

## Effects of Plug-In Hybrid Electric Vehicles in California Energy Markets

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### **Abstract**

Plug-in hybrid electric vehicles (PHEVs) can run in all-electric mode with grid-supplied electricity or in hybrid electric mode with liquid fuels. We use 1999 California electricity market data to show that millions of PHEVs could charge economically during both peak and off-peak hours with real-time electricity pricing and modest gasoline prices. However, the present value of fuel cost savings at current prices is probably smaller than the magnitude of potential marginal vehicle costs. We simulate the effects of large PHEV fleets on the system load curve under three charging scenarios and find that 1 million compact car PHEVs would not significantly affect the system peak. Larger fleets could require the expansion of system capacity if not charged during the hours of lowest demand. Our forecasts of possible PHEV adoption suggest that only in the most aggressive transition scenarios would there be several million PHEVs in California within a decade.

### **Introduction**

Plug-in hybrid electric vehicles (PHEVs) have been proposed as a next step in the evolution of transportation technologies towards increased energy efficiency and less pollution (Romm and Frank, 2006; Suppes, 2006). They are similar to current hybrid gasoline-electric vehicles but have larger batteries and can, if their owners choose, charge their batteries from the electric grid and operate for some number of miles in all-electric mode. Ordinary hybrid vehicles have proven popular as sales in the U.S. have grown by over 80% annually since 2000, despite questions about the value of their fuel savings relative to the additional costs of the vehicles (see [www.hybridcars.com](http://www.hybridcars.com) and Lave and MacLean, 2002). Several companies now offer to convert ordinary hybrid vehicles (e.g. the Toyota Prius and Ford Escape models) into PHEVs and plan to sell retrofit kits, while at least one PHEVs is being evaluated for sale in Europe (the Mercedes-Benz Hybrid Sprinter).

PHEVs are intriguing because they offer some of the best aspects of gasoline- and battery-powered vehicles (long range and low emissions, respectively) while overcoming key limitations of both. And by allowing stationary power sources to provide transportation energy, PHEVs offer a potential long-run substitute for petroleum. Prior analyses of PHEVs have focused on vehicle design and made optimistic, best-case assumptions about vehicle charging (Romm and Frank, 2006). We focus upon the effects that PHEVs may have on energy markets, and we attempt to bound the problem by considering both optimistic and pessimistic assumptions. This study focuses on the area served by the California Independent System Operator (CAISO) due to data availability and to California's high electricity prices, which make the state a lower limit in the U.S. for the desirability of all-electric operation of PHEVs.

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Prior analyses have examined the impact of battery electric vehicles (BEVs) on electricity markets, but PHEVs interact with the energy system in a fundamentally different way because drivers have more flexibility to choose if and when to charge their PHEVs (Ford, 1994; Koyanagi and Uriu, 1997). In a sense, PHEVs have two fuel tanks: they may use gasoline like a hybrid electric vehicle, or they may charge their batteries from the electric grid and run in all-electric mode until low battery charge leads the vehicle to switch to the gasoline-fueled hybrid electric mode. PHEVs promise to link the hitherto separate gasoline and electricity markets through the repeated marginal decisions of automotive fuel choice. As a result, PHEV owners should be more responsive than BEV owners to gasoline and electricity price signals, and unlike BEVs, the loads PHEVs place on the electric power system are discretionary because a PHEV can always operate on gasoline. In addition, because PHEVs are much more similar to conventional gasoline vehicles (CVs) than to BEVs in terms of technology and consumer experience, and are likely to have a smaller cost premium than BEVs, consumers may adopt PHEVs more readily. However, the flexibility PHEVs display in operation makes their implications for energy markets less straightforward to estimate.

There has also been considerable interest in the use of vehicles, especially those with fuel cells, to provide energy or energy services to the electrical grid (Williams, 1997; Kempton and Tomic, 2005; Kempton and Tomic, 2005). For simplicity, and because it would involve a far greater change from current practices, we ignore this application. We also ignore distribution-level constraints on the quantity and pattern of PHEV charging, although prior analysis found that these constraints could be important for BEVs (Rahman and Shrestha, 1993). However, the distribution system effects of BEV charging are due to the high initial charging rate associated with the lead-acid batteries assumed by Rahman and Shrestha (1993). Because PHEVs are expected to use nickel metal hydride (or possibly lithium ion) which have a much flatter charge curve, distribution system effects should be small for PHEVs.

This paper proceeds as follows. We first examine the choice of PHEV drivers about whether to operate on electricity or gasoline: we calculate the fuel prices that provide the equivalent cost per mile, and we determine the number of PHEVs that could economically charge from the 1999 CAISO system at various gasoline prices. As presented below, this is more than 5 million PHEVs in some hours. To explore the effects of PHEVs on the electric power system, we then model the impact of 1, 5, and 10 million PHEVs on CAISO system load under three charging scenarios. We next assess the adoption rates necessary to obtain such large numbers of PHEVs in the on-road fleet in a shorter period than that of electric power grid expansion. We also calculate the value of the fuel saved by the use of PHEVs to determine whether consumers are likely to have an incentive to purchase PHEVs for fuel cost savings. We conclude by discussing the effects of PHEVs on California gasoline markets and the commercial and policy implications of this research.

## Methods

For comparability, we adopt PHEV performance parameters from the most prominent prior study, which considered a compact PHEV car with gasoline fuel efficiency of 50 miles per gallon (mpg), all-electric efficiency of 130 miles per equivalent gasoline gallon, and an all-electric range of 20 miles (Duvall, 2002). (Using a conversion factor of 33.44 kWh per gallon of gasoline, the all-electric mode obtains 3.9 miles per kWh.) We also assume that the comparable conventional vehicle obtains 35 mpg. Note that 89% of personal vehicle trips nationwide cover 20 miles or less, suggesting that all-electric driving could become fairly common with these sorts of vehicles (U.S. Department of Transportation, 2001). Each vehicle will use 5 kWh of stored energy daily if it drives its entire all-electric range. In order to create upper bound estimates, we assume that all PHEVs are driven their entire all-electric

ranges between charges. (As discussed below, this means 40 all-electric miles per day in one charging scenario and 20 all-electric miles per day in the others.) We use an effective charge rate of 1 kWh/hr for all vehicles, which with a charger efficiency of 82% and a battery charging efficiency of 85% implies that each PHEV actually demands 1.4 kW when charging (Duvall, 2002 Table 2-6). Thus, to use 5kWh of stored energy, a PHEV demands 7kWh from the grid, which is what the customer must pay for. Such charge rates can be obtained by using ordinary 120V technology while higher charge rates may be obtained by investing in charging infrastructure such as 240V chargers (similar to what is used for some large household appliances).

We conduct a sensitivity analysis by assuming that PHEVs are full-size sport utility vehicles (SUVs) that have a fuel economy of 18 mpg as a CV, 30 mpg for the PHEV version running on gasoline, and 77 miles per equivalent gasoline gallon (2.3 miles per kWh) in all-electric mode (Duvall, 2002). These vehicles will consume 8.7 kWh of stored energy daily if they drive their entire 20-mile all-electric range each day, which implies 12.2 kWh of demand based on the charger and battery efficiencies given above. Any fleet of compact car PHEVs that poses problems for the electric grid would also pose problems if it were composed of SUV PHEVs; we only test the sensitivity to vehicle type of those compact car fleet sizes for which we find few significant implications for the grid.

For residential electricity customers of the Pacific Gas and Electric Company (PG&E) paying according to the current residential tariff (E-1), about 8.7¢/kWh of the baseline tariff is not due to generation (energy) costs but to transmission, distribution, and so forth (Pacific Gas and Electric Company, 2006). In reality, non-generation costs increase with consumption, but we hold these costs constant for all calculations. Using PHEV efficiency values, we calculate the retail electricity prices that would be equivalent to various retail gasoline prices in terms of cost per mile driven. We also subtract the non-generation costs to obtain the implied wholesale electricity prices (Table 1).

A similar calculation yields the gasoline costs that are equivalent to May 2006 PG&E electricity rates for the standard residential tariff (E-1) and for the residential time-of-use tariff (E-6) (Table 2). Both tariffs have inclined block structures whereby prices rise with consumption (Pacific Gas and Electric Company, 2006). The lowest price block for the standard tariff is about 11.4¢/kWh and is charged for consumption up to the “baseline” value, which ranges from 8 to 16 kWh per day depending upon climatic zone. As consumption rises above the baseline amount, additional energy becomes more expensive until the highest rate is reached when consumption exceeds three times the baseline. This rate is 34.6¢/kWh, about three times the baseline rate. The residential time-of-use tariff has one rate schedule for summer peak hours, another for summer partial-peak hours, and another for summer off-peak hours. The summer peak hours are from 1 PM to 7 PM on weekdays and have a baseline rate of 20.9¢/kWh. The summer off-peak hours largely occur on weekends and during the night and early morning on weekdays, and they have a baseline rate of 9.4¢/kWh. The partial-peak rates are similar to the standard tariff rate. All three rates rise with consumption.

Beyond comparing current electricity rates and gasoline prices, we also evaluate the marginal fuel decisions of PHEV drivers under the assumption that they pay a real-time electricity price based on wholesale prices plus constant non-generation costs of 8.7¢/kWh, as discussed above. The price history of the day-ahead electricity market from California’s restructured period and the supply and demand bids offered to the California Power Exchange (CALPX) are available at the web site for The Center for the Study of Energy Markets at the University of California Energy Institute. We use this data to investigate how large the PHEV fleet could become in the short run before the cost per mile of all-electric operation rose above the cost per mile of gasoline-fueled hybrid operation. For simplicity, we assume that all other electricity demand is perfectly price inelastic. We use wholesale price data from

California's old restructured electricity market because, unlike today, the prices and bids were publicly posted, and in 1999 the California electricity market had yet to lapse into disarray.

To bound the marginal fuel use decision, we selected the highest priced hour and the lowest priced hour for Tuesday, March 2, 1999 and for Tuesday, August 3, 1999. March and August are among the California electric power system's lowest and highest demand times, and using the first Tuesday in each month should capture typical workday patterns. Neither day seems anomalous with respect to the days around it. The lowest priced hour for each day was 4 AM. The highest priced hour for March 2 was 7 PM, and the highest priced hour for August 3 was 4 PM.

Residual supply curves for PHEV electricity were calculated from the supply bids and the market-clearing electricity demand in that hour. The residual supply curves show the supply of electricity in excess of actual day-ahead demand at each price, and these curves therefore show the supply of electricity available to PHEVs at each price. Using the demand bids instead of the actual market-clearing demand would increase the electricity available to PHEVs at prices higher than the actual market-clearing price.

We use the day-ahead market clearing quantities for each hour in 1999 to examine the effects of PHEV numbers and charging patterns on system load. Since the analysis above suggests that more than 5 million PHEVs might economically charge in some hours, we examine the effects of 1, 5, and 10 million PHEVs under three charging patterns. For each scenario, we develop representative daily load curves for the two days used in the fuel choice analysis. Using 2005 data from the CAISO web site yields similar results. The three charging pattern scenarios are as follows:

- 1) *Optimal Charging*. This corresponds to the best case assumptions used in prior analyses. It is optimal from the grid operator's perspective. The 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 for 5 continuous hours. This scenario bounds the possible beneficial load-leveling effects of PHEVs.
- 2) *Evening Charging*. The times at which the PHEVs begin charging are evenly distributed between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours. This represents drivers returning home from work and plugging in their vehicles. This and the next scenario are meant to provide worst-case baselines for possible behavior in the absence of price incentives or technical means of shaping charging patterns.
- 3) *Twice Per Day Charging*. This is a high demand scenario: each PHEV is assumed to be plugged in to charge fully at the end of each commute leg. Thus, each vehicle fully charges twice each day, once upon arriving at work in the morning and once upon arriving home in the evening. Charging start times are evenly distributed between 8 and 9 AM and again between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours in the morning and again in the evening.

The SUV sensitivity analysis uses the same scenarios but with a 9 hour charging time to allow the less efficient vehicles to have 20-mile all-electric ranges.

We next assess what assumptions about PHEV adoption and use are necessary for PHEVs to become a significant issue for the electricity system within the near-term as defined by electricity system planning. It often takes 5 or more years to plan, finance, construct, and commission new electricity generation, so we use twice this period, 10 years, as a rough definition of the near term. If adoption of

PHEVs is slow enough, or managed adequately for a decade or more, then long-run supply decisions could account for the extra load and electric power markets will have time to evolve appropriately.

We develop three simple cases to place an upper bound on the possibilities for PHEV adoption and to investigate the assumptions under which PHEVs would add sufficient demand to affect near-term operation of the electric power system. In each case, we assume that PHEVs are first sold in the next model year, MY 2008. The first case uses the current forecasts for regular hybrid vehicle sales and assumes that two current trends continue: that national sales increase by 20% per year and that California will continue to account for 30% of national sales ([www.hybridcars.com](http://www.hybridcars.com)). In this case, we also assume that all hybrids are PHEVs. The second and third cases apply a logistic growth curve to PHEV sales. The second is an ambitious 25-year transition to a 100% market share for PHEVs. The third is an aggressive transition to 100% PHEV market share in 12 years, or about two product cycles. We compare the predicted PHEV fleet sizes from these cases with the results of the prior analyses.

The final step of our analysis is to calculate the present value of fuel savings due to PHEV use, employing assumptions from a similar analysis in the literature (Lave and MacLean, 2001). Vehicles are assumed to travel 11,000 miles per year, which for PHEVs is all gasoline-fueled except for 20 all-electric miles during each workday.

## Results

### To Charge or To Pump

Figure 1 shows the relationship between PHEV electricity demand and wholesale electricity prices in the two peak hours and the two off-peak hours. Each of the four residual supply curves is price elastic over the left-hand part of the curve, and each becomes more price inelastic as more electricity is supplied. The gasoline price levels are marked at the wholesale electricity price for which the corresponding retail price would have the same cost per mile of travel. These gasoline price lines can be interpreted as the PHEV electricity demand curves, which are perfectly elastic at the equivalent wholesale price because higher electricity prices would cause a total switch to gasoline and lower electricity prices would cause the maximum feasible switch to electricity within the limitation of a 20-mile all-electric range.

The peak hours' residual supply curves become price inelastic at almost \$3.00 per gallon of gasoline and the off-peak hours' curves become price inelastic above \$2.00 per gallon, meaning that beyond these points higher electricity prices do not elicit proportionally as much extra supply. While higher gasoline prices than these may increase the PHEV demand for electricity, they would not greatly affect the quantity of electricity supplied and consumed in the short run. In terms of electricity consumption by PHEVs, the peak hours become price inelastic between 3 and 4 GW and the off-peak hours become price inelastic between 6 and 7 GW. If gasoline cost \$3.00 per gallon, it would be economical to charge over 6 million PHEVs during each of the off-peak hours and almost 3 million PHEVs during each of the peak hours. As there are about 17 million vehicles in the CAISO region, this analysis suggests that a substantial fraction of these vehicles could be PHEVs charging from the grid with 1999 electricity supply and demand conditions and recent gasoline prices (U.S. Department of Transportation, 2001).

Using values for full-size SUVs instead of compact cars leads to similar results: each wholesale price of electricity in Table 1 would change by an amount between \$1 and \$4 per MWh, each price of gasoline in Table 2 would change by an amount between 2 and 6 cents per gallon, and the PHEV electricity demand curves in Figure 1 would therefore not change much either. This is because both

SUVs and compact cars have a ratio of 2.6 between their miles per equivalent gasoline gallon and their miles per gallon in hybrid electric mode.

### System Load Curves Under 3 Charging Scenarios

Because it may be economical to charge millions of PHEVs rather than combust gasoline in hybrid electric mode, it is worth bounding the implications of PHEVs for the electricity system's load characteristics. Figure 2 shows the impact of 1, 5, and 10 million PHEVs on the 1999 CAISO system according to the three charging scenarios described earlier. Charge rates greater than 1 kWh per hour would increase the grid impact of a fleet of PHEVs when charging but may decrease the grid impacts by allowing them to charge for fewer hours.

The *Optimal Charging* scenario shows the maximum amount of load leveling possible from perfectly allocating each day's PHEV charging. This flattens the system load curve. The daily load curves show that PHEV demand is typically confined to the nighttime hours. In this best case, base load generators that currently shut off at night can pick up PHEV demand, which may not require any additions to electricity generation capacity.

In the *Evening Charging* scenario, PHEVs begin charging when their drivers return home from work between 6 and 8 PM. 1 million PHEVs have little effect on the system load curve other than to raise the late evening load a bit, which is not a significant outcome as sufficient capacity already exists to meet this load. They do not increase the peak demand for the August day, though the evening decline from the peak is slower. However, 5 million PHEVs do call for more capacity since the system's peak demand grows by 5 GW and occurs later in the day. At 10 million PHEVs, the peak grows by 12 GW, or 34%. In these cases, the electricity system would have to expand to support the additional load.

The *Twice Per Day Charging* scenario has those same evening-charging cars plugging in again in the morning when their owners arrive at work. Since the 5-hour charging time is for a PHEV with a 20-mile all-electric range, many commutes would drain the battery. The enhanced shoulder-raising effect of adding 5 million or more PHEVs creates a very different load shape with two peaks per day and with potentially significant implications for electricity generation, but 1 million vehicles still have a negligible effect on the system load curve. Because the summer peak determines system size and therefore has a strong influence on total system costs, this result suggests that even the worst-case assumptions made here do not yield a need for new electrical capacity investment to support 1 million PHEVs.

These results suggest that 1 million compact car PHEVs would not pose much of a problem for the 1999 California electricity system in even the upper bound of demand. The implications for other electricity systems depend upon the timing of their peak hours and the magnitude of the additional demand in those peak hours. We also run the worst-case charging pattern with 1 million SUV PHEVs and their 9 hour charging times to check for sensitivity to the lower charging time of compact cars. Figure 3 shows the impact of SUV *Twice Per Day Charging* on the system load. The longer charging times do have an effect, as 1 million SUVs reach more clearly into load-following generation units than do 1 million compact cars and as they even raise the system peak by 1.4 GW, therefore requiring 1.4 GW of new capacity. The daily load curve shows that the new system peak occurs at around the same hour as the old one. If all the PHEVs were SUVs with 9 hour charging times, the electric power system may have to adapt to even 1 million vehicles unless their charging were directed away from hours of peak demand.

### PHEV fleet size

A fleet of PHEV compact cars only poses problems for the electric grid when it reaches into the millions of vehicles. Might there be a fleet of millions of PHEVs within the long-run grid planning horizon of about 10 years so that the electricity supply would have time to adapt and account for the new demand? We answer this question by assessing the assumptions needed to obtain such fleet numbers. The three scenarios for the growth of the PHEV fleet (described above) are shown in Figure 4. Only in the aggressive scenario of 100% PHEV market share in 12 years does the number of PHEVs in the CAISO region exceed 1 million within ten years of their introduction, while the other two scenarios achieve fewer than 0.5 million within ten years. While the aggressive scenario does imply that over 8 million vehicles in the CAISO would be PHEVs within two product cycles (which is almost half the number of private vehicle registrations in the region in 2000), such rapid and complete adoption of PHEVs may require extreme circumstances.

### Present value analysis

While it appears to be economical for PHEVs to run in all-electric mode, is there a sufficient economic incentive for consumers to purchase PHEVs, given current and expected prices? Table 3 explores the conditions under which the decision to purchase a PHEV may be economical. Packages to convert HEVs to PHEVs currently cost about \$10,000 and void some of the manufacturer's warranty. The incremental cost of PHEVs produced by the original manufacturer should be lower, but the cost of additional electronics and battery capacity is expected to create a premium. With gasoline prices of \$3 per gallon and current electricity prices, PHEVs with a 20-mile all-electric range may save about \$400 annually relative to a CV, or about \$3,700 over the life of the vehicle at a modest (social) discount rate (14 years and 6%, following Lave and MacLean, 2002). This is \$1,000 more than a HEV would save. Current costs for PHEV conversions are about \$10,000 and predictions for future costs of the batteries alone (accounting for economies of scale and some technological improvements) are about \$2,000-\$3,000 for compact PHEV-20s (Duvall 2002 Table2-7). Thus, it appears that if consumers have low discount rates over long periods, they would find a PHEV economical compared to conventional vehicle, but not economical compared to an ordinary HEV. However, there are many factors that go into consumer choices about vehicles, and PHEVs may have other attributes that are socially desirable but are excluded from this analysis (Kurani et al., 1996).

### Implications for the gasoline market

This paper has so far focused on the relationship between PHEVs and electricity markets without mentioning their effects on gasoline markets. Californians used 14,379 million gallons of gasoline in 2000 for highway travel, or about 40 million gallons per day (Davis and Diegel, 2004). As an upper bound on the potential of PHEVs to affect state gasoline markets, we find that, relative to conventional vehicles, PHEVs could have displaced as much as 30% of California's daily gasoline consumption through maximum economical charging in every hour of the two days studied from 1999 if gasoline prices were \$3.00 per gallon. And if the PHEVs were SUVs, they could have displaced 15% more gasoline than could compact cars relative to conventional vehicles. Absent market power, this displacement is not likely to greatly affect gasoline prices, however, because gasoline can be transported and because refineries can adjust which products they produce from a barrel of oil.

California-blend gasoline costs more than conventional gasoline to produce, and if California did not import gasoline prior to PHEV adoption, then the medium-run price of gasoline in California should equal the price of gasoline in neighboring states plus the extra cost of producing California-blend gasoline minus any additional cost of transporting gasoline from California refineries to those states. In

the very short run, a drop in demand should not lead to prices in California that were any lower than prices in neighboring states minus the cost of transporting gasoline to those states because prices lower than this would lead firms to sell more outside the state. A sustained drop in demand would lead refineries to switch away from producing California-blend gasoline or to reconfigure their operations to produce less gasoline and more of other refined products, which is the reverse of the process described in the second section of (Borenstein et al., 2004). Over time, the supply of California-blend gasoline should drop until the price was again approximately equal to the price of gasoline in neighboring states plus the extra cost of producing California-blend gasoline minus the cost of exporting to those states.

If, on the other hand, California were importing gasoline prior to PHEV adoption, then the gallons of gasoline displaced by PHEVs may be sufficient to eliminate the need for imports. In that case, the price of gasoline in a competitive market should fall by the cost of transporting gasoline from out-of-state refineries. While California refineries produce almost all of the California-blend gasoline for in-state demand and also export to the neighboring states of Arizona and Nevada, California suppliers did import about 2.1 million gallons per day of gasoline and gasoline components in 2002 (Energy Information Administration, 2003: 23). PHEV adoption in California should not cause the price of gasoline to change by more than the cost of transporting gasoline, which was 12 cents or less a decade ago, depending on the location of the supply source (California Energy Commission and California Air Resources Board, 1997: 13 as cited in Energy Information Administration, 2003: 25). Widespread national adoption of PHEVs may affect gasoline prices more strongly, but that contingency would require a more extensive analysis.

## Discussion

Over 1 million PHEVs could economically charge even during peak hours on most days, but the worst-case effects of several million PHEVs on system load curves may well lead grid operators and utilities to try to adjust charging patterns. In addition, changing the load curve as in the worst-case charging scenarios could raise electricity prices for all consumers. The higher costs for all other electricity consumers could lead to calls for the government to influence charging patterns and would have many effects on other sectors in the California economy.

Even under worst-case charging scenarios, it is unlikely that we will see these effects in the near term (less than ten years) unless there is very rapid adoption of PHEV technologies. We show that this outcome is not entirely infeasible, but it would probably require extreme circumstances. However, the middle portions of logistic curves can be steep, so a logistic adoption pathway could strain electricity supplies, even if it occurred over several decades. Further, high concentrations of PHEVs in specific markets could stretch local electricity resources. This suggests that the electricity and automobile industries might need to coordinate, at least in terms of sharing PHEV market growth expectations.

If PHEVs do start to reach into the millions, what is the best approach to optimally directing their charging? Real-time electricity pricing would encourage charging at night, but this may be insufficient. Under recent conditions (i.e. current gasoline prices and electricity tariffs in northern California) it would often be a rational economic choice to charge PHEVs during the peak hours rather than buy gasoline. Therefore, if this is deemed socially inefficient, new pricing structures or other policies for PHEVs that strongly encourage something close to *Optimal Charging* might be needed, possibly in conjunction with technical means to coordinate PHEV charging and electric power system operation. For example, home PHEV chargers might be wired to supply power only during certain times determined by the utility, or they might offer strongly time-differentiated rates.

However, it is not clear that the economic incentives from fuel cost savings will be sufficient to induce large-scale purchases of PHEVs. Vehicle choice and the choice of fuels for multi-fuel vehicles

are complex behaviors, with little or nothing known about the latter. An important research program would be to learn and explain how consumers who buy PHEVs tend to operate them so that fair, efficient strategies for charging can be devised, tested, and implemented in time for large-scale PHEV deployment.

One more cautionary note about the potential of real-time electricity pricing to lead to socially efficient PHEV charging outcomes is that gasoline taxes in the U.S. currently adjust not only for gasoline-specific externalities but also for road maintenance. Electricity prices would not contain this charge even as PHEVs' lower fuel cost of driving would encourage more vehicle use (indeed, even aside from all-electric operation, HEV operators are already paying less of this charge solely because of their greater fuel efficiency), and the electric power system may not discriminate between PHEV load and other loads to apply this charge. All-electric operation would therefore appear that much cheaper, and non-PHEV owners would bear more of the burden of road maintenance.

At recent electricity and gasoline prices, PHEV owners would often desire to drive in all-electric mode. Our analysis of 1999 California Power Exchange electricity supply bids indicates that millions of PHEVs would need to charge from the grid in each hour before gasoline-fueled hybrid electric operation became cheaper per mile than all-electric operation. And without real-time pricing, households with all but the highest consumption levels (who therefore face the highest marginal prices) would find it economical to charge from the grid. Adding 1 million compact car PHEVs would not greatly affect the current electric power system, but unless their charging times were directed to the lowest demand hours, adding millions of PHEVs would greatly expand the role of load-following and peaker plants and may affect prices. If the charging is poorly timed, this addition could cause new system peaks in the morning and evening, but if charged at optimal times of lowest demand in the middle of the night, PHEVs could instead level the system load and employ unused nighttime base load capacity. It is unlikely, however, that there would be millions of PHEVs in the California Independent System Operator region within the next decade. If PHEVs ever do attain these numbers, the electric power system may have different load and generator characteristics and long-run investment and planning strategies would have had a chance to incorporate PHEVs. The advent of PHEVs may eventually require new electricity pricing strategies and the alteration of the tax structure for highway funding, and it may shift the locus of automobile pollution concerns from the tailpipe to the smokestack, thereby bringing automobile pollutants within existing and proposed cap-and-trade systems for the electric power sector.

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**Table 1: Gasoline prices and equivalent wholesale and retail electricity rates for PHEVs**

Gasoline price (\$/gal)	Equivalent electricity rate (\$/kWh)	Implied wholesale price of electricity (\$/MWh)
\$2.00	\$0.108	\$22
\$2.50	\$0.135	\$49
\$3.00	\$0.163	\$76
\$3.50	\$0.190	\$103
\$4.00	\$0.217	\$130

Notes: We assume that the PHEV efficiency is 50 miles/gallon and 3.89 miles/kWh, that the charger efficiency is 82%, and that the battery charging efficiency is 85% (Duvall 2002). Non-generation costs of electricity are assumed to be \$0.0867/kWh (Pacific Gas and Electric Company, 2006).

**Table 2: PG&E May 2006 residential electricity tariffs and equivalent gasoline prices for PHEVs**

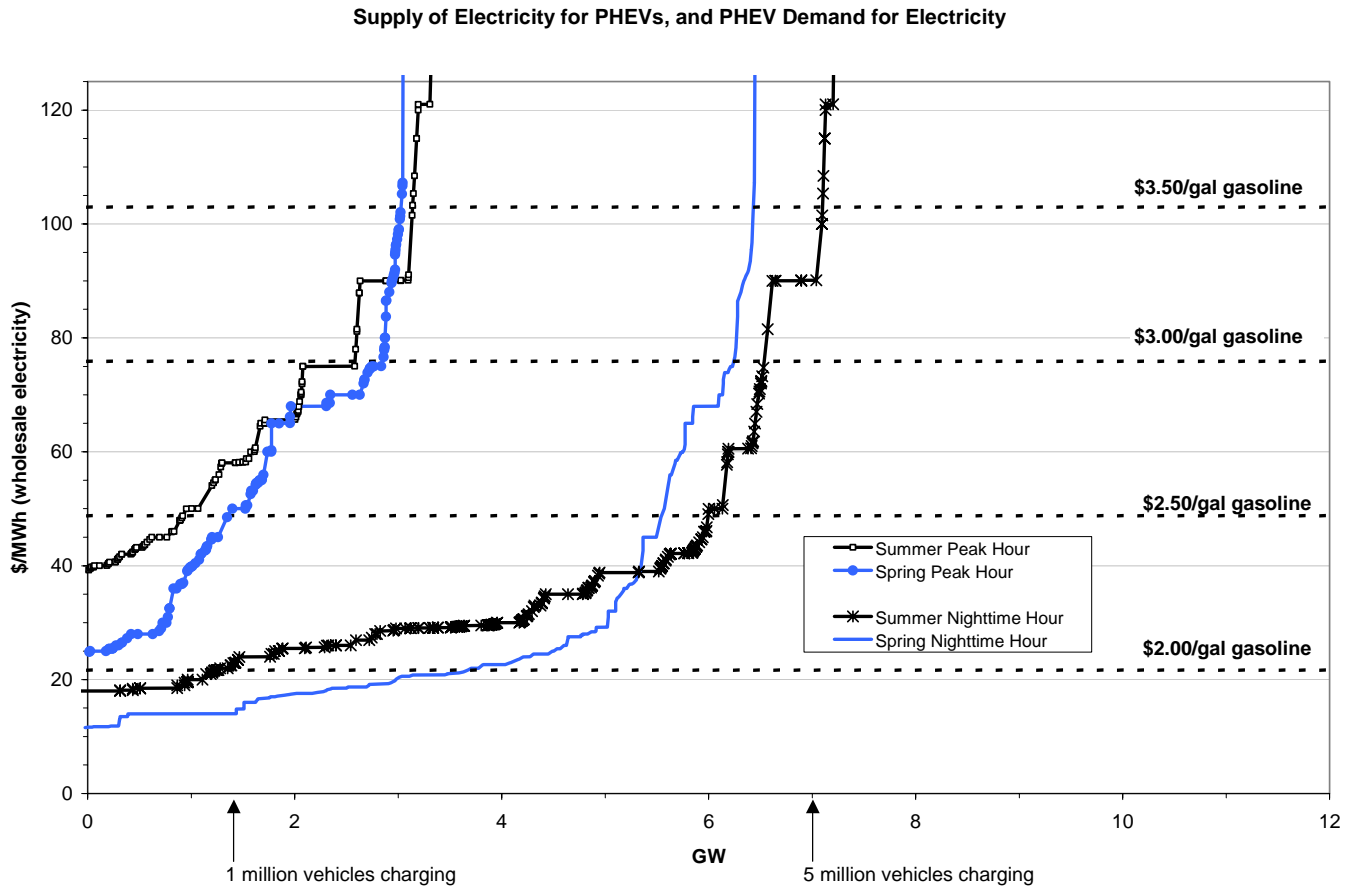
Standard residential tariff	Electricity rate (\$/kWh)	Equivalent gasoline price (\$/gal)		
Baseline usage	\$0.11430	\$2.11		
101%-130% of Baseline	\$0.12989	\$2.40		
131%-200% of Baseline	\$0.21981	\$4.06		
201%-300% of Baseline	\$0.30292	\$5.59		
Over 300% of Baseline	\$0.34648	\$6.39		
Time-of-use summer tariff	Electricity rate (\$/kWh)	Peak Equivalent gasoline price (\$/gal)	Off-Peak Electricity rate (\$/kWh)	Off-Peak Equivalent gasoline price (\$/gal)
Baseline usage	\$0.20863	\$3.85	\$0.09424	\$1.74
101%-130% of Baseline	\$0.22422	\$4.14	\$0.12739	\$2.35
131%-200% of Baseline	\$0.31414	\$5.80	\$0.19975	\$3.69
201%-300% of Baseline	\$0.39725	\$7.33	\$0.28286	\$5.22
Over 300% of Baseline	\$0.44081	\$8.13	\$0.32641	\$6.02

Notes: Electricity tariffs are from Pacific Gas and Electric Company (2006), and we assume that the PHEV efficiency is 50 miles/gallon and 3.89 miles/kWh, that the charger efficiency is 82%, and that the battery charging efficiency is 85% (Duvall 2002). Baseline usage ranges from 8-16 kWh per day, depending upon climatic zone.

**Table 3: Annual and present values of PHEV fuel savings relative to conventional vehicles**

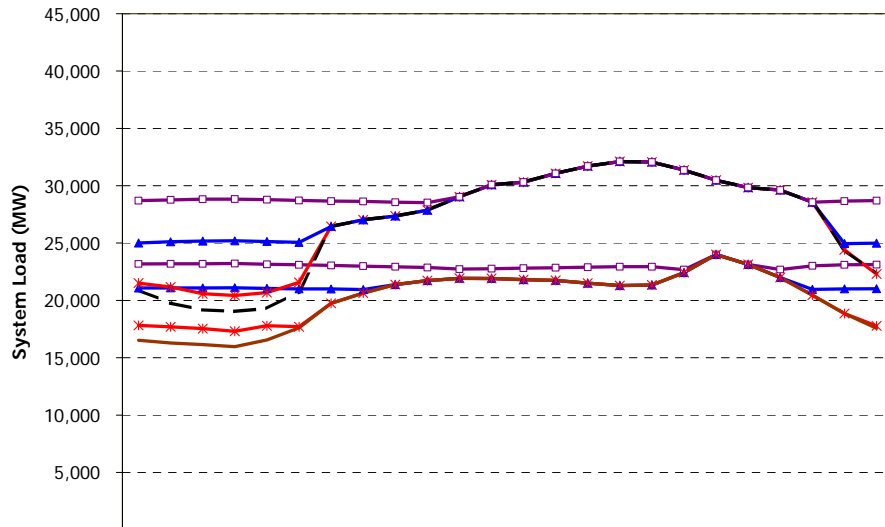
<b>Annual fuel savings</b>							
<i>Gasoline price (\$/gal)</i>		\$2		\$3		\$4	
		HEV	PHEV	HEV	PHEV	HEV	PHEV
<i>Electricity price (\$/kWh)</i>	\$0.05	\$190	\$298	\$285	\$493	\$380	\$688
	\$0.10	\$190	\$206	\$285	\$401	\$380	\$596
	\$0.15	\$190	\$114	\$285	\$309	\$380	\$504
	\$0.20	\$190	\$21	\$285	\$217	\$380	\$412
	\$0.25	\$190	-\$71	\$285	\$124	\$380	\$319
	\$0.30	\$190	-\$163	\$285	\$32	\$380	\$227
<b>Present value of fuel savings</b>				6% discount rate for 14 years			
<i>Gasoline price (\$/gal)</i>		\$2		\$3		\$4	
		HEV	PHEV	HEV	PHEV	HEV	PHEV
<i>Electricity price (\$/kWh)</i>	\$0.05	\$1,768	\$2,770	\$2,652	\$4,583	\$3,536	\$6,397
	\$0.10	\$1,768	\$1,913	\$2,652	\$3,726	\$3,536	\$5,540
	\$0.15	\$1,768	\$1,056	\$2,652	\$2,869	\$3,536	\$4,683
	\$0.20	\$1,768	\$198	\$2,652	\$2,012	\$3,536	\$3,826
	\$0.25	\$1,768	-\$659	\$2,652	\$1,155	\$3,536	\$2,969
	\$0.30	\$1,768	-\$1,516	\$2,652	\$298	\$3,536	\$2,112

Notes: We assume that the PHEV efficiency is 50 miles/gallon and 3.89 miles/kWh, that the charger efficiency is 82%, and that the battery charging efficiency is 85% (Duvall 2002). We also assume that the HEV efficiency is 50 miles/gallon, that the conventional vehicle efficiency is 35 miles per gallon, and that the PHEVs drive 20 all-electric miles each workday.

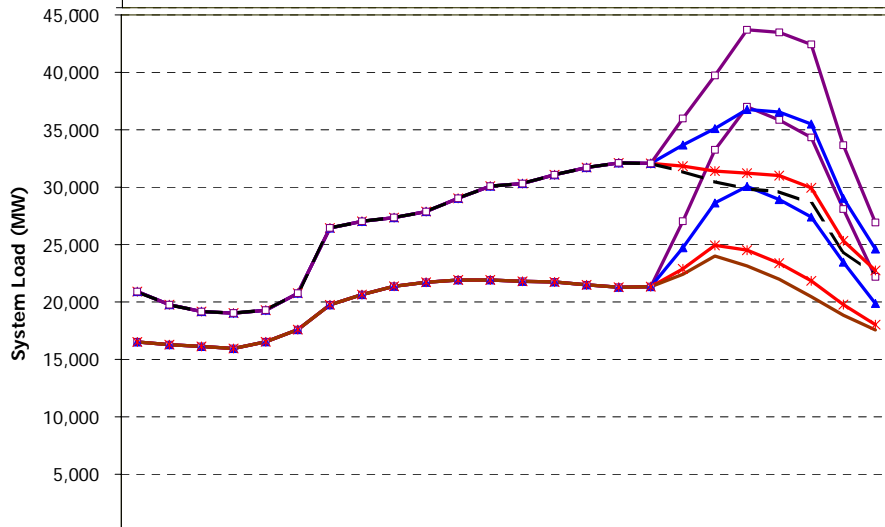


**Figure 1.** The quantity of electricity beyond observed demand available at each price, as determined by the supply bids given to the California Power Exchange. Also, the number of PHEVs that would need to charge during the hour to use that much electricity with a charge rate of 1 kWh/hr (or a charger size of 1.4 kW). The gasoline price lines provide the same cost per mile as the retail electricity rate that corresponds to the marked wholesale prices. The gasoline price lines can be read as PHEV demand for electricity with a given price of gasoline, assuming that gasoline and grid-supplied electricity are perfect substitutes. Households in the CAISO region own about 17 million vehicles (2001 NHTS).

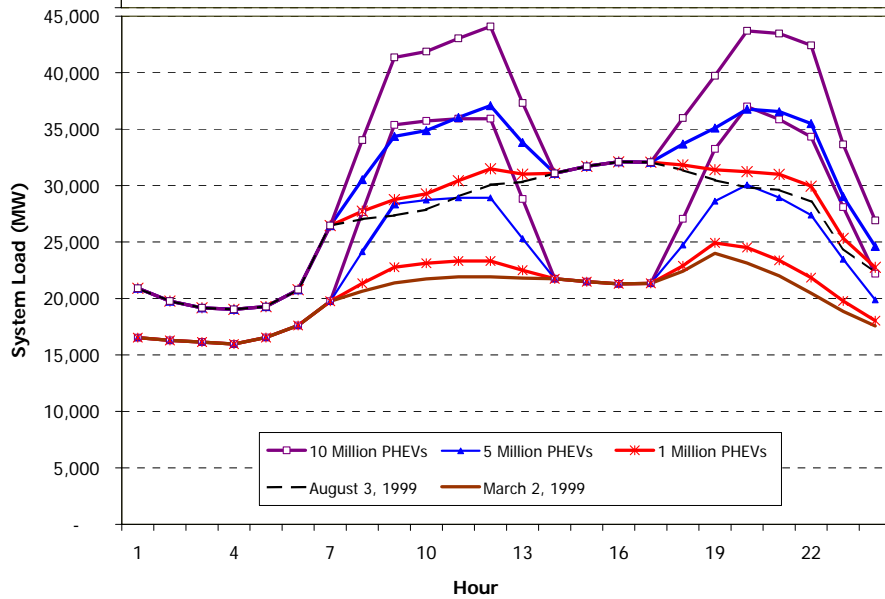
*Scenario A:  
Optimal  
Charging*



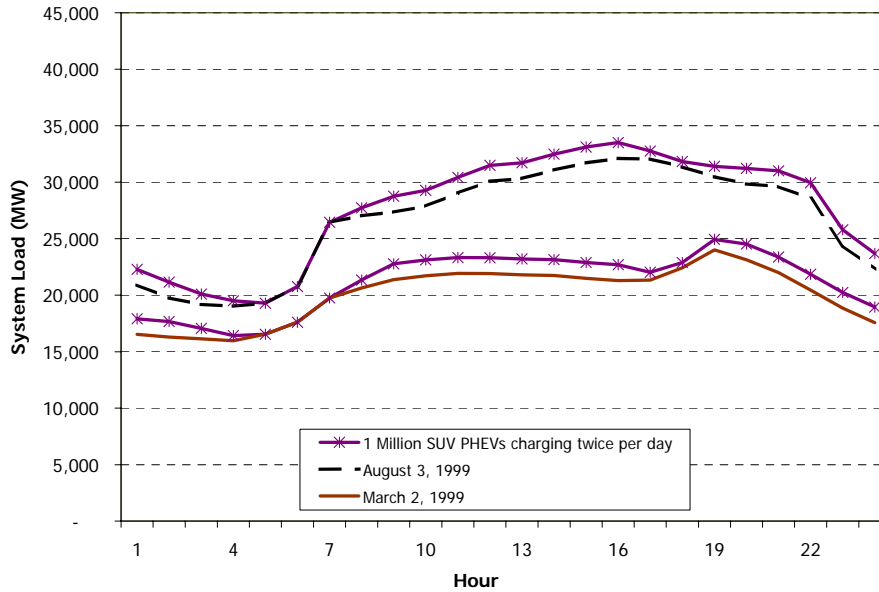
*Scenario B:  
Evening  
Charging*



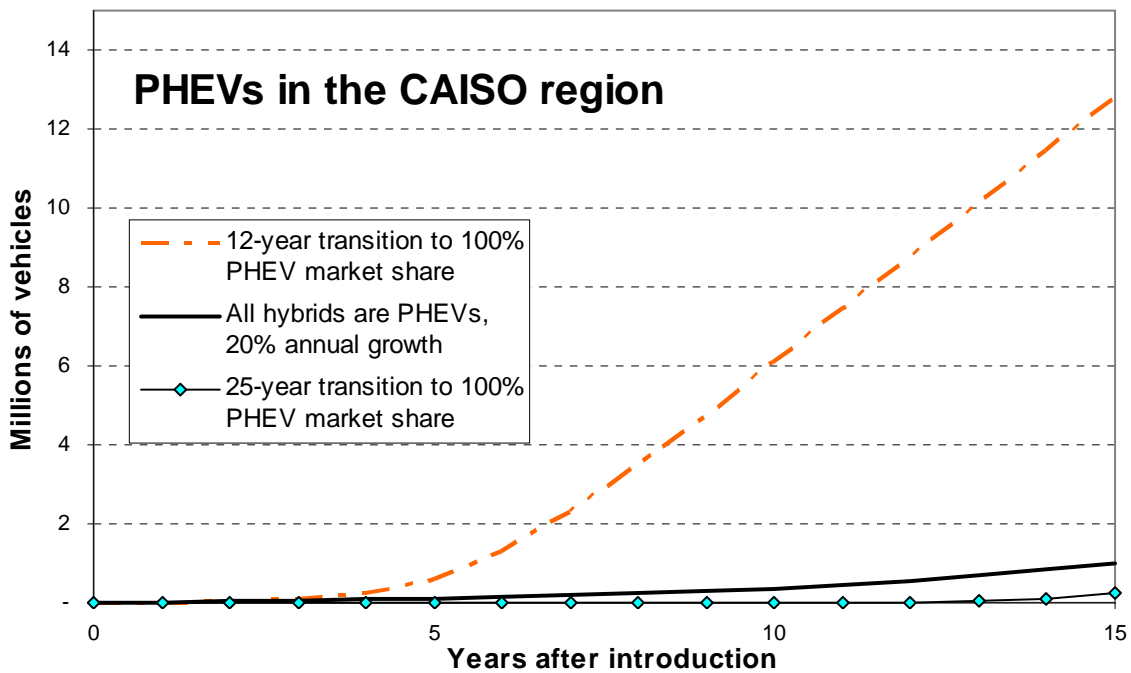
*Scenario C:  
Twice Per Day  
Charging*



**Figure 2.** 1999 CAISO system daily load curves for the two days analyzed with CALPX data with three compact-car PHEV fleet sizes and three charging scenarios.



**Figure 3.** 1999 CAISO system daily load curves for the two days analyzed with CALPX data with a fleet of one million SUV PHEVs in the twice per day charging scenario.



**Figure 4.** Three forecasts of PHEVs operating in the CAISO region. One forecast assumes that all hybrid vehicles sold after model year 2007 are PHEVs and that sales of these vehicles grow at 20% annually. The second models an ambitious transition to 100% market share over 25 years. The third shows an aggressive transition to 100% market share in 12 years, or about two product cycles. There are currently about 17 million vehicles in the CAISO region (U.S. Department of Transportation, 2001).