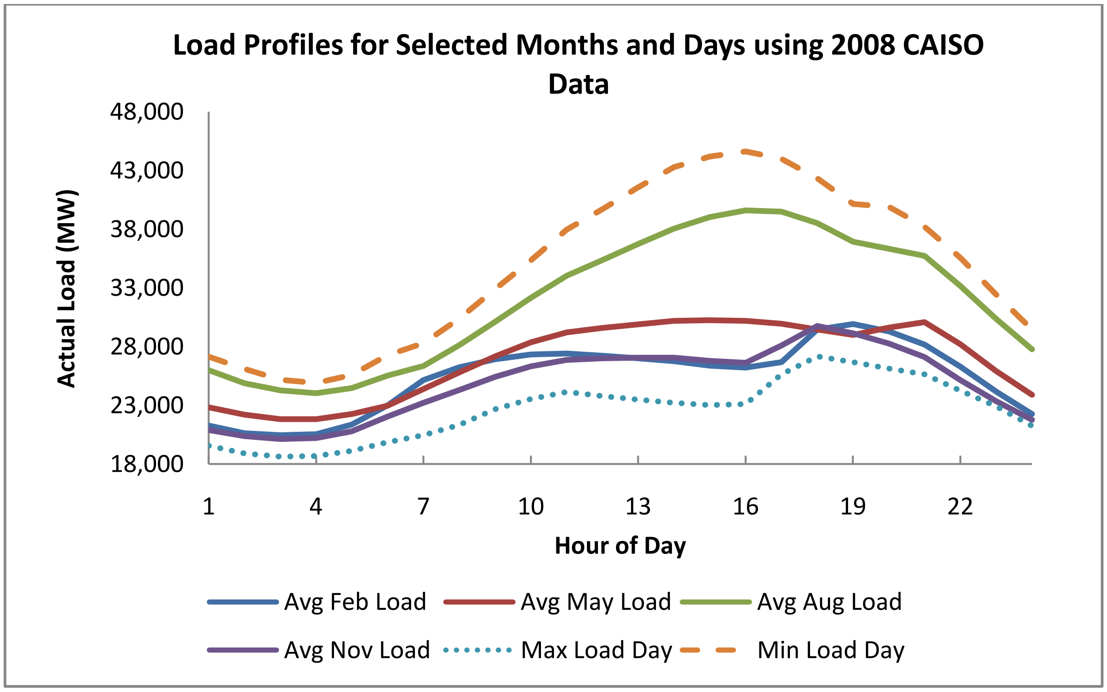
Data from CAISO's OASIS site provides data for day-ahead, hour-ahead, and actual load demand. The load data represents the aggregate amount of electricity (MW) on CAISO's transmission lines. The day-ahead data is used to forecast the demand for the next day in order to allow utilities within the region to prepare schedules to meet the potential demand. The hour-ahead load data is a similar forecast whose calculation is based on the previous hour's demand. These are used in short-term situations where an unpredicted change in demand may occur, requiring utilities to quickly ramp-up generation. The actual load data represents the electricity that ultimately reached the transmission lines. Since the actual load represents the demand of electricity within the CAISO region, it was used to construct 24-hour load profiles, reflecting the changes of electricity within a given day. Since seasonal variations can affect the use of electricity, average load profiles were created for each mid-season month starting in 2008. Additionally, 24-hour load profiles were created for a peak generation day, when electricity demand was particularly high, as well as for a day when electricity load was low. The load profiles constructed using 2008 actual load demand data from CAISO are summarized as the following:

- **Average February:** Represents the average winter electricity load. This is considered to be a "peak" season.
- **Average May:** Represents the average spring electricity load. This is also considered to be an "off-peak" season.
- **Average August:** Represent the average summer electricity load. This is considered to be a "peak" season.

- **Average November:** Represents the average fall electricity load. This is also considered to be an "off-peak" season.
- **Maximum Generation day:** Represents a day of high electricity generation. For this analysis, August 29, 2008 represented the peak load day.
- **Minimum Generation day**: Represents a day of low electricity generation. For this analysis, November 28, 2008 represented the minimum load day.

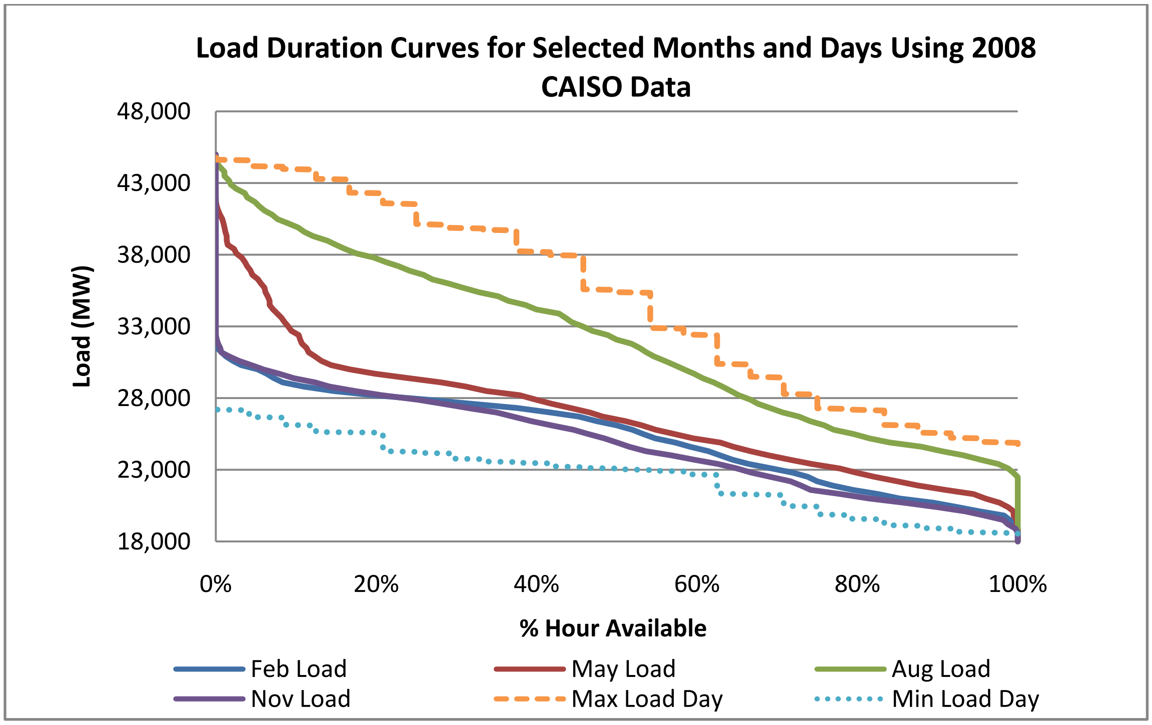
The electricity load data for each of the selected months were gathered in Excel and averaged over each hour. The MAX() and MIN() functions in Excel were used to determine days of high and low generation, respectively. Null values from CAISO data were removed from the average calculation. The load data representing the maximum generation day contained null values during some of the hours and was replaced with the next highest generation day. Figure 1 shows the 24-hour load profiles for each of the 4 months selected as well as the selected minimum and maximum generation days.

Table 4. Load Profiles for Selected Months and Days using 2008 CAISO Data



CAISO hourly load data for the above months and days were used in creating load duration curves. Load Duration Curves (LDCs) reorder demand by increasing power levels, showing the percentage that demand equals or exceeds a given load level. In other words, the duration curves demonstrate how much time (or percentage of time) a given level of capacity is needed. They are created by determining the number of hours in which a specific load level is maintained within month or day. In Excel, this is accomplished by establishing bins for the different load values and counting the total number of hours in which the given load range occurs. These hours are then converted into a percent of the hours for the entire time frame, in this case, for the entire month. Bin ranges even spaced between 18,000 MW and 48,000 MW were used, as these are the minimum and maximum load levels as shown in Figure 1 above. The converted load duration curves for the four selected months are shown in Figure 2 below.

Figure 2. Load Duration Curves for Selected Months and Days Using 2008 CAISO Data



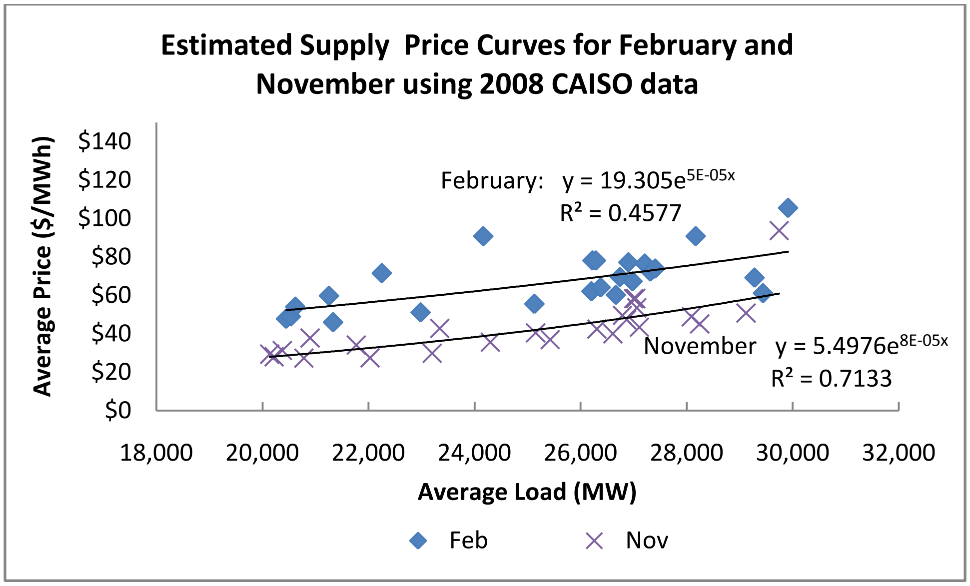
For the four selected months, all the hourly load values were used to create the load duration curve. The maximum and minimum load days each contained only 24 load values, resulting in a "stepped" load duration curve. The LDCs provides an indication of the baseload power and peak power ranges. The electricity loads used for short durations (0%- 20%) typically comes from peak power or "peaker" plants. This is particularly the case in the summer months when electricity is high. Electricity load levels which are constantly used (between 75% and 100% hours available), are generally considered baseload power. These levels are maintained throughout the day and come from plants that have high start-up and shutdown costs, such as nuclear plants. Baseload levels, from Figure 2 above, are between 18,000 MW, or 18 gigawatts (GW), and 26 GW, depending on the season. Peak power generation occurs around 30 GW during the winter, fall and spring months, but over 38 GW during the summer months. The area under each of the average load duration curves can be interpreted as the total average electricity generation (in MWh) for that month. While load profiles demonstrate the changes in electricity throughout the day, load duration curves provide insight into the utilization of different load levels. The load data from the ISO represent the electricity on the major transmission lines and the additional demand from PHEVs comes from the end-use of electricity, efficiency losses from transmission and distribution needed to be accounted for. The electricity losses due to transmission and distribution were assumed to be 6 percent, the same as in the University of Vermont Transportation Center study discussed in the literature review section above. Both load profile and load duration charts were used with the plug-in hybrid vehicle baseline scenarios to estimate impacts on CAISO's electricity grid. To determine the impacts on CAISO's electricity supply prices, curves were estimated using average hourly energy prices as described in the next section.

Electricity Supply Price Curve Estimations

Using real-time average hourly energy price data from CAISO for 2008 and existing actual load data used in the load profiles and LDCs, supply price curves were estimated. These electricity price curves represented the changes in electricity generation prices in dollars per megawatt across different power demand levels. CAISO schedules electricity onto the grid but does not sell electricity to end-users. Therefore, the pricing data represents the generation price and excludes the additional costs associated with the transmission and distribution of electricity.

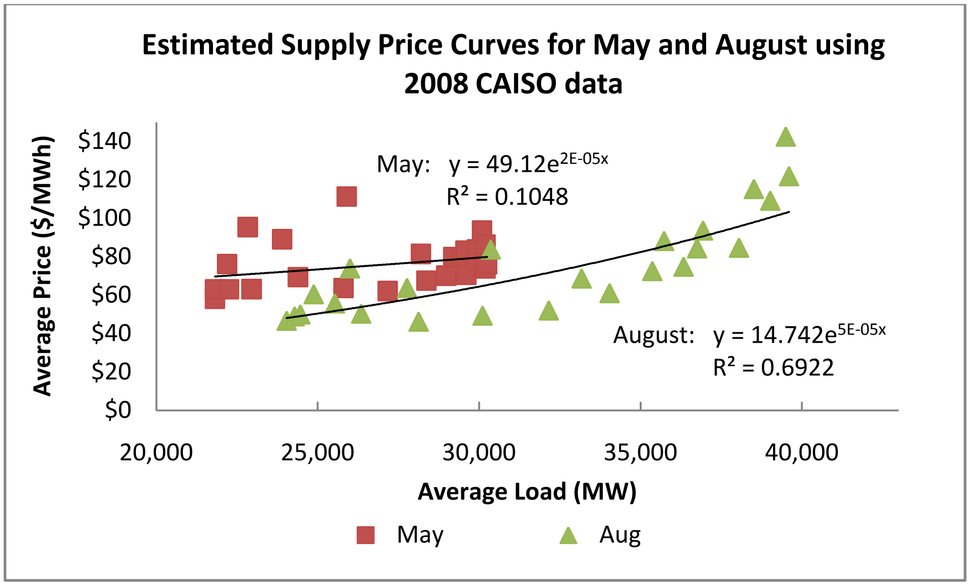
Supply curves were constructed for February, May, August, and November using the identical average hourly load data to establish average load profiles. The energy prices were averaged over each hour for the selected months, and then plotted versus the average load value. The trend line function in Excel was used to fit an equation to the supply price curves, and establish an R-squared value. Due to some volatile price data, supply curves were estimated using exponential trend lines. Other forms of trend lines were tested; however fitted exponential curves resulted in the least amount of variance. Figure 3 below shows the plotted data points and fitted exponential curve for the months of February and May.

Figure 3. Estimated Supply Price Curves for February and November Using 2008 CAISO data.



Similarly, Figure 4 below shows the data points and estimated supply price curves for the months of August and May. Note the difference in the x-axis values between the two graphs.

Figure 4. Estimated Supply Price Curves for May and August Using 2008 CAISO data.



Supply price curves were estimated for each of the four baseline months using the process described above. The resulting equations were used in conjunction with electricity load data and the baseline scenarios to estimate how electricity prices might change from the additional load demand created by plug-in hybrid vehicles.

Variations to Baseline Scenarios

Once the baseline PHEV scenarios were analyzed with the electricity load data and impacts on California's electricity grid and supply prices assessed, variations were performed on the scenarios. The baseline scenario incorporated different market penetrations of PHEV-20 mid-sized sedan recharging in the evening, using a 120V/15A circuit. While these parameters formed the basic analysis, it is also important to estimate how modifications to these scenarios could change the result. Adjustments were made to the baseline scenarios with respect to:

- **Time of Day Recharging:** Recharging in the morning (9 am) and nighttime (10 pm) hours, as opposed to the evening (6 pm).

- **Electric-Range of the Vehicle/Battery Capacity:** Altering type of plug-in hybrid vehicle from a PHEV-20 (6 kWh battery) to a PHEV-40 (12 kWh) and PHEV-60 (16 kWh) under the same vehicle class (mid-sized sedan)
- **Charging Circuit Size:** Modifying the circuit charger size from a 120V/15A to 240V/40A circuit.

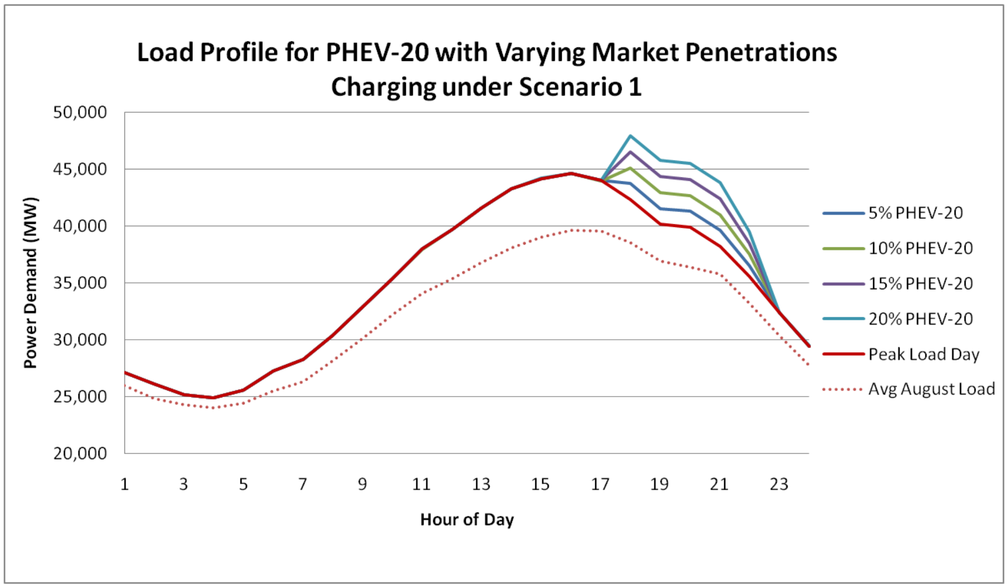
RESULTS

For electricity providers and public utility commissions, understanding the impact of plug-in hybrid vehicles on electricity grids is essential for proper planning. While the technology is not yet commercially available, production of such vehicles has commenced. This section of the report presents the results of such technology on California's CAISO electricity grid. The results in this section only include the impacts of charging PHEVs during the peak or maximum generation day in 2008, since this is when electricity generation is high.

Baseline Charging Scenarios

Using knowledge from previous EPRI studies on lithium-ion battery technology and power demand, baseline scenarios were created and applied to electricity load demand from the CAISO region. The results from the different baseline scenarios are presented with peak load day identified earlier. As a reference, the average load in August 2008 is also shown. Figure 5 provides a visual representation of how different market penetrations of PHEV-20s recharging at typical household electrical outlets might affect electricity load in California.

Figure 5. Load Profile for PHEV-20 with Varying Market Penetrations Charging under Scenario 1.



As shown by the peak load day and average August load curves, electricity load is the lowest (below 30 GW) between midnight and 8 am. Electricity generation begins to ramp up starting at 4 am up until 4 pm where it peaks. Electricity load decreases at a faster rate than its initial ramp-up and between the hours of 7 pm and 9 pm, load levels are sustained for a brief period. Peak hours roughly occur between 2 pm and 6 pm. The scenario above represents vehicle owners that all recharge at the same time in the evening (6pm) resulting in a sudden spike in demand. The small penetration of PHEV-20s (5% of the light duty fleet representing 1.2 million PHEVs) demand over 1,300 MW of additional power. In the extreme case, a 20% market penetration of plug-in hybrids (almost 5 million vehicles) requires over 5,000 MW power. In all penetration scenarios, the additional demand required by PHEV-20s is sustained for almost five hours, in order to fully recharge the vehicle. This demand information is compared to EIA's data on California's capacity and net generation as shown in Table 5.

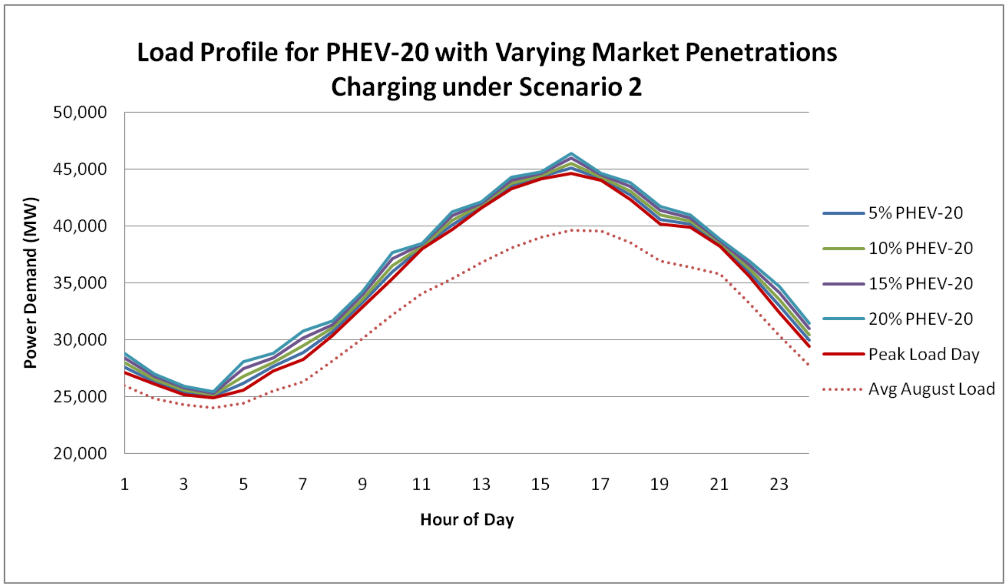
Table 5. Demand and Energy Assessment for Four PHEV-20 Penetration Scenarios

	Market Penetrations of PHEV-20			
	5%	**10%**	**15%**	**20%**
Demand (MW)	1,315	2,630	3,945	5,259
% 2007 Nameplate Capacity	1.92%	3.84%	5.76%	7.68%
% 2007 Summer Peak Capacity	2.06%	4.12%	6.18%	8.24%
Daily MWh (1 charge per day)	6,183	12,367	18,550	24,734
Annual MWh (1 charge 365 days)	2,256,957	4,513,914	6,770,871	9,027,829
% 2007 MWh	1.07%	2.14%	3.21%	4.28%

The nameplate capacity is the amount of power California's electricity generating units could produce, if all were running at maximum capacity. The summer peak capacity is hourly output which generating equipment is expected to supply to system load power as demonstrated by tests at the time of summer peak demand. In 2008, the nameplate and summer peak capacity for California are 68,500 and 63,800 respectively (EIA State Profiles). The additional demand from PHEV-20s requires between 1.92% and 7.68% of the nameplate capacity and between 2.06% and 8.24% of summer peak capacity in California. Assuming the PHEV-20s charge everyday, this translates into between 1% and over 4% of the annual net generation for California in 2008. While the energy requirements for the PHEV-20s is consistent throughout the three baseline scenarios, the simultaneous charging scenario requires the largest amount of power demand. The continuous and normal distribution charging scenarios require less additional power since charging is more distributed.

Figure 6 represents a continuous charging scenario, where up to 50% of PHEV owners could begin to recharge their vehicles at any one particular time. While its probable that PHEV owners will follow a more structured recharge pattern, this scenario helps demonstrate how free access to recharging can spread the demand throughout the day, with slight fluctuations.

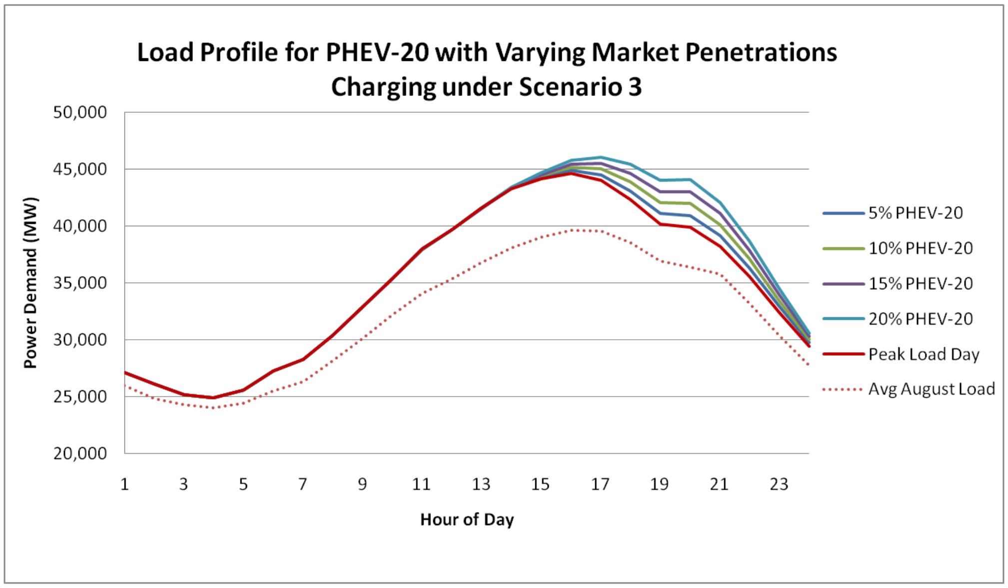
Figure 6. Load Profile for PHEV-20 with Varying Market Penetrations Charging under Scenario 2.



The amount of PHEV-20s that are allowed to charge at any given time is constrained to 50% in the above figure. Therefore, the additional power demand from plug-in hybrid vehicles in this scenario is at most half of those shown in Table 5. Open access to the power grid for PHEV owners in this scenario distributes the additional power demand throughout the day, creating a completely new load profile curve.

A more realistic scenario is represented in Figure 7, where recharging occurs as a normal distribution around a specific time period. In this case, it is assumed that most PHEV-20 owners will begin recharging once home from work, around 6 pm.

Figure 7. Electricity Demand for Different PHEV-20 Market Penetrations under Scenario 3.



Under Scenario 3, the initial wave of PHEV owners begin charging at 3 pm, and at 6 pm, almost 20% of the owners begin charging. Since the PHEV-20s that connected to the grid between 3 and 5 pm still have not finished fully charging, this lengthens the amount of load necessary to meet demand. The maximum additional electricity demand in this scenario occurs around 8 pm and the last set of PHEV-owners charge at 10 pm, requiring additional power into the late nighttime hours.

The amount of power demanded under the normal distribution scenario varies within each penetration grouping. The 5% market penetration group requires 35 MW of additional electric power at 3 pm, when few vehicle owners recharge. At 8 pm, when most of the PHEV-20s are connected to the grid, almost 1,000 MW of additional power is needed to meet demand. After 8 pm, some vehicles that recharged earlier have finished charging, requiring less power into the nighttime hours. For the high market penetration group of 20%, a maximum of almost 3,000 MW are needed during the hour when most vehicles are connected. A summary of the baseline scenarios and additional power demand is displayed in Table 6.

Table 6. Summary of PHEV-20 Scenarios and Additional Power Demand

Vehicle Type	Market Penetrations	Charge Scenarios under 120V/15A circuit	Additional Power Demand at any hour (MW)[6]
PHEV-20 Mid-Sized Sedan	5%	Simultaneous (6pm)	1,315
		Continuous	13 - 658
		Normal Distribution (mean 6pm)	35 – 996
	10%	Simultaneous (6pm)	2,630
		Continuous	26 - 1,315
		Normal Distribution (mean 6pm)	71 – 1,992
	15%	Simultaneous (6pm)	3,945
		Continuous	39 - 1,973
		Normal Distribution (mean 6pm)	107 – 2,988
	20%	Simultaneous (6pm)	5,259
		Continuous	53 - 2,629
		Normal Distribution (mean 6pm)	142 – 3,984

The additional power demand at any given hour for the simultaneous scenario represents the load that is sustained for the duration of the charge, in this case, over four hours. Whereas the simultaneous demand occurs over a short period, the continuous charging maintains a consistent load on the grid throughout the day with much smaller power required. The range for the normal distribution scenarios display the lowest power demand when the fewest PHEV-20s are charging, and the largest demand which occurs at 8 pm, when most vehicles are connected to the grid.

The load profiles curves for the simultaneous charging scenario are represented as load duration curves as shown in Figures 8 and 9 below. Each graph shows the difference between the LDC for the peak load day, and the given market penetration of PHEV-20.

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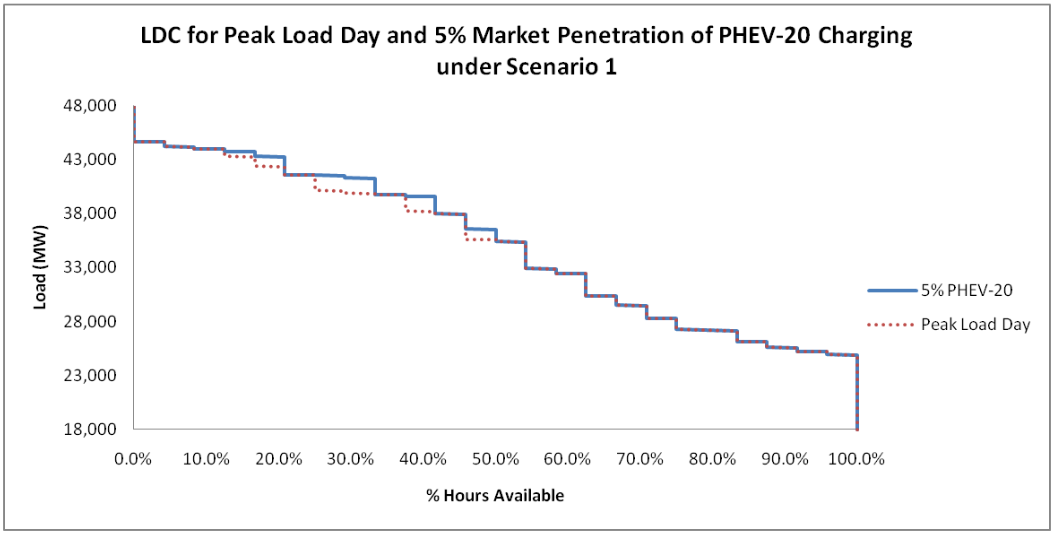
[6] Power demand does not include losses in transmission and distribution of electricity (6% in this case).

Figure 8. Load Duration Curves for 5% and 10% Market Penetrations of PHEV-20s Charging Under Scenario 1.



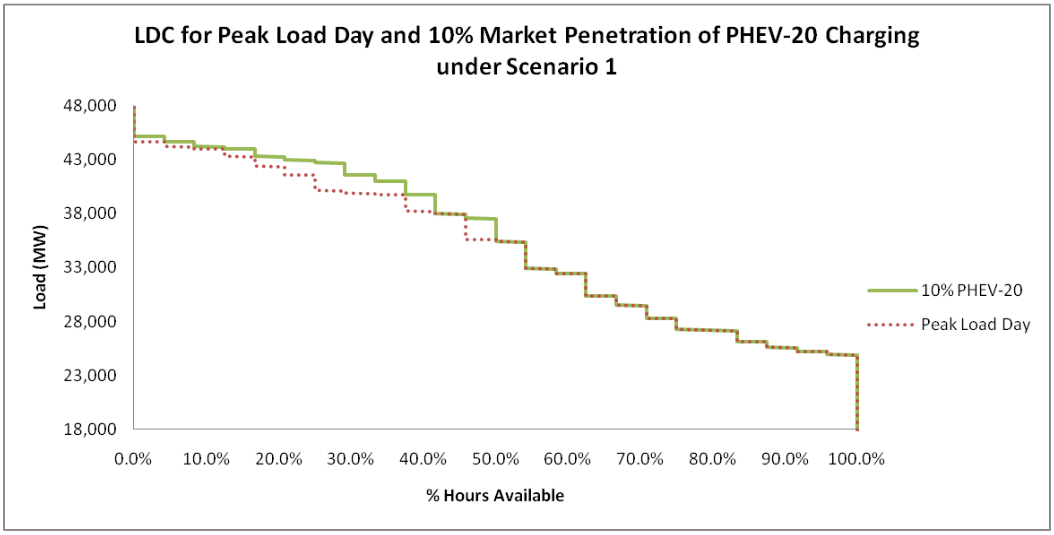
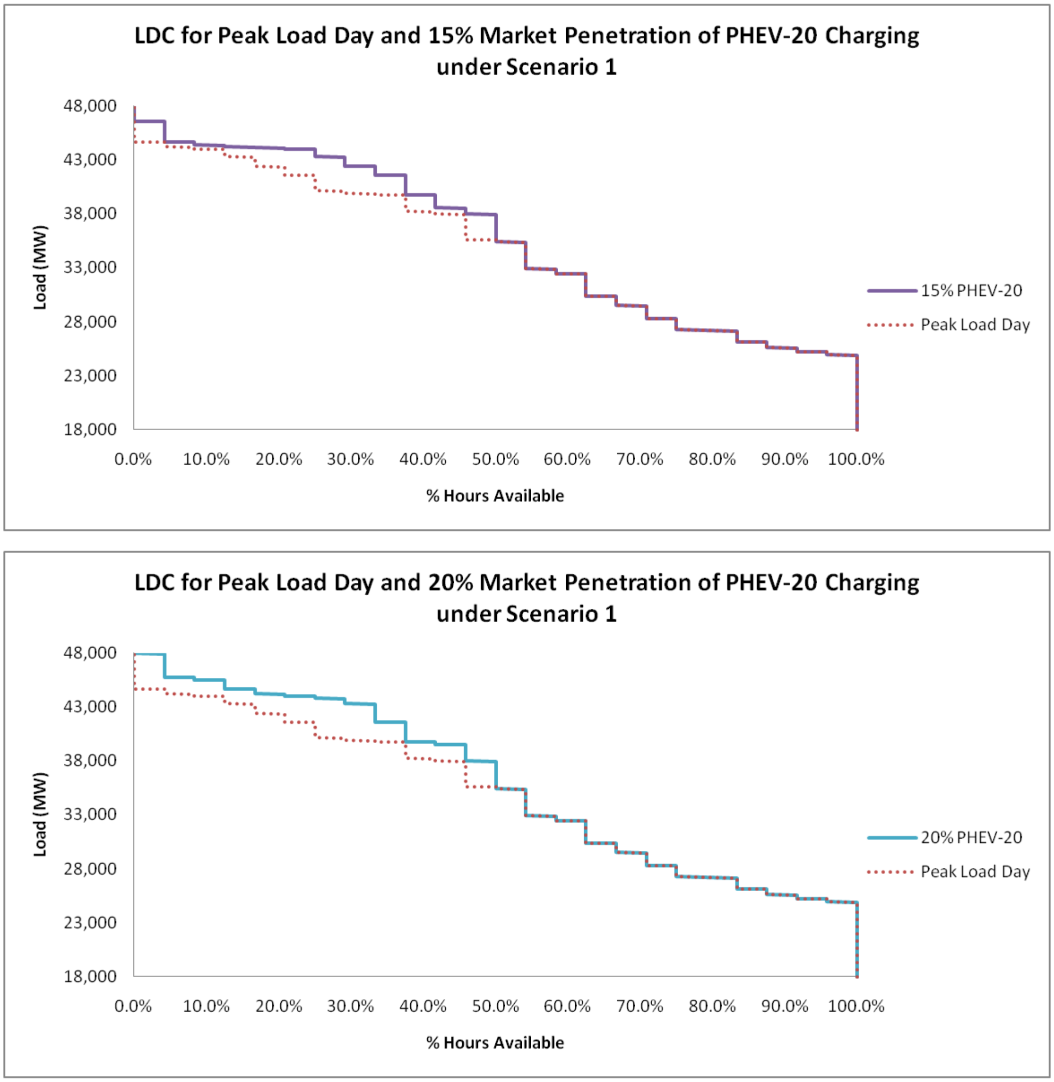


Figure 9. Load Duration Curves for 15% and 20% Market Penetrations of PHEV-20s Charging Under Scenario 1.



This alternative view shows no change in the LDC curves between 60% and 100% availability of resources. When resources become low, around 40% of hours available in a day, there is visible separation which is more evident in the higher penetrations. The largest separation occurs around 30% which is close to peak generation, after which, the curve begins to converge back onto the original LDC. The separation suggests that electricity generating units will need to remain online for a longer duration, and that additional generating units may be necessary to meet demand.

The 20% market penetration LDCs provides the most insight into the differences from the original curve, therefore only these are highlighted in the remainder of this section of the report. The LDCs for 20% market penetration under the continuous and normal distribution charging scenarios are presented in Figure 10 and 11 below.

Figure 10. Load Duration Curves for 20% Market Penetrations of PHEV-20s Charging Under Scenario 2.

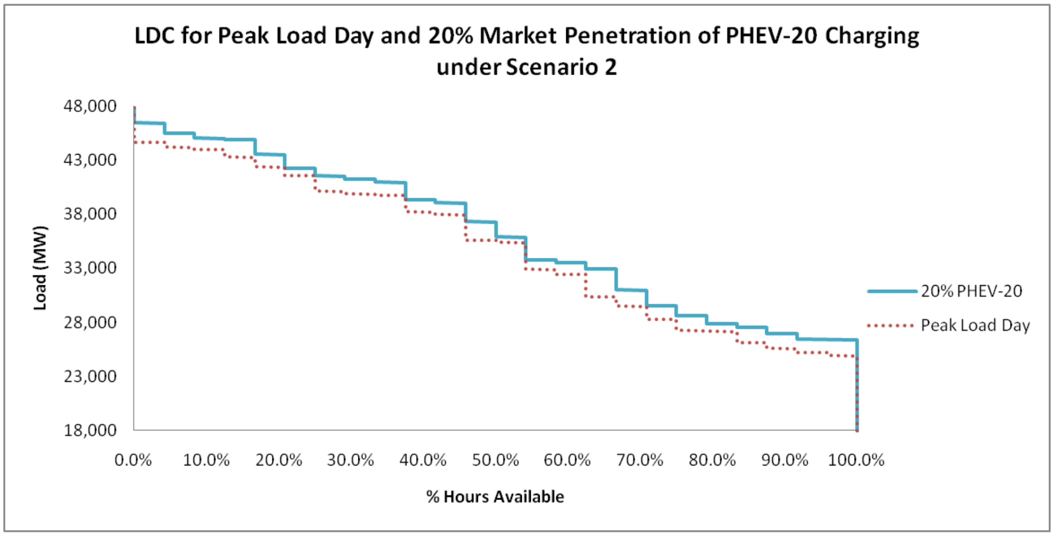
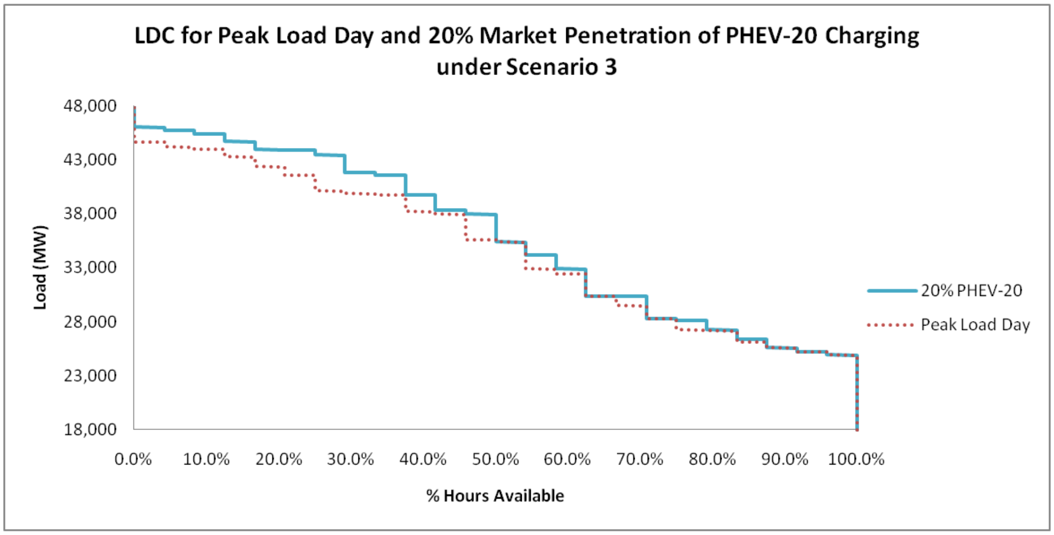


Figure 11. Load Duration Curves for 20% Market Penetrations of PHEV-20s Charging Under Scenario 3.



As expected, the LDC for the continuous charging scenario creates an upward shift from the original. In the normal distribution charge, separate begins earlier than in the simultaneous charging scenario; around 70% available hours as opposed to 40% in Scenario 1. This implies that generating resources that are used outside of peaking and baseload, also called intermediate or shoulder units, need to be online longer with the possibility of adding other units. While there is a significant difference between the original LDC and the PHEV scenario around 30% hours available range in Scenario 1, there is less of an impact by PHEVs in Scenario 3. Charging scenarios that follow a normal distribution are preferred over a simultaneous recharging since the constraints on resources are lessened.

Electricity Supply Prices

In the short term, as demand for a fixed resource increases, electricity in this case, the supply price will increase to reflect the limited amount of supply. Over time, a higher supply price will result in additional resources added to meet demand, lowering in supply price. If the current electricity mix for CAISO is taken as constant, then the addition of PHEVs into the market will likely create an increase in the supply price.

Monthly supply curves were fitted for February, May, August, and November using 2008 CAISO hourly energy prices. Average monthly load profiles were used with their respective monthly supply price curve to determine energy price changes. The tables below show the greatest difference in price when incorporating the PHEV scenarios.

Table 7. Estimated Maximum Price Increase ($/MWh) in Summer.

	Summer Estimated Max Price Increase ($/MWh)			
	5% PHEV-20	10% PHEV-20	15% PHEV-20	20% PHEV-20
Simultaneous – Evening with 120V/15A circuit	7.3	15.1	23.5	32.5
Continuous – with 120V/15A	3.2	6.5	9.8	13.3
Normal Distribution - Evening with 120V/15A circuit	4.6	9.5	14.6	20.0

Table 8. Estimated Maximum Price Increase ($/MWh) in Winter.

	Winter Estimated Max Price Increase ($/MWh)			
	5% PHEV-20	10% PHEV-20	15% PHEV-20	20% PHEV-20
Simultaneous – Evening with 120V/15A circuit	6.1	12.6	19.6	27.0
Continuous – with 120V/15A	2.8	5.7	8.7	11.7
Normal Distribution - Evening with 120V/15A circuit	4.3	8.7	13.5	18.4

Table 9. Estimated Maximum Price Increase ($/MWh) in Spring

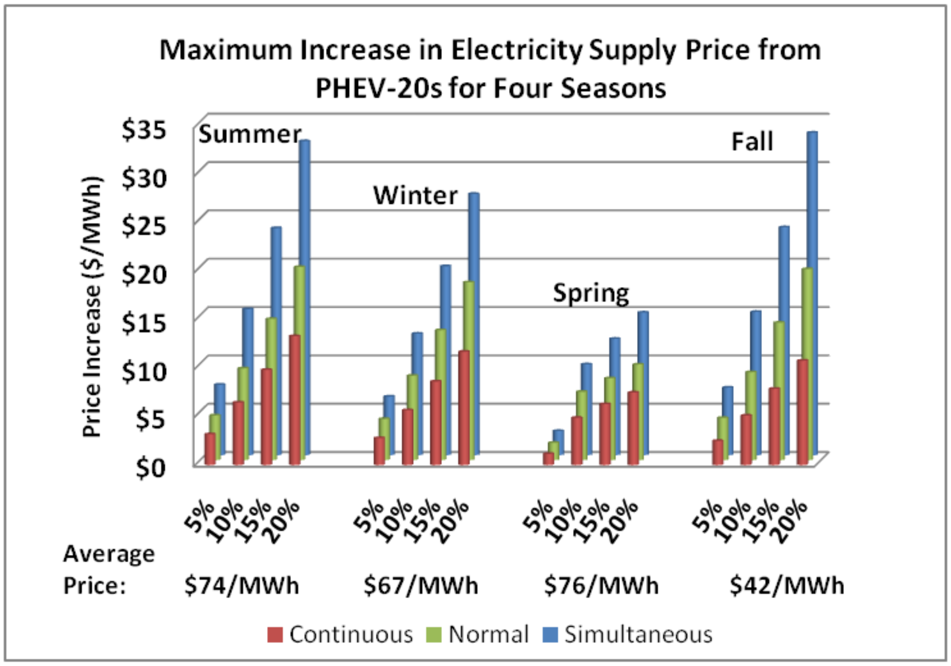
	Spring Estimated Max Price Increase ($/MWh)			
	5% PHEV-20	10% PHEV-20	15% PHEV-20	20% PHEV-20
Simultaneous – Evening with 120V/15A circuit	2.5	9.4	12.0	14.8
Continuous – with 120V/15A	1.2	4.9	6.3	7.5
Normal Distribution - Evening with 120V/15A circuit	1.8	7.1	8.5	9.9

Table 10. Table 7. Estimated Maximum Price Increase ($/MWh) in Fall

	Fall Estimated Max Price Increase ($/MWh)			
	5% PHEV-20	10% PHEV-20	15% PHEV-20	20% PHEV-20
Simultaneous – Evening with 120V/15A circuit	7.0	14.8	23.6	33.4
Continuous – with 120V/15A	2.5	5.1	7.9	10.8
Normal Distribution - Evening with 120V/15A circuit	4.4	9.1	14.2	19.8

As shown above, the simultaneous charging scenario increases the price between $7.3/MWh and $32.5/MWh in the summer months as market penetrations increase. During the same season, the continuous charging scenario increase the energy price from $3.2/MWh in the 5% PHEV scenario and $13.3/MWh in the 20% PHEV scenario. The increases in price during normal distribution charging scenario range from $4.6/MWh to $20.0/MWh depending on the PHEV penetration rate. The figure below displays the maximum increases in energy prices for the three baseline scenarios, across the four seasons. Additionally, the average seasonal energy prices are provided on the chart.

Figure 12. Maximum Increase in Electricity Price from Varying Market Penetrations of PHEV-20s Under Various Scenarios.



In each case, the simultaneous charging scenario creates the greatest increase in price relatively to no PHEVs. The lowest increase in price occurs under the continuous charging scenario, and the normal distribution scenario's price increases are between the two extremes. The changes in price are consistent the load demand; the greater the demand on the electric grid, the higher the increase in supply price. Increasing demand by adding the PHEV penetration rates onto CAISO's electricity grid creates the largest increase in price during the summer and fall months, which range between $4/MWh to $20/MWh under the normal distribution charging scenario. Price increases range from $3/MWh to $18/MWh under the same scenario during the winter. Spring exhibits the lowest degree of increases in energy price, with values ranging between $2/MWh to $10/MWh for the various penetration rates under the Scenario 3.

Although the changes in energy prices during the fall are comparable to the increases in the summer, the average energy prices for the fall are much lower than the other seasons. In the spring however, the average energy prices are high but the increases in prices from PHEVs results in a lower overall price compared to the other seasons. The summer and winter seasons are the seasons that have overall highest energy prices when adding the increases in prices from PHEVs with the average price.

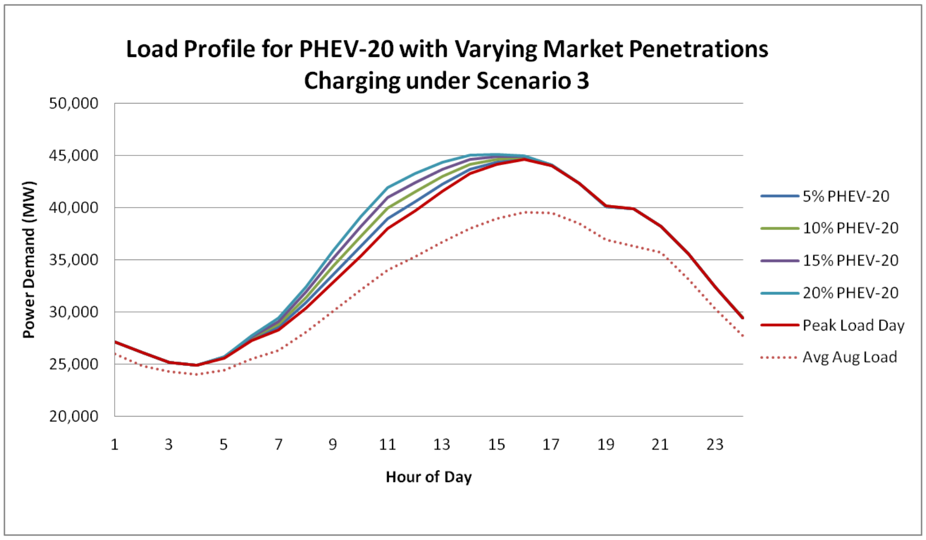
Variations to Baseline Scenarios

Power demand and energy price results from adjusting the baseline scenario with respect to time, battery capacity, and charging circuit are presented in this section. In each of these variations, the normal distribution charging scenarios are applied to the peak load day.

Time of Day Charging Variations

The first variation from the baseline scenario is altering the time of day that charging of plug-in hybrid vehicles begin. Shifting the charging to the morning creates the potential for additional load during peak hours. Figure 13 below shows the load profile for the peak day, applying a morning (mean hour of 9 am) charge to the load curve.

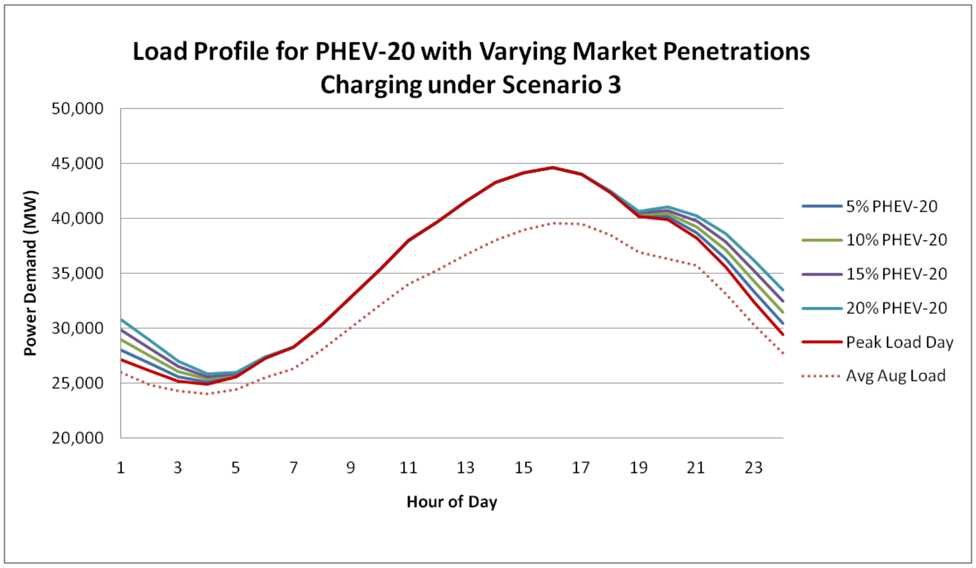
Figure 13. Load Profile for PHEV-20 with Varying Market Penetrations Charging under a Morning (9 am) Normal Distribution Scenario.



The power demand requirements are the same as the baseline PHEV-20 normal distribution charging scenario, however these 35 to 3,900 MW are necessary during hours of the day when overall generation is ramping up. The majority of the electricity demand occurs during 11 am and 12 pm, and the peak hours of 2 pm and 4 pm, there is minimal additional demand.

As the morning charging scenario demonstrates additional that could occur when PHEV owners plug-in their vehicles after the morning commute leg, the following scenario shows how a nighttime charging scenario might impact California's grid, as shown in Figure 14.

Figure 14. Load Profile for PHEV-20 with Varying Market Penetrations Charging under a Nighttime (10 pm) Normal Distribution Scenario.



Charging the PHEV-20s around a mean hour of 10 pm creates additional demand during the hours when load is diminishing, and reaches into hours when load is the lowest (3 and 4 am). Although the additional demand by PHEVs will ultimately require more electricity generation, charging during the nighttime hours, as shown above, helps to flatten the load curve. Utilizing electricity generation resources into hours when load is low and some electricity is unused, improves efficiency. Although more electricity supply is necessary to meet the demand from

PHEVs in all cases, charging at night reduces the need for generating resources to be turned off and back on again.

Electric Capacity Variations

The outcome from adjusting the electric capacity of the mid-sized sedan plug-in hybrid vehicles are presented and discussed in this section. A higher battery capacity of the same vehicle class size (mid-sized sedan) increases the all-electric range of the vehicle. Two sets of load profiles are demonstrated, each applying the PHEV scenario to the peak load generation day. The results from a mid-sized-sedan PHEV-40 with a battery capacity of 12 kWh and a mid-sized sedan PHEV-60 scenario with a capacity of 18 kWh are presented below. These variations are applied to the normal distribution scenario and to a morning, evening, and nighttime charge time. The first set of battery electric capacity variations are shown in Figure 15 through 17 below.

Figure 15. Load Profile for PHEV-40 with Varying Market Penetrations Charging under an Evening (6 pm) Normal Distribution Scenario.

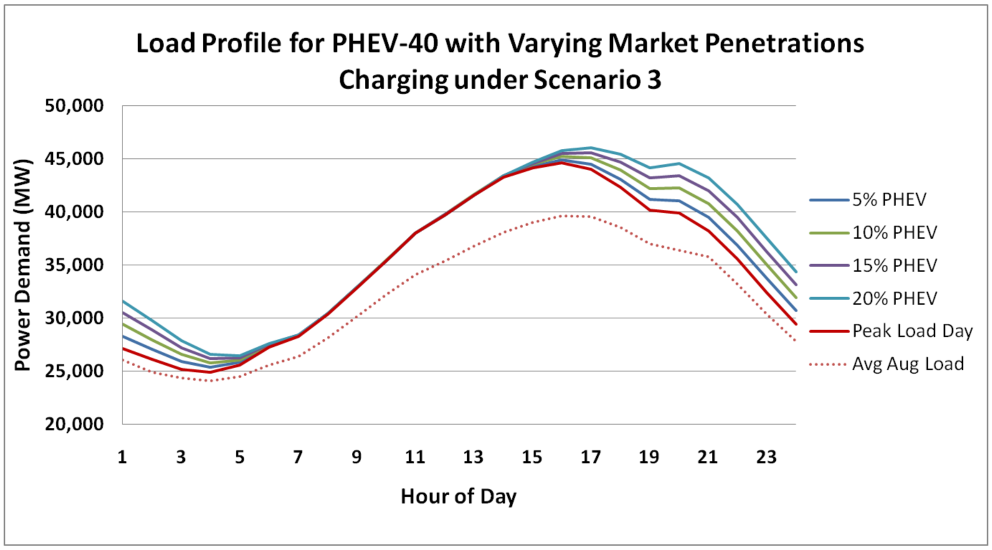


Figure 16. Load Profile for PHEV-40 with Varying Market Penetrations Charging under a Morning (9 am) Normal Distribution Scenario.

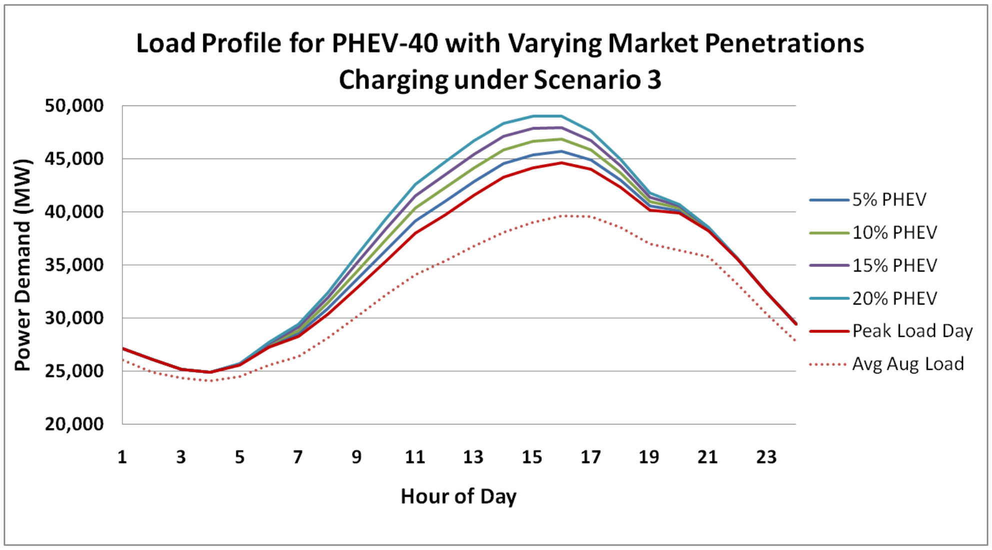
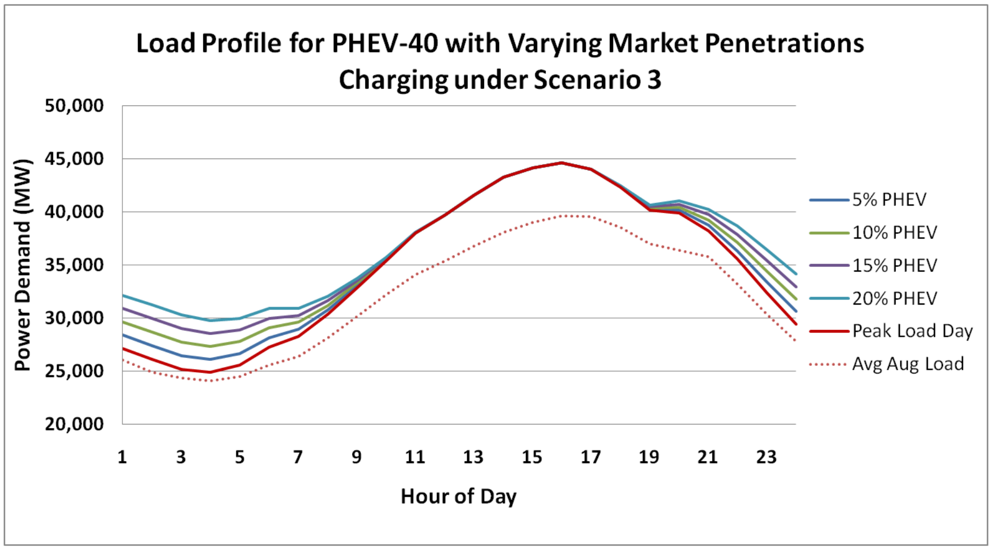


Figure 17. Load Profile for PHEV-40 with Varying Market Penetrations Charging under a Nighttime (10 pm) Normal Distribution Scenario.



From the baseline PHEV-20 scenario, PHEV-40s elongate the additional power demand, requiring more energy from the electricity grid. Since the electric capacity of PHEV-40 is double that of the PHEV-20, it requires twice the time to recharge the battery under a 120V/15A circuit.

As a result, additional load is created into the nighttime and early morning hours when PHEVs recharge in the evening. Under the PHEV-20 morning charging scenario where the additional power demand diminished close to peak hours, the PHEVs now require power during peak hours. As a result, additional resources are needed to meet daily demand. Nighttime charging further fills in the hours of low load demand, and requires the additional power demand be met until 9 am. The table below provides an energy assessment, assuming all the PHEVs that recharge under CAISO's electricity grid come from mid-sized sedan PHEV-40s.

Table 11. Demand and Energy Assessment for Four PHEV-60 Penetration Scenarios

	Market Penetrations of PHEV-40			
	5%	**10%**	**15%**	**20%**
Demand (MW)	1,315	2,630	3,945	5,259
% 2007 Nameplate Capacity	1.92%	3.84%	5.76%	7.68%
% 2007 Summer Peak Capacity	2.06%	4.12%	6.18%	8.24%
Daily MWh (1 charge per day)	12,576	25,153	37,729	50,306
Annual MWh (1 charge 365 days)	4,590,421	9,180,843	13,771,264	18,361,685
% 2007 MWh	2.18%	4.35%	6.53%	8.71%

As shown in the table above, increase the battery capacity from 6 kWh to 12 kWh results in a doubling of energy requirements. The low penetration (5% PHEV-40) and high penetration rates would add 2.18% and 8.71% to California's 2007 net generation.

The results from the same scenario analysis using PHEV-60s are shown in Figure 18 through 20 below.

Figure 18. Load Profile for PHEV-60 with Varying Market Penetrations Charging under an Evening (6 pm) Normal Distribution Scenario.

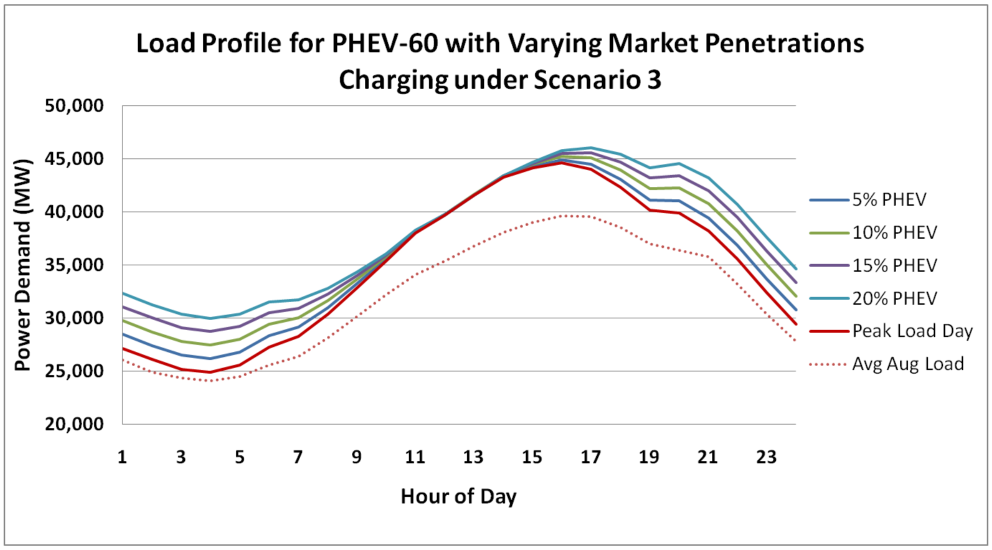


Figure 19. Load Profile for PHEV-60 with Varying Market Penetrations Charging under a Morning (9 am) Normal Distribution.

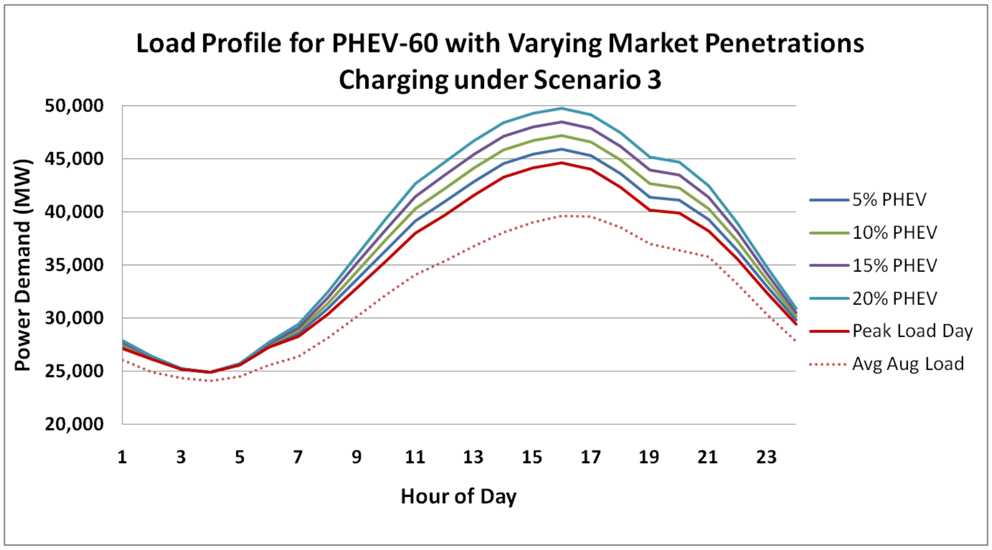
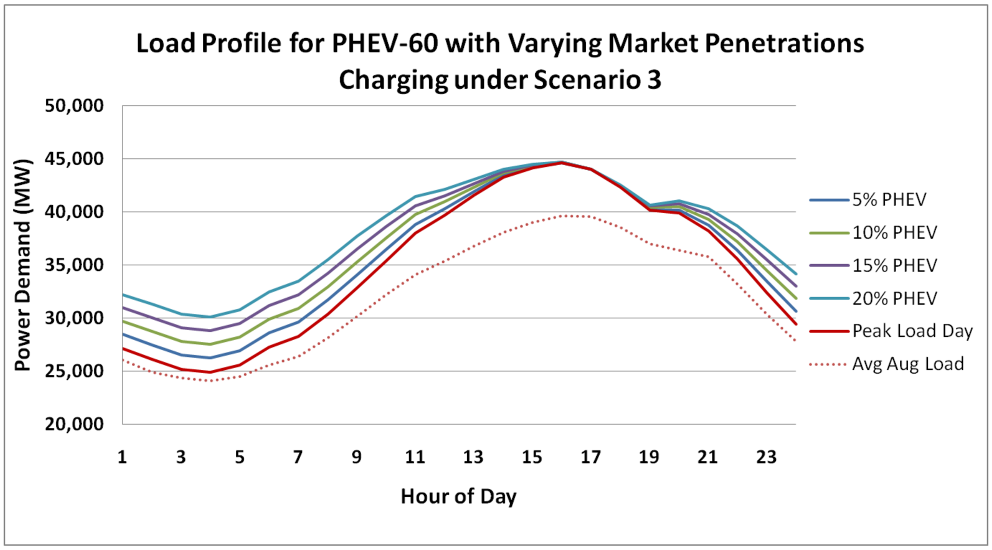


Figure 20. Load Profile for PHEV-60 with Varying Market Penetrations Charging under a Nighttime (10 pm) Normal Distribution Scenario.



PHEVs with larger battery capabilities lengthen the need for additional power from 13 hours in the baseline scenario to 18 hours in the PHEV-40 and 22 hours in the PHEV-60 scenarios. The PHEV-60s create the largest energy demands out of the three battery capacities. The energy requirements relative to California's current energy state are provided in Table 12 below.

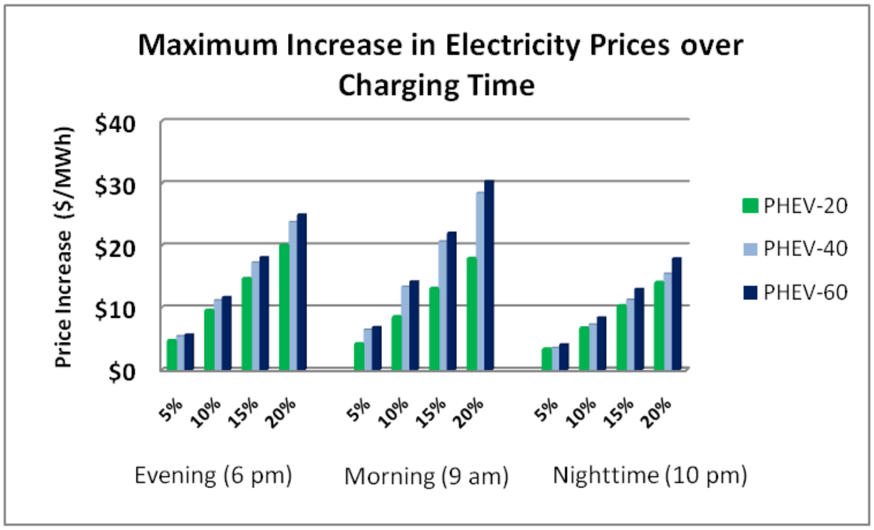
Table 12. Demand and Energy Assessment for Four PHEV-60 Penetration Scenarios

	Market Penetrations of PHEV-60			
	5%	10%	15%	20%
Demand (MW)	1,315	2,630	3,945	5,259
% 2007 Nameplate Capacity	1.92%	3.84%	5.76%	7.68%
% 2007 Summer Peak Capacity	2.06%	4.12%	6.18%	8.24%
Daily MWh (1 charge per day)	18,865	37,729	56,594	75,459
Annual MWh (1 charge 365 days)	6,885,632	13,771,264	20,656,896	27,542,528
% 2007 MWh	3.27%	6.53%	9.80%	13.06%

As with the PHEV-40, the annual energy requirements increase if each PHEV-60 is allowed to charge everyday for an entire year. If 1.2 million PHEVs in California are PHEV-60s, it would represent 3.27% of the net generation. While this is a significant amount of energy to meet the requirements for these vehicles, it is unlikely that PHEV-60s will need to fully charge every day since most commutes in the State occur under 30 miles.

The following graph demonstrates increases energy prices relative to the time of recharging PHEVs. In each of the cases, the normal distribution charging scenario is used to determine changes in energy prices.

Figure 21. Maximum Increase in Electricity Price over Charging Time.

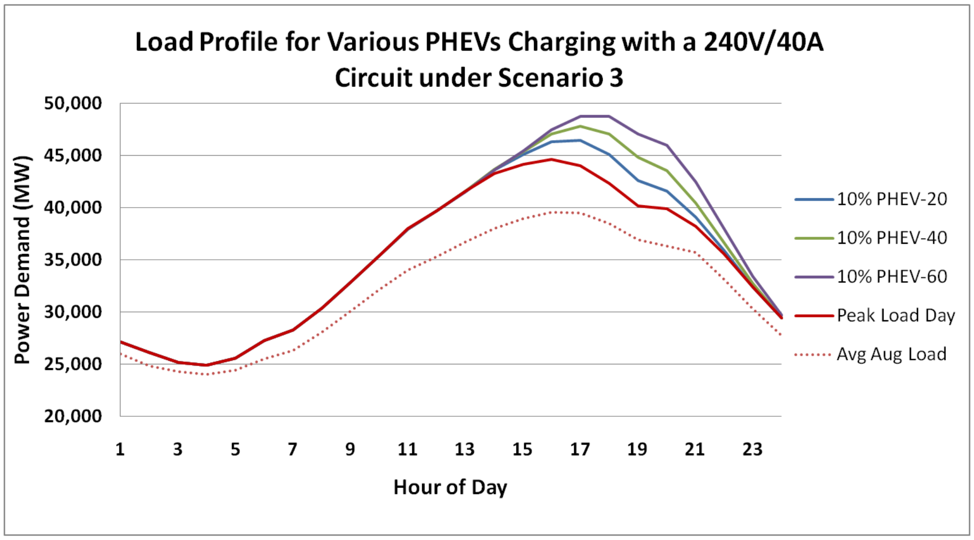


An increase in energy price from $5/MWh to $25/MWh can occur across different market penetrations charging around 6 pm. For PHEVs charging in the morning, larger battery capacities can greater increase in prices. As seen in the load profile curves above, PHEV-40 and PHEV-60s that charge at 9 am are still charging during peak hours, creating a greater increase in energy price than the PHEV-20 which is fully charged before peak hours. During the nighttime hours, prices range from $3/MWh to $18MWh at most for high market penetrations. As a result delaying the charging of plug-in hybrids into the nighttime hours can reduce the price impacts by 30% from the evening charging scenario.

Circuit Size Variation

In all previous scenarios, a 120V/15A circuit size was assumed the standard in charging the plug-in hybrids. While most household maintain these types of circuits, it is possible that vehicle manufactures will provide vehicle chargers designed to sustain higher voltages and amperages, reducing the time needed to fully recharge the Li-ion battery. The EPRI studies analyzed different circuit sizes, including a 120V/15A and 240V/40A circuit. The following figure displays how a 240V/40A circuit may affect power demand across a 10% market penetration of PHEVs (about 2.5 million vehicles). Again, a normal distribution charging scenario is used and in this case the vehicles begin charging in the evening.

Figure 22. Load Profile for Various PHEVs Charging with a 240V/40A Circuit under a Evening Normal Distribution Scenario.



Whereas the 120V/15A circuit allowed for 1.0 kW of power to be supplied to the battery per hour, the 240V/40A circuit allows 5.3 kW of power to be drawn from the grid. This reduces the time to charge the vehicle from 4.7 hours to under an hour for a PHEV-20. For PHEV-40 and PHEV-60s, the time to fully charge the battery occurs within 1.8 and 2.7 hours respectively. While its ideal to have faster charging times for vehicles with larger battery capacities, this creates a significant impact on the electric grid. The power demand under a 120V/15A circuit for a 10% market penetration of PHEVs is about 2.6 GW, whereas an increased circuit size of

240V/40A requires 14 GW, if all PHEVs charged simultaneously. The table below summarizes the demand in terms of California's energy requirements.

Table 13. Demand and Energy Assessment for PHEVs Charging under 240V/40A Circuit.

	Market Penetrations of PHEVs		
	10% PHEV-20	**10% PHEV-40**	**10% PHEV-60**
Demand (MW)	14,025	14,025	14,025
% 2007 Nameplate Capacity	20.47%	20.47%	20.47%
% 2007 Summer Peak Capacity	21.98%	21.98%	21.98%
Daily MWh (1 charge per day)	12,367	25,153	37,729
Annual MWh (1 charge 365 days)	4,513,914	9,180,843	13,771,264
% 2007 MWh	2.14%	4.35%	6.53%

The drastic increase in demand from using a larger circuit would require 20% of California's 2007 nameplate capacity. This amount of power is larger than many states' reserve capacity, which are required to maintain reliability. It is important to note that different types of charging circuits can have different impacts on the grid, and while many PHEV owners may use household outlets, certain charging stations may prove troublesome for electric utilities attempting to plan for plug-in hybrids.

A summary of the results from the variation with respect to the baseline scenarios are provided in Table 14 below.

Table 14. Summary of PHEV Charging Variations

Baseline Parameter	Baseline Scenario Value	Variation Value	Difference from the Baseline
Time of Charge	Evening (6 pm)	Morning (9 am)	Power demand (1.3 to 5.2 GW) added during ramp-up periods of the day.
		Nighttime (10 pm)	Power demand (1.3 to 5.2 GW) added during lowest load hours.
Battery Capacity	5.9 kWh (PHEV-20)	12 kWh (PHEV-40)	Doubling of daily/annual energy requirements; recharge length per vehicle increased from 4.7 to 9.6 hours
		18 kWh (PHEV-60)	Tripling of daily/annual energy requirements; recharge length per vehicle increased from 4.7 to 14.3 hours
Charging Circuit	120V/15A	240V/40A	Reduces charge time to charge from 4.7 to 0.9 hours per vehicle for PHEV-20s; increases additional demand from 2.6 GW to 14 GW in 10% penetration rate of PHEVs.

Impacts on Current Installed Capacity

To understand the potential impacts of PHEVs on electricity resources in California, an installed capacity supply curve chart is shown. The chart below was created using published fuel and variable costs for each of the different electricity generating technologies in California. The short-term marginal price for each the generating technologies[7] (shown as the black solid line) is plotted as a function of cumulative capacity. The area under this curve represents the total installed capacity in California as of 2007. The graph demonstrates the different generating technologies used for the given demand, assuming that these power plants come online starting with the least cost plants first. The load duration curves for the minimum load day ("Low Demand Day") and maximum load day ("High Demand Day") are represented on the chart. The blue and red lines are similar to the LDC curves described, however these are plotted as the percent of hours available (in a day) versus capacity.

The plants furthest to the left are mainly renewable power plants (wind, solar, geothermal etc). Around 20,000 MW, the power plants are landfill natural gas, coal, and nuclear. The stretch between 28 to 40 GW represents combined cycle natural gas plants, and the technologies furthest to the right are peaking units using simple cycle combustion. Starting with the minimum

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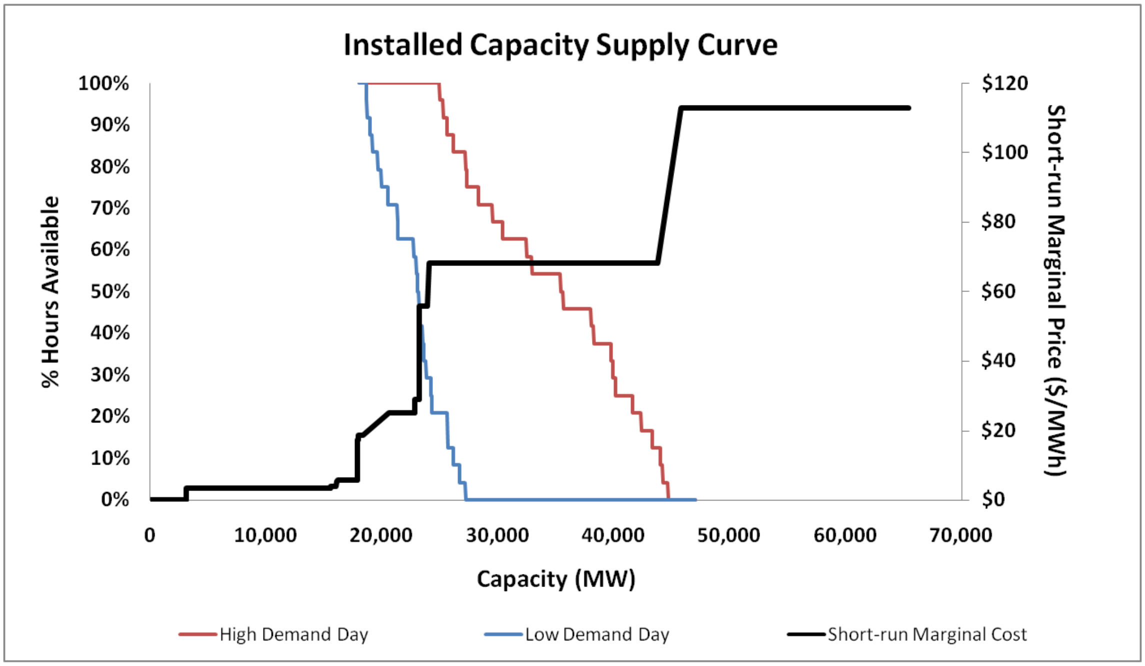
[7] Fuel and variable costs of the different generating technologies in California are provided in Appendix A.

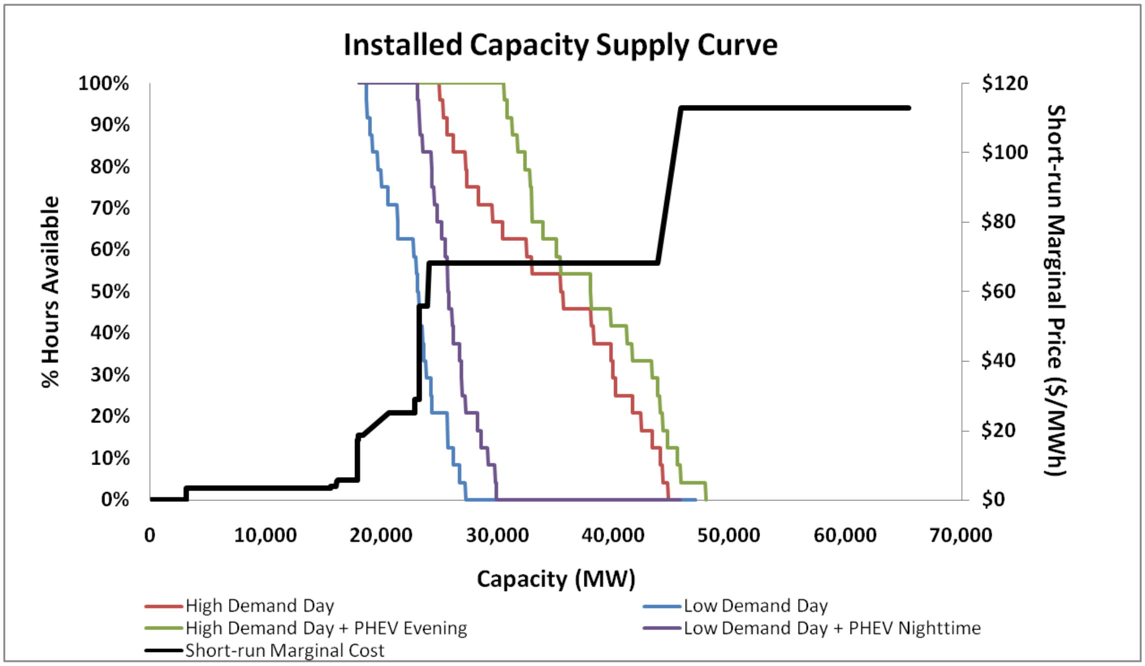
demand day, the baseload hours (between 100% and 80%) occur roughly at 20,000 MW. This represents at most approximately $25/MWh to use these power plants to meet the minimum demand. As demand increases during the day, reaching almost 30 GW, combined cycle plants are utilized to meet demand. The maximum load demand day has a base demand that requires almost the same units to be on, increasing short-term prices to $65/MWh. Load demand increases to 45,000 MW, almost reaching into the peaking units. It is important to note that these units would come online in this order absent of scheduled downtime. Not all power plants are able to run at full capacity, meaning that portion of generation is replaced by other units, potentially peaking units if demand is already high. Furthermore, the short-term prices do not include capital costs, and other costs that could affect when they will sell electricity to the grid, such as pollution costs.

Figure 23. Installed Capacity Supply Curve for California with Low and High Demand Days.



Adding in plug-in hybrid vehicles onto the minimum and maximum load days, shown in Figure 24 below, shows LDCs shift, inevitably requiring the utilization of more generating resources. The purple line represents the minimum load day with the inclusion of a 20% penetration rate of PHEV-40s charging at nighttime hours (10 pm). The green line represents the maximum load day plus PHEV-40s charging in the evening. The purple line now requires demand of at least 25,000 MW, which intersects the short-term marginal price curve at roughly $60/MWh. This increases the price by almost 60% from the minimum load day. In the short-term, if all load demand from PHEVs is met by in-state generation, additional capacity will be necessary to mitigate substantial increases in price. Incorporating the same market penetration rate of PHEV-40s charging in the evening (6 pm) onto the high demand day results in a maximum load of 50,000 MW. This level of generation exploits the use of peaking units, costing approximately $115/MWh. As mentioned before, this does not necessarily mean that peaking units were not utilized to meet demand during a high demand day initially; nevertheless, the introduction of PHEVs further employs these resources.

Figure 24. Installed Capacity Supply Curve for California with PHEV Charging Scenarios



DISCUSSION

Baseline Charging Scenarios

The results of the study have provided insight into the how California's electricity grid may be impacted from the introduction of plug-in hybrid vehicles. Hours of the day when recharging is expected to occur in large numbers, such as when commuters arrive home from work, can have significant impacts on demand. In the absence of dramatic infrastructure changes with respect to charging stations for PHEVs, most owners will recharge using standard 120V/15A electrical outlets. Recharging a typical lithium-ion battery from 20% SOC through one of these outlets draws 1.0 kW and would take approximately 5 hours for a mid-sized PHEV-20 to fully recharge. The charging of PHEV-20 under a 120V/15A circuit would not inconvenience most vehicle owners. It is possible that some homeowners might choose to upgrade an outlet to a 240 volt and 40 ampere circuit to allow for faster charging times; however such upgrades would incur additional costs. For PHEVs with longer electric ranges, and therefore larger Li-ion battery packs, it may be beneficial to upgrade to higher charger sizes to reduce the charging length.

Under the simultaneous charging, sharp increases can incur, requiring 1.3 to 5 GW of additional electricity load, and although this is unlikely, it is important to understand this as a potential "worst case" scenario. This demand from PHEVs represents between 2 and 8% of California's 2007 summer net capacity. The second recharge scenario, where less than 50% of PHEV owners are actively charging their vehicles, the overall load profile experiences a shift to meet the elevated demand. Although vehicle owners may have the capability to recharge their vehicles multiple times per day, due to the smaller battery power capacity of PHEV-20, vehicle owners may not frequently recharge. For longer electric range PHEVs, such as a PHEV-60, or larger vehicle designs, such as Sport Utility Vehicles (SUVs) which require more energy, the battery may require multiple recharges throughout the day, if the goal is to fully utilize electric drive capability. The final recharge scenario, where recharging follows a normal distribution around 6pm, demonstrates a more realistic behavior pattern. While no sharp increases in demand are expected, it is anticipated that a gradual ramp up in load demand occur during the late afternoon hours and that these resources would be utilized into the evening hours. Higher market penetrations can also create a second peak under the third scenario, which would extend the use of peaking plants in California.

The fitted supply curves used to determine changes in energy prices are consistent with the additional load demanded from baseline scenarios. Dramatic increases in load demand causes from the simultaneous scenario, creates higher maximum increases in price. Conversely, slight increases created from the continuous scenarios have minor impacts on price for small market penetration. A 5% market penetration creates an estimated maximum elevated price of $7/MWh during the summer months for simultaneous charging. A continuous charging reduces the maximum $3.2/MWh and $4.6/MWh if charges follow a normal distribution, during the peak summer months. Compared to the summer months, the spring months prices are 60-70% lower. The overall impact on prices is greatest during the summer and winter months. It should be noted that although the results show that spring price impacts are much lower, the data used to estimate supply curves was particular inconsistent for the month of May, and may not accurately reflect price changes.

Variations to Baseline Scenarios

The time of day for recharging plug-in hybrid vehicles is an important factor to be considered when planning for this new technology. Late evening hour recharges create additional demand when electricity generation begins to ramp down, only requiring existing generating units to be utilized for a longer duration. If the addition of recharge stations in parking lots where incorporated into the scenario, it would be possible for a portion of vehicle owners to recharge when generation is beginning to ramp up, as shown in the morning charging scenarios. This can affect the availability of resources as well as the price of electricity. Shifting the additional demand of 1.3 to 5.2 GW during the daytime hours would require more generating units to be used during the ramping up periods of the day and may require additional capacity. Under some circumstances, such as PHEVs that have higher battery capacities, recharge these vehicles in the morning could push additional demand into the peak hours. The need for more resources during times when fewer resources are available has the potential to create technical and economic issues. As shown in the results, delaying recharging from the evening to the nighttime hours can help reduce the price impacts by 30%.

Adjusting the charging time to occur during at 10 pm can elevate the minimum load from 25 GW to 30 GW, for a high adoption rate of PHEVs. This leveling of the load profile reduces the fluctuation between high and low generation in a peak day by 25%. Although this requires greater baseload generation, it reduces the need to turn generation resources on and off frequently, which can be incur additional costs. Generating electricity from baseload sources can be less expensive in terms of variable and fuel costs than resources used during peak hours. Relying on more baseload generation than peaking units to meet demand may help reduce the overall costs of generation electricity, assuming there is adequate baseload to meet the additional demand from PHEVs. .

Charging stations that provide higher voltages and amperages, such as dedicated 240V/40A stations, can increase the charging rate to 5.3 kW per hour, while decreasing the time to fully charge. For PHEV-20s, a full recharge can occur within 30 minutes, whereas larger battery capacities can take just over an hour. These combinations of charging circuits and PHEV designs can dramatically change the PHEV load curves introduced onto the grid. While, infrastructure for these types of stations has not occurred on a large scale, designs for public charging stations may occur as PHEVs gain market penetration. Under a constant charging circuit, increasing the electric range of a plug-in hybrid vehicle requires a larger battery capacity and therefore a longer time to fully recharge. For larger vehicle classes, such as mid and full-sized SUVs, the same electric range will also require a higher battery capacity and a longer recharge time. It is possible that these larger vehicle classes cause the battery to reach charge sustaining mode (CS) faster than smaller classes, and would likely take advantage of multiple charges per day or circuit chargers equipped to handle higher voltages and amperages. The different variations have shown that dramatic changes to electric grids can occur depending on the time of day for charging, the type of vehicle, and circuit sizes. Based on the variations described, it is ideal to have PHEVs charge during the nighttime hours under a standard circuit size in order for utilities to anticipate and meet demand without the need for additional capacity.

Current Installed Capacity

The installed capacity curve provides insight into what electricity resources are used to meet demand. Including PHEVs demonstrates that baseload short-run prices may increase over \$60/MWh and peak demand prices may rise even further into the \$120/MWh range, if resources remain constant. While these prices may not reflect actual changes in market prices, it does provide insight into how California may approach planning for plug-in hybrids. Increasing the baseload generation will help to mitigate the cost of using combined cycle natural gas plants to meet the minimum demand. Adding more intermediate or shoulder units will help lessen the constraint on peaking units during days of high generation. It is also foreseeable in the short-term that the state may import electricity to meet demand from PHEVs until new power plants can be operational.

Limitations

The market penetrations used in this analysis are higher than the current penetration of hybrid electric vehicles in California (about 2% of the current fleet). Higher market penetration rates of plug-in hybrids were used in order to estimate significant impacts. Furthermore some HEVs can be retrofitted to be plug-ins and may help to increase the market penetration in the short-term. The supply curves estimations in this study provide insightful estimations of how generation price might be affected, however due to variance in the data used, should not be assumed accurately reflect prices. In particular, the variance for the supply curve for May was very low (0.32). A more accurate method of obtaining a supply curve would be to define the costs at which each plant is willing to selling electricity to the grid. The fitted supply curve estimations were calculated using existing data from CAISO, which contained some volatility in energy prices. These changes in prices could be due to resource availability changes or geographic differences in electricity demand.

CONCLUSION

Plug-in hybrid electric vehicles can have a significant impact on California's electric grid. As shown in the scenario analysis, 1.2 million vehicles requires over 2% of the summer's peak capacity and over 1% of the total net generation. Unusually high market penetrations of plug-in vehicles (20% of California's light duty vehicle fleet) can require over 5,000 MW of additional capacity onto CAISO's grid. The major question for electric utilities is when this demand will occur. During the morning and evening hours, a portion of the demand from PHEVs will have to be met during peak hours, requiring additional capacity. Charging during the evening hours can also cause constraints on peaking units in California, since these units will need to be utilized longer and more frequently than without PHEVs. Using more natural gas peaking units has the potential to inflate the short-run marginal costs by 40%. If charging of these vehicles is delayed until the nighttime hours, the load profile curve could be leveled up to 25% for peak generation days and a reduction in price increases by 30% can be expected. However, nighttime charging can increase the minimum load demand, requiring more units to be used to meet minimum demand in the short-term. This may require the use of more natural gas combined cycle plants to operate more frequently, if in-state generation and electricity imports do not increase. The repercussions of this include potentially inflating the baseload short-term marginal costs by $40/MWh.

Although PHEVs may have a significant impact on the electric grid in large numbers, these impacts will be gradual as plug-ins begin to capture the market allowing time for utilities to adequately adapt to the additional demand. In the short term, most demand from PHEVs will be met by existing natural gas units in California. It is recommended that PHEV market penetrations higher than 10% should be charged during nighttime hours due to economic and technical constraints. This can be accomplished through use of charging stations that delay the recharge until a specific time. As PHEVs gain higher market penetrations, there is a greater potential to increase the efficiency of the grid under a nighttime charging scenario. If utilities in California adequately plan for plug-in hybrid vehicles, what once could be considered a cost could be transformed into a benefit.

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APPENDIX A

The following fuel and variable costs were taken from a 2007 study titled “Comparative Costs of California Central Station Electricity Generation Technologies” by the California Energy Commission. Since the study did not include all of the generating technologies currently installed in California, some this information was supplemented by the EIA’s “Cost and Performance Characteristics of New Central Station Electricity Generating Technologies”.

Table 15. Fuel and Variable Costs for Generating Technologies in California

Generating Technology	Fuel Costs ($/MWh)	Variable ($/MWh)
Combined Cycle	62.76	5.29
Integrated Gasification Combined Cycle	24.63	4.16
Simple Cycle	81.93	30.86
Biomass - Landfill Gas	0	18.64
Geothermal Binary	0	5.59
Geothermal Dual Flash	0	5.49
Hydro In Conduit	0	17.22
Hydro Small Scale	0	3.97
Conventional Hydro (EIA)	0	3.41
Biomass - Direct Combustion	51.69	3.97
Municipal Solid Waste (EIA)	0	0.01
Solar - Photovoltaic	0	0
Solar Thermal - Parabolic Trough	0	0
Biomass - WWTP	0	18.64
Wind	0	0
Nuclear	23.49	1.67

IMPACT OF PLUG-IN HYBRID ELECTRIC VEHICLES ON CALIFORNIA'S ELECTRICITY GRID

by

Jason Wynne

May 2009

Several automakers are preparing for the next generation of passenger transportation, Plug-in Hybrid Electric Vehicles (PHEVs). These vehicles are slated to be commercially available starting in 2010. PHEVs operate similar to Hybrid Electric Vehicles (HEVs) which utilize a significant portion of energy from the battery for drive; however PHEV batteries have the capability of recharging through most standard electrical outlets. For these vehicle owners, the demand for gasoline will be offset and replaced by an increased demand in electricity. Using data from the California Independent Systems Operator (CAISO), this report sought to understand how different charging scenarios for PHEVs could impact electricity demand in California. Furthermore, this study aimed to understand how the additional demand from plug-in hybrid vehicles would affect the supply price of generating electricity.

The results from this study estimated that PHEVs would require between 2% of California's summer peak capacity for a low market penetrations and 8% for a high market penetrations of PHEVs. At most, a \$5/MWh increase in electricity price can be expected for a 5% market penetration of PHEVs charging under a normal distribution scenario in the evening. Under the same scenario, a 20% market penetration of plug-ins will result in a maximum supply price increase of \$20/MWh. Nighttime charging of these vehicles can help level the load curve up to 25% during peak generation days and can decrease the price impact by an average of 30%. Furthermore, the introduction of plug-ins onto CAISO's grid can increase the amount of electricity needed to meet the minimum load demand, requiring more baseload generation. Under a scenario in which PHEVs are allowed to charge during peak hours, the additional demand can lead to constraints on the existing "peaking units" in California.

Approved

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(MP advisor signature here)
Dr. Lincoln Pratson

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Date

Master's Project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment, Duke University
May 2009