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An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles

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Abstract

Plug-in hybrid electric vehicles (PHEVs) can use both grid-supplied electricity and liquid fuels. We show that under recent conditions, millions of PHEVs could have charged economically in California during both peak and off-peak hours even with modest gasoline prices and real-time electricity pricing. Special electricity rate tariffs already in place for electric vehicles could successfully render on-peak charging uneconomical and off-peak charging very attractive. However, unless battery prices fall by at least a factor of two, or gasoline prices double, the present value of fuel savings is smaller than the marginal vehicle costs, likely slowing PHEV market penetration in California. We also find that assumptions about how PHEVs are charged strongly influence the number of PHEVs that can be charged before the electric power system must be expanded. If most PHEVs are charged after the workday, and thus after the time of peak electricity demand, our forecasts suggest that several million PHEVs could be deployed in California without requiring new generation capacity, and we also find that the state's PHEV fleet is unlikely to reach into the millions within the current electricity sector planning cycle. To ensure desirable outcomes, appropriate technologies and incentives for PHEV charging will be needed if PHEV adoption becomes mainstream.

Keywords: plug-in, hybrid, electric vehicle, battery, charging, present value, fuel savings, electricity, grid, fuel price

1. 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 electric vehicles (HEVs) but have larger batteries that can be charged from the electric grid. HEVs have proven popular as sales in the US have grown by over 80% annually since 2000, despite questions about the value of their fuel savings relative to the additional cost of the vehicles (see http://www.hybridcars.com and Lave and MacLean (2002)). Several companies now offer to convert HEVs (such as the Toyota Prius and Ford Escape models) into PHEVs and plan to sell retrofit kits, and several leading automobile manufacturers are developing and testing PHEVs.

PHEVs are intriguing because they combine the long range and accessible fueling infrastructure of gasoline-powered vehicles with the low emissions of battery-powered

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vehicles, and by allowing stationary power sources to provide transportation energy, PHEVs offer a potential long-run substitute for petroleum. Because they introduce fuel competition into the transportation sector, PHEVs may play an important role in climate change and energy security strategies. 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 interaction of PHEVs with energy markets and the electric grid, and we bound the possibilities by considering both optimistic and pessimistic assumptions about charging patterns. We study the area served by the California Independent System Operator (CAISO), which includes about 80% of California electricity demand. CAISO's high electricity prices and tight supply conditions should make on-peak charging less desirable there than in most other places in the US.

Prior analyses have examined the impact of battery electric vehicles (BEVs) on electricity markets (Ford 1994, Koyanagi and Uriu 1997), 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. In a sense, PHEVs have two fuel tanks: they may use gasoline like an HEV, or they may charge their batteries from the electric grid and use this stored energy until low battery charge leads the vehicle to switch to the gasoline-fueled hybrid electric mode. PHEVs promise to link gasoline and electricity markets through the repeated marginal decisions of automobile fuel choice. 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 operate on liquid fuels such as gasoline or biofuels.

There has been considerable interest in the use of vehicles, especially those with fuel cells, to provide energy or energy services to the electric grid (Williams 1997, 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. A prior analysis found that these constraints could be important for BEVs (Rahman and Shrestha 1993), but the anticipated effects of BEV charging on the distribution system were mainly due to the assumed method and duration of charging. Their charging method used high charging loads in the first two hours and then charged the batteries at a decreasing rate for another six hours. Rahman and Shrestha used this charging cycle because it would protect the lead-acid batteries. The long charging time restricted their ability to shift BEV charging into late-night hours, and the high initial charging loads created excessive system load when the BEVs began charging. PHEVs will likely use more advanced batteries such as lithium-ion batteries, and these more advanced batteries need not use the lead-acid batteries' charging method and may not need to charge for as long (Linden and Reddy 2002). Further, PHEVs would need smaller batteries than would BEVs because they can have shorter all-electric ranges without sacrificing functionality, which would again mean that PHEVs may not need to charge for as long. PHEVs should therefore have fewer effects on the distribution system than would BEVs.

We will answer five questions. Would PHEV owners prefer to charge from the grid with recent electricity tariffs and gasoline prices? If subject to real-time electricity pricing, how many PHEVs could economically charge from the grid before the price of electricity rose above the equivalent price of gasoline? What charging patterns and PHEV fleet sizes would create a need for new generation capacity? What sorts of PHEV adoption pathways could produce potentially problematic fleet sizes in the near term? If PHEV adoption depends upon expected fuel savings compensating vehicle owners for the additional battery cost, do current battery costs make rapid adoption pathways likely? The future of PHEVs is uncertain: innovation, marketing, government policies, fuel prices, consumer preferences and behavior, and even moral suasion may all play an important role in determining PHEV adoption and charging patterns. This renders the development of probabilities for different adoption and charging scenarios speculative and not very meaningful. Instead, we use a bounding analysis with robustness checks to examine the range of possible outcomes. We find that millions of PHEVs could economically charge during peak hours with real-time pricing and that California PHEVs are unlikely to require new generation capacity unless there are more than 1 million of them and their charging is not directed away from peak hours. Barring potential pro-PHEV policies or technological developments, it is unlikely that the California fleet will contain 1 million PHEVs in the near term of electric power system planning because current battery prices do not provide the economic incentives that could sustain such a rapid adoption pathway.

2. Methods

We adopt performance parameters from EPRI (2002): a compact car PHEV with an all-electric range of 20 miles has gasoline-fueled efficiency of 52.7 miles/gallon and all-electric efficiency of 4.010 miles/kWh, compact car HEV efficiency is 49.4 miles/gallon, and compact car conventional vehicle (CV) efficiency is 37.7 miles/gallon.[6] The all-electric efficiency includes losses from charging (EPRI 2001). A charging rate of 1 kWh/h can be obtained by using ordinary 120 V technology with a charger efficiency of 82% and a charger size of 1.2 kW, and higher charging rates may be obtained by investing in infrastructure such as 240 V chargers. Each compact car PHEV will use 4.1 kWh of stored energy if it drives its entire all-electric range and will require 4.1 h to fully recharge, and each full-size sport utility vehicle (SUV) PHEV will use 7.1 kWh of stored energy if it drives its entire all-electric range and will require 7.1 h to fully recharge[7]. If PHEVs have all-electric ranges that are less than 20 miles so as to reduce initial costs,

[6] The performance parameters in EPRI (2002) assume that the PHEVs use their grid-supplied electricity to run in an all-electric mode that uses only the electric motor, but another option is blended operation in which grid-supplied electricity and gasoline fuel the vehicle at the same time or in intervals. Blended operation would allow for better sizing of the electric motor. Also, we focus on PHEVs for residential use, but commercial and off-road PHEVs may be adopted first and may have significantly different characteristics.

[7] We corrected two inconsistencies in table 2-6 of EPRI (2002) when we determined the length of time that a PHEV would need to fully charge from the grid. The charger should be rated at 1.2 kW and the SUV rated battery pack size should be 7.1 kWh.

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

Gasoline price ($/gal)	Equivalent electricity rate ($/kWh)[a]	Equivalent wholesale electricity price ($/MWh)[b]
$1.50	$0.114	$36
$2.00	$0.152	$74
$2.50	$0.190	$112
$3.00	$0.228	$150
$3.50	$0.266	$188
$4.00	$0.304	$226

[a] Fuel prices are equivalent if they yield the same cost per mile of PHEV operation. PHEV efficiency is 52.7 miles/gallon and 4.010 miles/kWh (EPRI 2002).

[b] Non-generation costs of electricity are $0.07816/kWh (Pacific Gas and Electric Company 2006).

then each PHEV would require less electricity to fully charge but may charge more often.

We calculate the retail electricity prices that would be equivalent to various retail gasoline prices in terms of PHEVs' fuel cost per mile driven, and we subtract non-generation costs to obtain the implied wholesale electricity prices (table 1). We also calculate the gasoline prices that are equivalent to May 2006 Pacific Gas and Electric Company (PG&E) electricity rates for the standard residential tariff (E-1) and for the residential time-of-use tariff for electric vehicle (EV) owners (E-9) (table 2). The EV tariff is currently required for EV owners who charge their vehicles at home. Both the standard tariff and the EV tariff have inclined block structures whereby prices rise with consumption.

Next, we 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. We only use the real-time pricing assumption to derive the PHEV electricity demand curves; we do not use this assumption anywhere else in our analysis. 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 are available at the web site for The Center for the Study of Energy Markets at the University of California Energy Institute (http://www.ucei.berkeley.edu/). We use these data to investigate how large the PHEV fleet could have become in the short run before the cost per mile of all-electric operation rose above the cost per mile of gasoline-fueled hybrid electric operation. For simplicity, we assume that all other electricity demand is fixed so that increased prices due to PHEV demand do not decrease non-PHEV electricity use. Relaxing this assumption would increase the supply of electricity available to PHEVs at a given price and so also the number of PHEVs that could economically charge. We use 1999 wholesale price data and supply bids from California's former restructured electricity market because the most recent publicly posted supply bids date from 2000 and because in 1999 the California electricity market had yet to exhibit serious problems.

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

Residual supply curves for PHEV electricity come 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, which is also the supply of electricity that would have been 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.

The analysis above suggests that more than 5 million PHEVs might economically charge in some hours, so we next examine the grid impacts of 1, 5, and 10 million PHEVs under three plausible charging pattern scenarios (described in section 3.2). Note that we do not evaluate the worst-case situation in which PHEVs inevitably charge during the peak electric load. Because PHEVs represent new demand in the electric power system, this peak-charging case would obviously result in higher peak loads and would quickly create a need for more generation and transmission capacity. The charging pattern scenarios described below seem more likely than inevitable on-peak charging because they match typical commute patterns. However, PHEVs are not yet available so we do not know how consumers will behave if they obtain PHEVs. For consistency, we use system load data for 1999, but repeating the analysis with 2005 CAISO load data does not substantially change the results. In 1999, CAISO peak load was 35 GW, and in 2005, CAISO peak load was 45 GW.

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 five or more years to plan, finance, construct, and commission new electricity generation, so we use twice this period, or 10 years, as a rough definition of the near term. 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), that vehicles are retired after 15 years, that 1.8 million new vehicles are sold in California each year, and that the CAISO contains 75% of the state's vehicle fleet. The first case assumes that all HEV sales in California become PHEV sales from MY 2008 on and that these sales increase by 20% per year, the rate of growth forecast for HEVs (J D Power and Associates 2006). Because the adoption pathways of new technologies often follow S-shaped logistic growth curves (Geroski 2000), the second and third cases apply logistic growth curves to PHEV sales: the second models an aggressive 25 year transition to 100% market share for PHEVs, and the third models an extreme transition to 100% PHEV market share in 12 years, or about two product

Table 2. Pacific Gas and Electric Company May 2006 residential electricity tariffs and equivalent gasoline prices for PHEVs.

Standard residential tariff	Electricity rate ($/kWh)	Equivalent gasoline price ($/gal)[a]		
Baseline usage[b]	$0.11430	$1.50		
101%–130% of baseline	$0.12989	$1.71		
131%–200% of baseline	$0.21981	$2.89		
201%–300% of baseline	$0.30292	$3.98		
Over 300% of baseline	$0.34648	$4.55		
	Peak[c]		Off-peak[c]	
Electric vehicle summer tariff	Electricity rate ($/kWh)	Equivalent gasoline price ($/gal)[a]	Electricity rate ($/kWh)	Equivalent gasoline price ($/gal)[a]
Baseline usage[b]	$0.28368	$3.73	$0.04965	$0.65
101%–130% of baseline	$0.28368	$3.73	$0.04965	$0.65
131%–200% of baseline	$0.38323	$5.04	$0.14920	$1.96
201%–300% of baseline	$0.47525	$6.25	$0.24122	$3.17
Over 300% of baseline	$0.52348	$6.88	$0.28945	$3.80

[a] The gasoline prices yield the same cost per mile of PHEV operation as do the electricity rates. PHEV efficiency is 52.7 miles/gallon and 4.010 miles/kWh (EPRI 2002).
[b] Baseline allowances range from 8–19 kWh per day, depending upon climatic zone and time of year, and they may be even higher for households with electric heating.
[c] The summer peak hours are from 2 to 9 PM on weekdays, the summer off-peak hours occur during non-evening weekend hours and during the night and early morning on weekdays, and the part-peak hours occur in the remaining hours and have rates similar to the standard tariff rates. Customers may opt for slightly lower peak rates and slightly higher off-peak rates if they have a separately metered EV battery charger.

cycles. We compare the predicted PHEV fleet sizes from these cases with the results of the grid impact analyses. These three cases probably overestimate PHEV adoption and so provide upper bounds for possible residential PHEV charging in the near term.

The final step in our analysis is to calculate the present value of fuel savings due to PHEV use as well as the implied break-even battery cost, which is the fuel savings divided by the additional battery kWh required for the vehicle. If vehicle buyers are willing to spend no more than their expected fuel savings on the extra vehicle cost of a PHEV, and if the battery cost represents the entire marginal vehicle cost, then the break-even battery cost is that which would make cost-conscious consumers indifferent between purchasing a PHEV and purchasing a comparable HEV or CV. However, PHEVs will likely include additional components that could contribute to marginal vehicle cost, which makes these results more like an upper bound for break-even battery costs with vehicle efficiencies as in EPRI (2002). Since no PHEVs have been mass-produced, we do not know how much of the marginal vehicle cost would be due to batteries. While other factors such as aesthetics, symbolism, manufacturer reputation, environmental benefits, and independence from oil consumption may be important in consumer choice of vehicles, we ignore them in this analysis. As discussed below, we assume that fuel prices are constant over the lifetime of the vehicle and are known with certainty at the time of purchase.

3. Results

3.1. To charge or to pump?

Tables 1 and 2 show that PG&E electricity customers paying the standard baseline rate would be indifferent (on a pure energetic basis) between using gasoline and electricity if gasoline prices were $1.50/gallon. Higher gasoline prices would lead them to drive as many of their miles in all-electric mode as possible, and lower gasoline prices would lead them to always drive in gasoline-fueled hybrid electric mode. Consumers would never want to recharge during peak EV electricity rates unless gasoline cost more than $3.73/gallon, and consumers would always want to recharge at off-peak EV electricity rates unless gasoline prices fell below $2.00/gallon or they were using more than 200% of their baseline electricity allowance.

Figure 1 shows the relationship between electricity supply for PHEVs and wholesale electricity prices in the two peak hours and the two off-peak hours. As expected, each of the four residual supply curves is flat at low levels of supply and becomes steeper with greater levels of supply. The gasoline price lines 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.

If gasoline cost $3.00/gallon, then even with real-time electricity pricing it would be economical to charge over 6 million PHEVs during each of the off-peak hours and over 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 vehicles could be PHEVs charging from the grid with 1999 electricity supply and

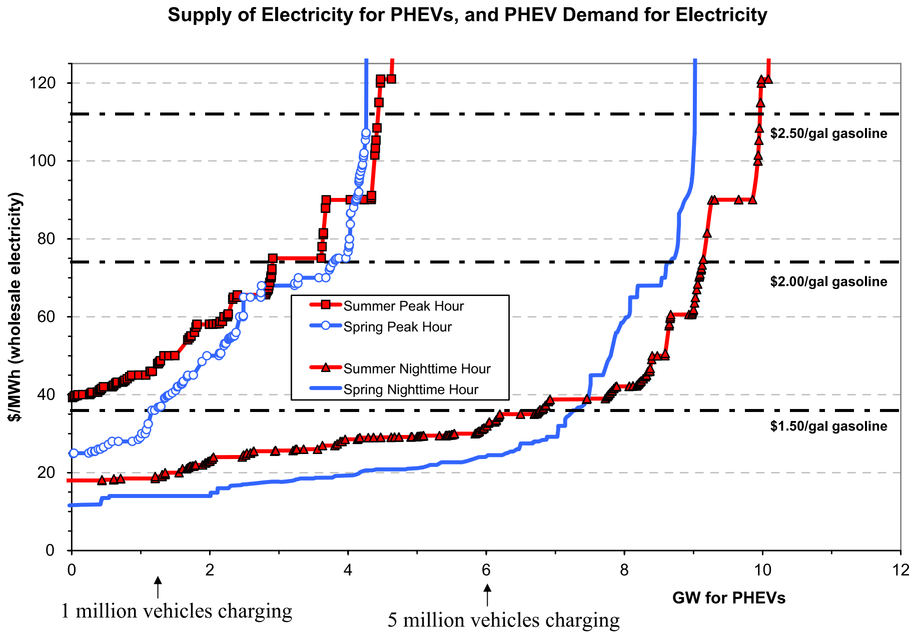

Figure 1. The quantity of electricity beyond observed demand available at each price, as determined by the supply bids given to the California Power Exchange in 1999. Also, the number of PHEVs that would need to charge during the hour to use that much electricity with a charge rate of 1 kWh/h (or a charger size of 1.2 kW). The gasoline price lines provide the same cost per mile as the retail electricity rates that correspond to the marked wholesale prices. The gasoline price lines can be read as the PHEV demand for electricity with a given price of gasoline, assuming that gasoline and grid-supplied electricity are perfect substitutes, that consumers see real-time electricity prices with constant non-generation costs of $0.07816 per kWh (Pacific Gas and Electric Company 2006), and that vehicle efficiencies are as in table 1. Households in the CAISO region own approximately 17 million vehicles (US Department of Transportation 2001).

demand conditions and recent gasoline prices (US Department of Transportation 2001).

Using efficiencies for full-size SUVs instead of compact cars leads to similar results for tables 1 and 2 because the ratio of energy efficiency in all-electric mode to energy efficiency in hybrid electric mode is similar for both vehicle classes (EPRI 2002). Because we assume SUV PHEVs charge at the same rate as compact car PHEVs, the results associated with the demand curves in figure 1 are identical for both vehicle types.

One cautionary note about the potential of real-time electricity pricing to lead to socially efficient PHEV charging outcomes is that gasoline taxes in the US currently adjust not only for gasoline-specific externalities but also for road maintenance. The electric power system may not discriminate between PHEV load and other load to apply this charge, even as PHEVs' lower fuel cost of driving would encourage more vehicle use. Table 3 shows the equivalent tax rates for the different vehicle types based on cost per mile of operation. In 2006, California state and federal gasoline taxes totaled $0.364/gallon (California State Board of Equalization 2006). PHEVs would require taxes of $0.51/gallon and $0.04/kWh in order to recover the tax revenue provided by a CV. If these taxes are not applied, PHEV all-electric operation would appear artificially cheaper, and owners of other vehicle types would bear more of the burden of road maintenance.

Table 3. Gasoline tax rates for CVs and equivalent tax rates for HEVs and PHEVs.

Gasoline tax for CV[a]	Equivalent HEV tax[b]	Equivalent PHEV tax[b]	
($/gal)	($/gal)	($/gal)	($/kWh)
$0.10	$0.13	$0.14	$0.011
$0.30	$0.39	$0.42	$0.032
$0.50	$0.66	$0.70	$0.053

[a] In 2006, the US federal gasoline tax was $0.184/gallon, the California state gasoline tax was $0.18/gallon, and the California state underground storage tank fee was $0.014/gallon (California State Board of Equalization 2006). Sales tax rates vary by city and county.

[b] Tax rates are equivalent if they yield the same cost per mile of vehicle operation. PHEV efficiency is 52.7 miles/gallon and 4.010 miles/kWh, HEV efficiency is 49.4 miles/gallon, and CV efficiency is 37.7 miles/gallon (EPRI 2002).

3.2. 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 exploring the implications of PHEVs for the electricity system's load characteristics. We are interested in the charging patterns and fleet sizes that increase the 1999 CAISO system peak load of 35 GW, which occurred at 4 PM on August 26. For illustration and compatibility with the real-time pricing results, figure 2 shows the daily load curve for 3 August 1999 with 1, 5, and 10 million PHEVs charging according to the three scenarios described below. We assume in the first two scenarios that each PHEV fully charges once each day and we assume in the third scenario that each PHEV fully charges twice each day, which means that each vehicle drives 20 all-electric miles per day in the first two scenarios and 40 all-electric miles per day in the third. Each PHEV draws 1.2 kWh

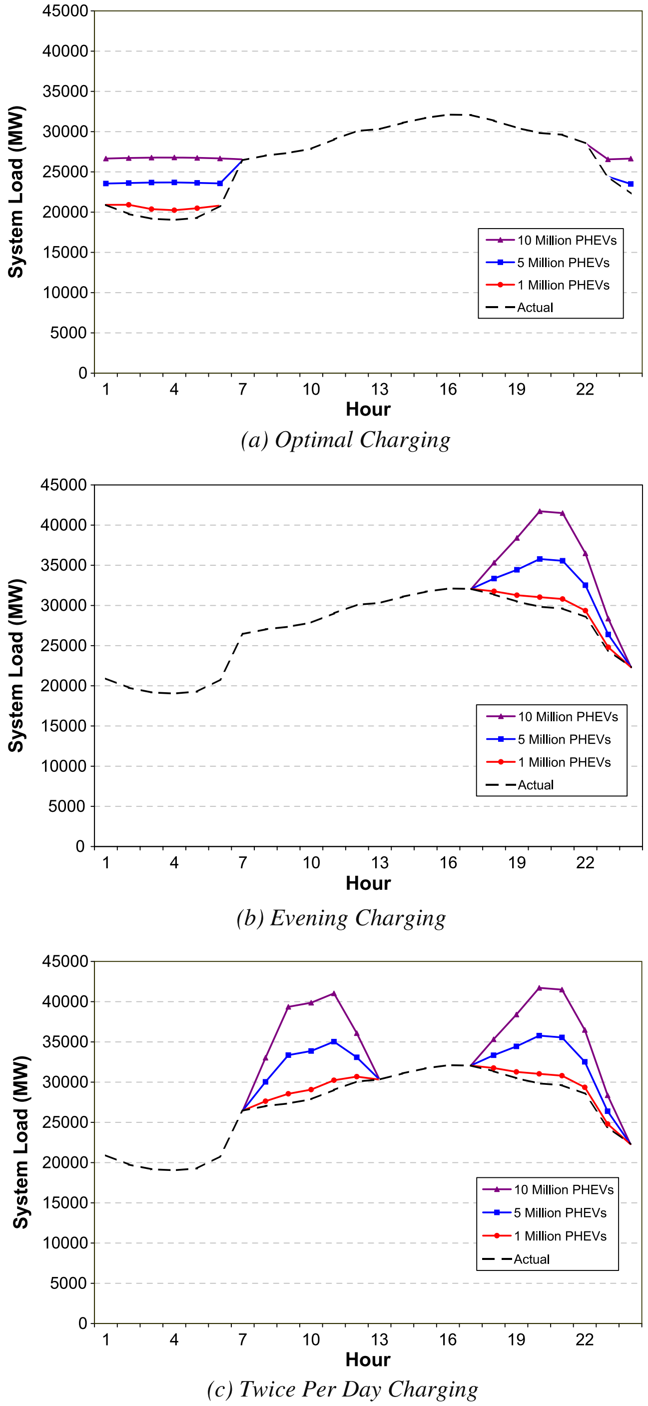

Figure 2. The 1999 CAISO system daily load curve for 3 August 1999 with three compact car PHEV fleet sizes. (*a*) shows the daily load curve with optimal charging, (*b*) shows the daily load curve with evening charging, and (*c*) shows the daily load curve with twice per day charging. Compact car PHEVs charge at a rate of 1 kWh/h and require 4.1 kWh to recharge their batteries (EPRI 2002).

of grid electricity per hour of charging. Charger sizes greater than 1.2 kW would increase the grid impact of a fleet of PHEVs when they are charging but may also avoid some significant grid impacts by allowing the vehicles to fully charge in fewer hours.

The first scenario, called *Optimal Charging*, perfectly allocates each day's PHEV charging to flatten the system load

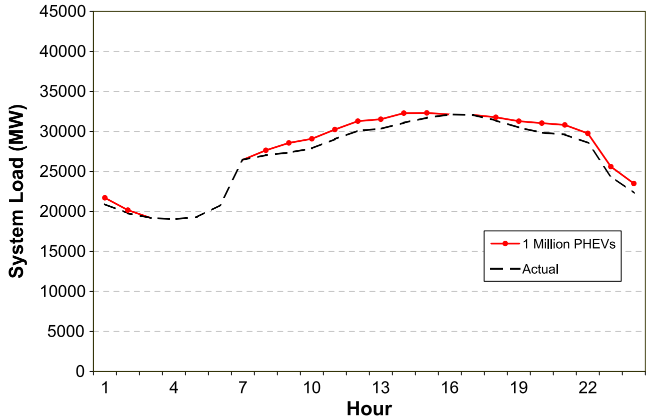

Figure 3. The 1999 CAISO system daily load curve for 3 August 1999 with a fleet of 1 million full-size sport utility vehicle (SUV) PHEVs in the *Twice Per Day Charging* scenario. SUV PHEVs charge at a rate of 1 kWh/h and require 7.1 kWh to recharge their batteries (EPRI 2002).

curve as much as possible. The vehicles charge during periods of lowest demand and need not charge continuously. This scenario bounds the possible beneficial load-leveling effects of PHEVs and would require technologies to monitor and control charging. The daily load curve in figure 2(*a*) shows that, with these assumptions, PHEV demand is typically confined to the nighttime hours. In this best case, generators that currently shut off at night could pick up PHEV demand, and PHEVs would not require additional generation, transmission, or distribution capacity.

In the *Evening Charging* scenario, PHEVs begin charging when their drivers return home from work between 6 and 8 PM (figure 2(*b*)). Each PHEV charges for 4 continuous hours. This and the next scenario are meant to provide examples of possible behavior that matches commute patterns and the use of simple chargers in the absence of price incentives. 1 million PHEVs have little effect on system load curves as they only raise the late evening load a bit, which is not a significant outcome because sufficient capacity already exists to meet this additional load. However, 5 million PHEVs do call for more capacity since the year's peak load grows by 4 GW, or 12%. The peak also now occurs later in the day. At 10 million PHEVs, the year's peak load grows by 10 GW, or 29%. However, PHEVs would account for over half of all vehicles in use in this case, a possibility that is many years away.

The *Twice Per Day Charging* scenario has those same evening-charging cars plugging in again in the morning when their owners arrive at work between 8 and 9 AM with drained batteries (figure 2(*c*)). This is a high demand scenario: we assume that each PHEV is plugged in to charge fully at the end of each commute leg. 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 compact cars still do not affect the year's peak system load.

This analysis suggests that, as long as on-peak charging is avoided, PHEV fleets in the CAISO region may be able to reach 1 million vehicles before new generation or transmission

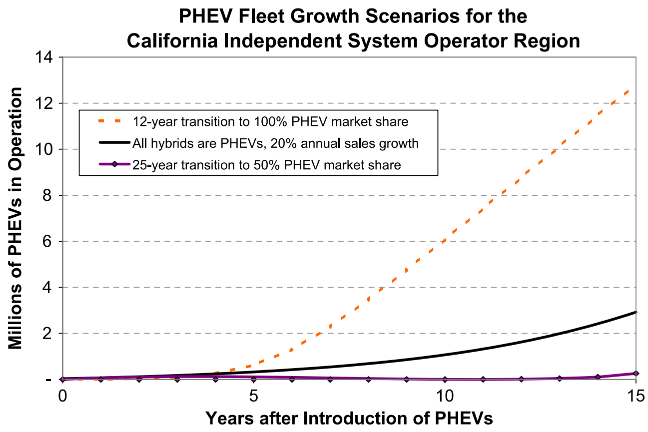

Figure 4. Three simple forecasts of the number of PHEVs operating in the CAISO region showing that obtaining a fleet size of 1 million PHEVs within 10 years may require extreme growth scenarios. One forecast assumes that all hybrid vehicles sold after model year 2007 are PHEVs and that state sales of 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 (US Department of Transportation 2001).

investments are needed. However, if PHEV fleets grow to several million vehicles and charging is not optimally timed, new investments would be required. The implications for other electricity systems depend upon the timing of their hours of peak load relative to the timing of probable PHEV charging.

Because the SUV PHEVs use the same chargers but have longer charging times, they will pose problems for the grid in any charging and fleet size scenario in which compact cars pose problems. However, it may be that SUVs raise the peak system load in scenarios in which compact cars do not. We check the robustness of our finding of insignificant grid impacts for fleet sizes of 1 million compact cars by running the worst-case charging pattern scenario with 1 million SUV PHEVs and their 7 hour charging times. We use the *Twice Per Day Charging* scenario because that one is the most likely to be affected by 7 hour charging times. Indeed, the longer charging times have a significant impact, as 1 million SUVs raise the year's peak load by 0.8 GW (or 2%) and so could require new capacity. As can be seen in the daily load curve in figure 3, the new peak load (like the old one) occurs on a summer afternoon because the longer charging times mean that some morning-charging PHEVs will still be drawing power in the afternoon.

3.3. PHEV fleet size

A fleet of PHEV compact cars with 20 mile all-electric ranges only poses problems for the electric grid when it reaches into the millions of vehicles. Might there be a fleet of millions of PHEVs in a time span shorter than that of the long-run grid planning horizon of about 10 years? If so, then the supply of electricity may not have time to adequately adapt and account for the new demand. We answer this question by assessing the assumptions needed to obtain such fleet numbers. Figure 4 shows three scenarios for the growth of the PHEV fleet (described in section 2). Only in the most extreme scenario with 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. The other two scenarios achieve fewer than 0.5 million PHEVs within ten years, and even these are probably overestimates. Obtaining a fleet of millions of PHEVs within 10 years would probably require strong pro-PHEV policies or substantial fuel savings from all-electric operation.

3.4. Present value analysis

While it appears to be economical for PHEVs to run in all-electric mode, would consumers purchase PHEVs with current and expected fuel prices? Many factors affect consumer choices about vehicles, and PHEVs may have desirable attributes other than fuel savings that are excluded from this analysis (Heffner *et al* 2007), but promised fuel savings may be important in achieving large numbers of sales. Table 4 explores the price conditions under which the decision to purchase a PHEV may be economical. With gasoline prices of \$3/gallon and electricity prices of \$0.10/kWh, compact car PHEVs with a 20 mile all-electric range may save \$409 annually relative to a CV and \$202 annually relative to an HEV, which the vehicle purchaser may value at \$2126 and \$1048 respectively. Individual packages to convert HEVs to PHEVs are currently offered at \$5000 to \$10 000, although it is not clear how many (or if any) such packages have been purchased to date. The incremental cost of PHEVs produced by the original manufacturer should be lower with economies of scale and technological innovation, but the cost of additional electronics and battery capacity will still create a premium. Considering vehicle purchase and fuel costs only, consumers may require battery prices below \$400/kWh if they are to purchase compact car PHEVs instead of HEVs. Current battery prices for PHEV applications are difficult to determine reliably, but they are expected to be over \$600 per kWh for a 5.1 kWh battery even after substantial mass production (Kalhammer *et al* 2007, table 3-13). Because battery costs increase less than linearly with battery size, larger batteries would have a lower cost per kWh, but fuel savings may also scale less than linearly with battery size: the cost-effectiveness of larger batteries depends upon driving habits since greater all-electric ranges make it more likely that many PHEV owners will not drive enough to use their entire all-electric range each day. The break-even battery costs for full-size SUV PHEVs with efficiencies as in EPRI (2002) are generally about 1.5 times the values for compact car PHEVs, suggesting that SUV PHEVs may become economical first. This effect occurs because the SUV PHEVs' all-electric operation saves more gallons of gasoline per mile driven.

4. Discussion

Because well over 1 million PHEVs could economically charge in California even during peak hours with real-time electricity pricing, PHEVs could allow electricity sector climate policies to affect transportation sector greenhouse gas emissions. However, current battery costs probably make

Table 4. Annual and present value of PHEV fuel savings and break-even PHEV battery costs relative to comparable hybrid electric vehicles (HEVs) and to comparable conventional vehicles (CVs).

Annual fuel savings from PHEVs[a]						
	Gasoline price ($/gal)					
	$2		$3		$4	
Electricity price ($/kWh)	HEV	CV	HEV	CV	HEV	CV
$0.05	$155	$294	$264	$471	$373	$649
$0.10	$93	$231	$202	$409	$311	$587
$0.15	$31	$169	$139	$347	$248	$525
$0.20	−$32	$106	$77	$284	$186	$462
$0.25	−$94	$44	$15	$222	$124	$400
$0.30	−$156	−$18	−$48	$160	$61	$338
Present value of fuel savings from PHEVs	16% discount rate over 12 years[b]					
	Gasoline price ($/gal)					
	$2		$3		$4	
Electricity price ($/kWh)	HEV	CV	HEV	CV	HEV	CV
$0.05	$807	$1525	$1372	$2450	$1938	$3375
$0.10	$483	$1201	$1048	$2126	$1614	$3051
$0.15	$159	$877	$724	$1802	$1290	$2727
$0.20	−$165	$553	$400	$1478	$966	$2403
$0.25	−$489	$229	$77	$1154	$642	$2079
$0.30	−$813	−$95	−$247	$830	$318	$1755
Break-even PHEV battery cost ($/**kWh**)[c]	16% discount rate over 12 years[b]					
	Gasoline price ($/gal)					
	$2		$3		$4	
Electricity price ($/kWh)	HEV	CV	HEV	CV	HEV	CV
$0.05	$277	$298	$472	$479	$666	$660
$0.10	$166	$235	$360	$416	$555	$597
$0.15	$55	$172	$249	$353	$443	$534
$0.20	−$57	$108	$138	$289	$332	$470
$0.25	−$168	$45	$26	$226	$221	$407
$0.30	−$279	−$19	−$85	$162	$109	$343

[a] PHEV efficiency is 52.7 miles/gallon and 4.010 miles/kWh, HEV efficiency is 49.4 miles/gallon, and CV efficiency is 37.7 miles/gallon (EPRI 2002). Each vehicle travels 11 000 miles per year (US Department of Transportation 2001). PHEVs drive 20 all-electric miles during each of the 250 workdays in the year; the rest of their miles are gasoline-fueled.

[b] The 16% discount rate corrects for vehicle depreciation and declining vehicle usage over a 12 year vehicle lifetime and is based on an interest rate of 6% (Greene and DeCicco 2000).

[c] Accounting for an 80% depth-of-discharge limitation, the HEV battery pack size is 2.2 kWh and the PHEV battery pack size is 5.1 kWh (EPRI 2002). We take the additional battery cost to represent the entire marginal vehicle cost, we do not include battery replacement, we treat future fuel prices as constant and certain, and we assume that the purchase of a PHEV does not change the cost of other household electricity consumption.

PHEVs uneconomical with 20 mile all-electric ranges because the fuel savings do not pay back the vehicle price premium. Even with gasoline dear at $4.00/gallon and electricity cheap at $0.05/kWh, vehicle purchasers may only find a compact car PHEV economical if its cost premium relative to an ordinary hybrid vehicle were under $2000 and if its cost premium relative to a conventional vehicle were under $3500. Such price premiums may require battery pack costs (including electronics, etc) under $650/kWh, while current battery pack prices for PHEV applications may well be in excess of $1000/kWh.

All these calculations ignore other factors that influence vehicle purchase decisions. We believe PHEVs can be introduced successfully into the market because these non-financial factors are very important, including the symbolism of using a green vehicle and of promoting independence from oil consumption. However, with current technologies and policies, PHEVs are only likely to occupy a small niche of vehicle sales. For the large volume sales needed to make PHEVs significant in California energy and environmental markets, technological, financial, and/or policy innovation must lower the cost premium incurred by their larger batteries.

Two other considerations could make it even harder for PHEVs to compete in the marketplace. First, our analysis assumes that battery packs last the lifetime of the vehicle. If batteries need to be replaced, PHEVs would require still cheaper batteries or alternative business models. Second, since buying the more expensive PHEV is a partially irreversible investment in efficiency technology and since fuel prices over the lifetime of a vehicle are uncertain, an option value premium would further lower the acceptable cost difference between a PHEV and other types of vehicles, also suggesting a need for still cheaper batteries (Dixit and Pindyck 1994). The more volatile are fuel prices, the greater will be the value of delaying this investment to obtain more information about future fuel prices. (On the other hand, this same volatility could provide a hedging value if PHEVs help drivers avoid gasoline price spikes.) Therefore, assuming that efficiencies are close to those reported in EPRI (2002) and barring policies that provide substantial incentives for PHEV ownership, we find it unlikely that current economic incentives would lead enough consumers to buy PHEVs to create the need for expanded electricity generation or transmission capacity in the CAISO region in the near term (i.e., within a decade).

However, there are some conditions under which residential PHEVs could affect peak grid capacity. First, any on-peak charging would add to currently forecasted peak loads. Second, if the adoption pathway for PHEVs does prove to be logistic, then long-run electric power planning could still fail to correctly account for future numbers of PHEVs because the middle portions of logistic curves can be quite steep. This is true even if widespread adoption takes decades. Third, if PHEV adoption becomes concentrated in specific markets, even low aggregate fleet sizes could stretch local transmission and distribution 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 it may be insufficient: figure 1 shows that millions of consumers with real-time pricing in 1999 may have chosen to charge even during peak hours. If the government or utilities deem such peak-hour charging undesirable, then they would need to implement new pricing structures or technical means to coordinate PHEV charging and electric power system operation. For example, utilities might offer time- and use-differentiated rates, home PHEV chargers might have timers or could be wired to supply power only during certain times determined by the utility, or charging could be controlled by a sophisticated meter and control unit onboard the vehicle. The current EV tariffs are a step in the first direction, but it remains to be seen how consistently they would be applied. Finally, many vehicle owners do not own a garage with their own outlet. These owners may require access to dedicated charging infrastructure before they purchase PHEVs, and their charging patterns could adversely affect the electric grid if dedicated charging infrastructure is most accessible during the workday.

In the absence of special PHEV pricing structures or charging interfaces, subsidizing PHEVs could raise the system peak since peak-hour charging would likely be economical for PHEV owners. The extent to which PHEVs would raise the system peak depends upon the timing of the system peak and the as-yet-unknown charging behavior of PHEV owners. Crucially, we do not yet know how vehicle choice, fuel pricing, and the choice of fuels for multi-fuel vehicles interact. An important research program would be to investigate how consumers who buy PHEVs tend to operate them so that effective technologies and fair, efficient tariffs for charging can be devised, tested, and implemented in time for possible large-scale PHEV deployment.

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