Transportation Research Part D 15 (2010) 212–219

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Anticipating plug-in hybrid vehicle energy impacts in California: Constructing consumer-informed recharge profiles

Jonn Axsen *, Kenneth S. Kurani

Institute of Transportation Studies, University of California at Davis, 2028 Academic Surge, One Shields Avenue, Davis, CA 95616, USA

ARTICLE INFO

Keywords:
Plug-in hybrid vehicles
Energy
Electricity demand

ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) can be powered by gasoline, grid electricity, or both. To explore potential PHEV energy impacts, a three-part survey instrument collected data from new vehicle buyers in California. We combine the available information to estimate the electricity and gasoline use under three recharging scenarios. Results suggest that the use of PHEV vehicles could halve gasoline use relative to conventional vehicles. Using three scenarios to represent plausible conditions on PHEV drivers' recharge patterns (immediate and unconstrained, universal workplace access, and off-peak only), tradeoffs are described between the magnitude and timing of PHEV electricity use. PHEV electricity use could be increased through policies supporting non-home recharge opportunities, but this increase occurs during daytime hours and could contribute to peak electricity demand. Deferring all recharging to off-peak hours could eliminate all additions to daytime electricity demand from PHEVs, although less electricity is used and less gasoline displaced.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) can be powered by gasoline, electricity from the power grid, or both. A PHEV can be driven in one of two modes, defined by the net effect on the battery's state of charge: charge depleting (CD) or charge sustaining (CS). During the former, the vehicle is powered either by electricity only (all-electric operation) or by electricity and gasoline (blended operation). Once the battery is depleted to a minimum state of charge, the PHEV uses only gasoline energy in CS mode, achieving gasoline-only fuel economy typical of today's hybrid electric vehicles. A PHEV's use of gasoline and electricity depends on the interaction between: the type of PHEV (e.g., battery size and drivetrain design), driving patterns (e.g., how far and how fast), and recharge behavior (e.g., when and how long). This complexity creates inherent uncertainty for policymakers, automakers, electric utilities, and others interested in the energy, environmental and societal impacts of PHEV technology. Despite the inherent effect of consumer behavior on the energy and environmental potential of PHEVs, prior studies of PHEV energy impacts have at best assumed consumer behavior by relying on over-simplified assumptions (Duvall et al., 2007; Samaras and Meisterling, 2008).

We focus on the energy impacts that can be anticipated with significant PHEV market penetration if we add information from consumers. We do this by examining recharge scenarios based on data collected through a web-based survey of new vehicle buying households.

* Corresponding author. Tel.: +1 530 574 2150.
E-mail address: jaxsen@ucdavis.edu (J. Axsen).

1361-9209/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.trd.2010.02.004

2. Methodology

2.1. Survey design

Consumer data was collected using a multi-part online survey (Axsen and Kurani, 2009). Driving patterns and recharge potential were elicited using a plug-in potential diary of driving and parking for a vehicle purchased new (model year 2002 or later) that is driven several times per week by the respondent's household. Respondents were assigned a day of the week and instructed to record information for a 24-h period starting with their first trip of that day. Information includes the timing and distance of each trip, parking locations, and the proximity of those locations to an electrical outlet. Respondents recorded data in a diary printed from a PDF document and then inputted their data online. The respondent's diary was immediately depicted to them as a graph, using a technique similar to that used by Kurani et al. (1994) to help respondents better understand their own driving behavior, and how an electric-drive vehicle could fit into their lifestyle.

The PHEV design priority data used in this analysis were collected with design games. Commonly, researchers will infer preferences for attributes of alternative fuelled vehicles by presenting respondents with a description of one or several new technologies, followed with a set of hypothetical choice scenarios in which respondents make several choices from sets of vehicles of different attributes (Bunch et al., 1993; Potoglou and Kanaroglou, 2007). However, such methods may not capture the complexity of vehicle purchase behavior, particularly regarding unfamiliar vehicle technologies. Constructive design processes, such as the design games used in this study, are consistent with theories of constructed preferences that view consumer preferences as outcomes of, not inputs to, decision contexts and processes (Bettman et al., 1998). To improve the quality of data gathered through the online survey, prior to the PHEV design exercises, respondents were provided two types of preparatory information: the 24-h diary exercise described above, and a PHEV buyers' guide describing basic design options for PHEVs. Respondents then completed a purchase design game with design possibilities priced in dollars; respondents could reject buying a PHEV and retain a conventional vehicle.

The dimensions of the PHEV design space and the specific attribute levels within that space that were offered to respondents were informed by previous analysis of early PHEV drivers (Heffner et al., 2009). There were four PHEV design attributes respondents could manipulate: hours required for complete recharge of a depleted battery, gasoline use in charge-depleting (CD) mode, miles of range in CD mode, and gasoline use in CS mode. In each game, a base PHEV design was offered with capabilities easily achievable by current technology: a PHEV that requires up to 8 h to completely recharge, that can be driven for the first 10 miles in CD mode using blended operation that increases gasoline-only fuel economy to 75 mpg, and that can improve fuel economy by 10 mpg when operating in CS mode over a conventional, i.e., gasoline-ICE, version of the same vehicle.

Respondents were given opportunities to improve each attribute under the different price conditions depicted in Table 1. The PHEV design exercise was framed in the context of the household's next new vehicle purchase. The questionnaire first elicited information about the anticipated price, make and model of the next new vehicle the respondent's household would buy. The respondent then completed two PHEV purchase exercises, each comparing their anticipated conventional vehicle with a PHEV version of the same. Respondents were presented with "higher" price and "lower" price PHEV purchase conditions, where prices in both conditions also depended on whether the vehicle was a car or truck. Each exercise started with the same base PHEV model, with additional upgrades available for added price. In each exercise, the respondent could opt to

Table 1
Price of upgrades for purchase design game (prices incremental to conventional vehicle).

Attributes	Attribute level	"Higher" price		"Lower" price	
		Car	Truck	Car	Truck
Base premium over conventional vehicle		\$3000	\$4000	\$2000	\$3000
Added premiums					
Recharge time	8 h	0	0	0	0
	4 h	+\$500	+\$1000	+\$250	+\$500
	2 h	+\$1000	+\$2000	+\$500	+\$1000
	1 h	+\$1500	+\$3000	+\$750	+\$1500
CD MPG and type	Blended				
	75 MPG	0	0	0	0
	100 MPG	+\$1000	+\$2000	+\$500	+\$1000
	125 MPG	+\$2000	+\$4000	+\$1000	+\$2000
	All-electric	+\$4000	+\$8000	+\$2000	+\$4000
CD range	10 miles	0	0	0	0
	20 miles	+\$2000	+\$4000	+\$1000	+\$2000
	40 miles	+\$4000	+\$8000	+\$2000	+\$4000
CS mpg	Conventional MPG +10	0	0	0	0
	Conventional MPG +20	+\$500	+\$1000	+\$250	+\$500
	Conventional MPG +30	+\$1000	+\$2000	+\$500	+\$1000

Note: To ease comparison with other work, fuel use is reported in miles per gallon.

purchase their anticipated conventional vehicle, the offered (base) PHEV version, or an upgraded PHEV version. The prices in Table 1 are largely hypothetical, where ''higher'' and ''lower'' scenarios cover a range of conditions comparable to previous near-term and later-term price estimates (Kalhammer et al., 2007; Kromer and Heywood, 2007; Markel et al., 2006).

2.2. Data collection

The target population is new vehicle buying households in California. To qualify, respondents had to own a gasoline vehicle that they purchased new in 2002 or later, which they personally drove at least three times per week. The respondent also must report that they played a significant role in the household's decision to purchase this vehicle. We rely on the respondents to interpret ''significant role'' and ask that when completing the questionnaires they consult other household members just as they may for an actual vehicle purchase. By limiting our sample to new car buyers, the portion of the early market for PHEVs examined here is thus limited to households that tend to buy new vehicles. Eight hundred and seventy-seven respondents completed the survey in December, 2007.

The survey was web-based. Relative to mail and telephone methods, this mode is thought to improve design flexibility, response interaction, response accuracy for travel diaries, and data administration time and cost. In recent years, web-based surveys were susceptible to non-coverage error where a significant portion of the target population, in this case new car buyers, could be excluded if they did not have Internet access. This concern is declining in the US as internet usage has grown from 44% in 2000 to over 70% in 2007 (IWS, Internet World Stats, 2007). Also, we suspect there is a positive correlation between Internet access and likeliness to buy new vehicles, implying an even higher usage rate among the target population. Non-response bias, however, is still an important concern because those without Internet access tend to be disproportionally older, with lower incomes and less education.

Respondents were recruited by Harris Interactive from their internet panel. To counteract concerns of non-coverage and non-response error, Harris estimated weights to better match the realized sample to the target population. Weights are based on geographic, demographic and attitudinal data, and matched to existing databases collected through multiple survey modes (including mail and telephone). All results use these weights to match the sample to the California population of new vehicle buyers.

To assess the external validity of the sample, we compare the sample distributions with a sub-sample of 389 California households owning new vehicles drawn from the 2001 National Household Travel Survey (NHTS). We find that the income levels of both samples are about 40% higher than general population estimates from similar years. Also, gender and age follow similar distributions between the two samples of new vehicle buying households. Our sample does have fewer households without any college level education (8.8%) relative to the NHTS sample (22.1%), and fewer households living in detached homes (68.1%) than the NHTS sample (79.4%). Overall, we feel these differences are not likely to be problematic. We conclude that the sample matches well with one other sample of new car owners on these socio-demographic measures, strengthening claims that our results can be extended to the California population of new-car owning, and therefore, new car-buying, households.

2.3. Constructing energy-use profiles

Potential time of day demand for electricity (recharge profiles) and gasoline for our respondents are calculated in a spreadsheet model. First, a portion of the entire sample is identified as the plausible early market for PHEV adoption, based on recharge access and demonstrated interest in purchasing some variety of PHEV. Each respondent's use of a PHEV is modeled as if they drive the PHEV they designed during their elicited driving diary day. Their 24-h day is broken into 15-min intervals. For each interval the respondent is modeled as either: driving in CD mode (blended or all-electric), driving in CS mode, parked and recharging, or parked and not recharging. From this model, time of day gasoline use is estimated as the sum of gasoline use rates (gallons per minute) across respondents for a given interval. Similarly, time of day electricity use is estimated as the sum of electricity use rates (kW) across respondents for a given time interval.

The construction of these energy-use profiles relies on the following assumptions:

- All respondents have access to recharging at home.
- Gasoline use is modeled using the estimated miles per gallon reported for their anticipated next vehicle, without accounting for potential variation in driving patterns. In other words, if the respondent reports their vehicle as being rated at 20 mpg, we assume a constant rate for each mile driven during their diary day (neglecting potential for different drive patterns over a given trip, across trips or across drivers).
- For CD operation, electricity use (kWh/mile) and available battery energy capacity (kWh) is estimated as in Table 2, based on previous estimates (Axsen et al., 2010).
- Each vehicle's assumed battery state of charge at the beginning of the day is a function of the distance driven the previous day (assumed to be the same as the diary day due to lack of multi-day data) and the respondent's estimated hours of recharge potential from the previous day (elicited elsewhere on the survey).
- Each vehicle drives using CD operation while the (available) state of charge is greater than zero, and drives using CS operation when the state of charge is zero. The battery state of charge is assumed to deplete at the rate given in the CD electricity use values (0.12–0.38 kWh/mile) portrayed in Table 2.

Table 2
Assumed energy requirements of PHEV designs.

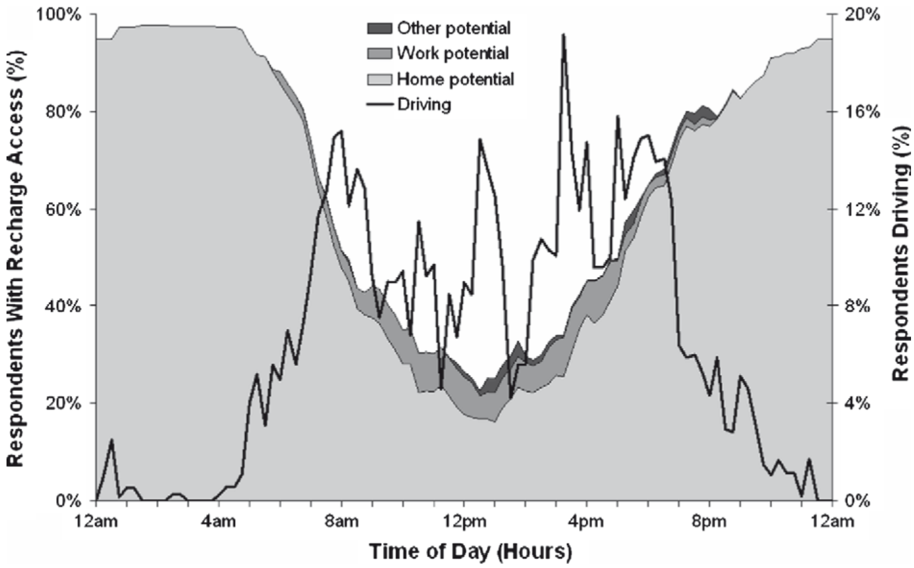
CD mpg		Car	Truck
75 MPG	CD electricity use	0.12 kWh/mile	0.15 kWh/mile
	10 mile capacity	1.2 kWh	1.5 kWh
	20 mile capacity	2.3 kWh	3.0 kWh
	40 mile capacity	4.6 kWh	5.9 kWh
100 MPG	CD electricity use	0.14 kWh/mile	0.17 kWh/mile
	10 mile capacity	1.4 kWh	1.7 kWh
	20 mile capacity	2.7 kWh	3.5 kWh
	40 mile capacity	8.0 kWh	7.0 kWh
125 MPG	CD electricity use	0.18 kWh/mile	0.23 kWh/mile
	10 mile capacity	1.8 kWh	2.3 kWh
	20 mile capacity	3.6 kWh	4.7 kWh
	40 mile capacity	7.3 kWh	9.3 kWh
All-electric	CD electricity use	0.30 kWh/mile	0.38 kWh/mile
	10 mile capacity	3.0 kWh	3.8 kWh
	20 mile capacity	6.0 kWh	7.7 kWh
	40 mile capacity	12.0 kWh	15.4 kWh

Source: Axsen, et al. (2010)

- The minimum recharge rate for a PHEV battery using a regular 110–120 V outlet is 1 kWh per hour (delivered to the battery). If the respondent's PHEV design has a recharge rate faster than that required for their battery size, we apply the shorter of the two recharge times. For example, if the respondent selected a PHEV requiring 8 h for complete recharge, yet their battery size is only 1.2 kWh (requiring a maximum of 1.2 h for full recharge), the 1.2 h time is applied. In contrast, if the same respondent selected a recharge time of 1 h, we apply the 1-h time.
- Following Lemoine et al.'s (2008) assumptions, vehicle recharging is approximately 83% efficient—increasing the battery's state of charge by 1 kWh requires 1.2 kWh from the electrical outlet.
- Each scenario is scaled up to represent 1 million vehicles. This value is not selected in anticipation of a particular sales volume for a particular year, but instead is a relatively feasible market size that serves to normalize energy use to allow comparisons across scenarios. (An alternative approach would be to estimate the effect of each recharge scenario on the size of the potential PHEV market, such as the addition of potential PHEV buyers resulting from the expansion of public vehicle recharge infrastructure, e.g., at the workplace.)
- Vehicles are recharged on a daily basis.
- The PHEVs are used precisely as were their non-PHEV variants; the scenarios are based on replicating the travel-days as recorded in the diaries and do not allow for households to change the assignment of vehicles within the household or otherwise change vehicle use in response to the PHEV.
- This analysis assumes that 1-day cross-sectional data are adequate to characterize travel and therefore energy impacts. One-day diaries systematically under-represent longer trips unless the sampling is conducted according to the frequency distribution of travel-day or trip distances across people and days. By sampling across all seven days of the week we attempt to reduce the effect on our analysis, but do not represent that it is immune. It seems plausible that we, and anyone using 1-day travel data, will underestimate total energy use and gasoline use in particular.

Following these assumptions, four scenarios are created using data from the plausible early market respondents:

- *No PHEVs*: In this scenario, gasoline use is estimated and aggregated based on the respondents' anticipated next conventional vehicles and recorded diary days.
- *Plug and play*: Gasoline use is simulated for driving and the electricity use is simulated for recharging, allowing that the conventional vehicles are displaced by a vehicle with the PHEV designed in the purchase design game. Drivers are assumed to immediately plug-in and recharge whenever they are parked within 25 ft of an electrical outlet. In other words, there are no pricing mechanisms, e.g., time of use electricity tariffs, or technologies, e.g., smart charging mechanisms, to divert recharging to off-peak.
- *Enhanced workplace access*: This scenario starts with the conditions in "plug and play," but further supposes that all respondents who parked at their workplace during their diary day can and do recharge at work—even if their recharge potential derived from their one-day diary did not include workplace recharging.
- *Off-peak only*: Using the same recharge potential and PHEV designs as "plug and play," in this scenario no PHEV recharging is allowed during daytime peak hours (6 am to 8 pm). The timing of electricity use over the off-peak period is represented as constant (the actual distribution would likely vary according to the needs of a particular electric utility).



Note: Weekdays only, n = 231

Fig. 1. Time of day driving and recharge potential for plausible early market respondents.

3. Results

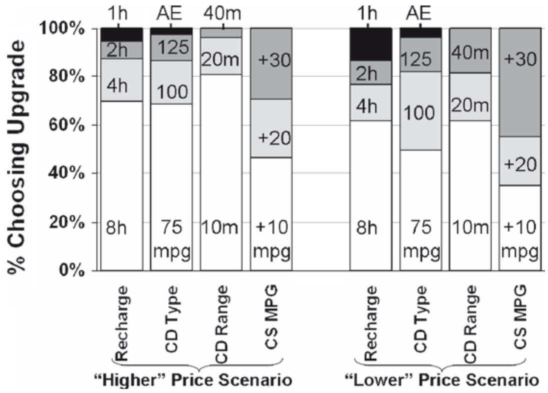
3.1. Recharge potential

Results from the plug-in potential vehicle diary indicate that more new vehicle buyers may be pre-adapted for vehicle recharging than estimated in previous constraints analyses (Williams and Kurani, 2006). A parking spot is considered to be viable for recharging if located within 25 feet of an electrical outlet. Of the 877 respondents, 52.1% found at least one viable recharge location during their 24-h diary day, and 45.3% identified one at their home. This study differs from prior ones in that it elicits reports of vehicle parking proximity to electrical outlets, not circuits, directly from respondents, not via proxy data such as census-based data on housing types. Regarding non-home recharge potential, we find that only 4.4% of respondents found outlets at work, and 9.1% found outlets at all other non-home locations (e.g., friend's home, school, or commercial site).

Because perceived recharge opportunities are relatively rare at work and other non-home locations, home recharging has been selected as the key criteria to characterize a plausible early PHEV market in this analysis. Thus, for the remainder of this study, consideration is limited to the 45.3% of the full California sample that identified an electrical outlet within 25 ft of their vehicle parking spot at their home location at some time during their 24-h diary. We further constrain this segment based on PHEV interest as indicated by purchase intentions in the design games (described in the next section). Among respondents with home recharge potential, 73.3% designed a PHEV for their next new vehicle in the ‘‘higher" price condition, and 84.0% did so in the ‘‘lower" price condition. Thus, respondents that demonstrate both access to sufficient recharge infrastructure and PHEV interest—33.2% using the ‘‘higher" price scenarios and 38.1% using the ‘‘lower" price scenarios—have been selected to represent the early PHEV market in California. These subsets are referred to as the plausible early market respondents.

Fig. 1 presents driving and recharge potential over a 24-h cycle for plausible early market respondents (in 15 min intervals); the sample was proportionally assigned a weekday or weekend day to complete their diary. On weekdays, the proportion of respondents' driving follows an expected daily pattern, peaking during the early morning and mid-afternoon. In any given 15-min interval, total recharge potential ranges from over 90% of respondents from 10:00 pm to 5:30 am, to under 30% from 11:30 am to 1:30 pm. Throughout the day, home is by far the most frequent location of recharge opportunities within respondents' existing travel and recharge potential. Neither work nor other non-home locations presently have recharge potential that surpass 9% of respondents for any 15 min interval during the day. The general pattern in the figure is consistent with driving patterns; recharge potential drops when many respondents are driving or parked at work or other locations, and rises when vehicles are parked at home.[1]

[1] Driving patterns on weekend days do not show morning and afternoon peaks, but rather a single broad mid-day rise to a peak at around 4:00 pm (with a lesser peak in the later evening). Weekend recharge potential during any given 15 min interval ranges from a high of 96.8% to a low of 49.6% of respondents; home also dominates the potential recharge locations for weekends.



Note: White bars represent base level PHEV upgrades, grey and black bars represent upgrades

Fig. 2. Distribution of selected PHEV upgrades (plausible early market respondents).

3.2. PHEV design and value

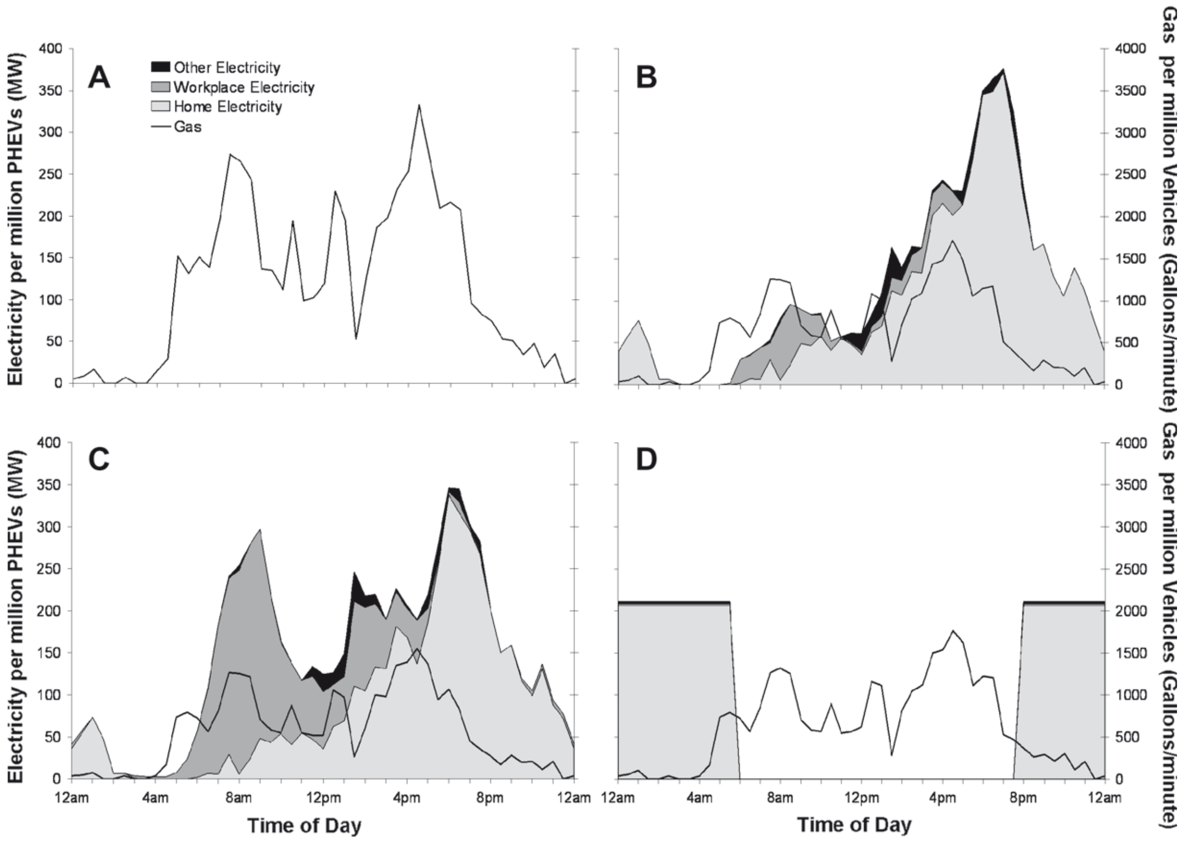
Focusing on the interests of these plausible early market respondents, results of the PHEV design games are summarized in Fig. 2. The white portion of each attribute bar represents the "base" level of that attribute—the level that is included in the "base" PHEV model (incrementally costing \$0 in Table 1). The grey and black portions represent attribute upgrades to the base PHEV (which add price to the base cost in Table 1). PHEV performance priorities varied widely; no majority PHEV design emerged. A substantial portion of plausible early market respondents selected the base PHEV models with no upgrades—31.5% in the higher price condition and 23.2% in the lower. Among those that designed more expensive PHEVs, CS fuel economy upgrades were most common (+20 and +30 mpg), and there is no evidence of strong interest in all-electric CD operation. All-electric CD operation was incorporated into PHEV designs by only 2.7% and 3.9% of respondents in the higher and lower cost conditions. CD operation and range improvements were selected relatively less often than CS upgrades.

3.3. PHEV energy use scenarios

To create scenarios of gasoline and electricity use among early PHEV buyers, we integrate the information from respondents in the plausible early market segment: driving behavior and recharge potential they recorded in their 24-h diary, and PHEV designs created in the purchase design game. Taken together, these scenarios represent plausible market conditions, that is, where the entire market adheres to a selected condition, i.e., no recharge regulation, enhanced workplace access, or off-peak charging. The early PHEV market may include elements of more than one of these scenarios, as well as other potential conditions we do not consider here. Further, these conditions are likely to change over time. Recognizing this, the purpose of this exercise is to present these conditions to frame discussions of the potential benefits and drawbacks of different recharge strategies and policies.

Fig. 3 portrays recharge profiles constructed for each scenario for respondents who completed weekday diaries given the PHEV designs they selected in the "higher" price purchase design game. Table 3 includes these as well as results from respondents with weekend day diaries, and results from the "lower" price design game. Fig. 3 depicts the time of day gasoline use (gallons per minute) using a black line and electricity use (MW) per million vehicles using shaded areas over 24-h. The areas under the curves represent the gallons of gasoline, or MWh of electricity, used over the day. In the "plug and play" scenario, most recharging occurs at home, peaking at 7:00 pm at 376 MW (454 MW in the "lower" vehicle price condition). These peaks are more dispersed than in previous analyses because we allow for substantial, realistic variation in consumers' PHEV designs, daily driving, and start times for recharging.

Time of day gasoline use corresponds with the rush hour periods observed in Fig. 1. These simulations indicate that the "plug and play" scenario may cut gasoline use by half relative to the "no PHEV" scenario. Gasoline use is reduced by a larger degree in the morning due to the higher proportion of miles driven in CD mode earlier in the day. Table 3 also shows that a large portion of this gasoline reduction (75–85%) is due to upgrades to CS fuel economy. (However, simulating only CS fuel economy upgrades may be inappropriate—respondents might not have selected these upgrades without plug-in and CD capabilities). For this reason, overall gasoline savings varies little across the charging scenarios or the vehicle price levels in the design game; in all instances, gasoline use is cut in about half compared to the "no PHEV" scenario. Gasoline use also does not vary much among the PHEV scenarios because most of the selected PHEV designs are fairly "mild" PHEVs, which use more gasoline than would the all-electric PHEV-20s and PHEV-40s typically assumed in previous analyses. Thus, in all scenarios, energy use is dominated by gasoline, which is not strongly sensitive to the recharge scenarios we test here.



Note: Weekdays only; n = 231; A is "no PHEVs"; B is "plug and play"; C is "enhanced workplace access": D is "off-peak only"

Fig. 3. Gasoline use and grid electricity recharge profiles using "higher" price scenario.

Table 3
Summary of electricity and gasoline use, scaled to one million PHEVs.

Scenario		PHEV Design Game: "Higher" price		PHEV Design Game: "Lower" price	
		Weekday (*n* = 231)	Weekend (*n* = 52)	Weekday (*n* = 265)	Weekend (*n* = 58)
No PHEVs	Gasoline (Gal.)	1,658,895	1,353,784	1,627,466	1,347,016
CS Upgrade only	Gasoline (Gal.)	1,024,708	820,077	952,423	804,611
	% Gas reduced	38.2%	39.4%	41.5%	40.3%
Plug and play	Gasoline (Gal.)	870,444	690,669	778,571	678,475
	% Gas reduced	47.5%	49.0%	52.2%	49.6%
	Electricity (MWh)	2828	2453	3666	2777
	Peak (MW)	376	266	454	334
	Peak time	7:00 pm	5:30 pm	7:00 pm	6:00 pm
Enhanced workplace access	Gasoline (Gal.)	826,251	686,557	737,325	672,658
	% Gas reduced	50.2%	49.3%	54.7%	50.1%
	Electricity (MWh)	3590	2550	4445	2936
	Peak (MW)	346	262	432	331
	Peak time	6:00 pm	5:00 pm	6:00 pm	6:00 pm
Off-peak only	Gasoline (Gal.)	909,208	717,625	815,810	700,178
	% Gas reduced	45.2%	47.0%	49.9%	48.0%
	Electricity (MWh)	2115	1936	2883	2340
	Peak (MW)	212	194	288	234
	Peak time (by definition)	8 pm–6 am	8 pm–6 am	8 pm–6 am	8 pm–6 am

The magnitude and timing of electricity demand, however, vary significantly across the scenarios. The "enhanced workplace access" scenario increases overall electricity use by 27% relative to "plug and play," with much of the addition occurring in the morning as drivers arrive at work. In contrast, the "off-peak only" scenario reduces electricity use by 25%, largely due to the elimination of work and other non-home recharge opportunities that occur during peak hours. Of course, this scenario has the benefit of eliminating all electricity use during peak hours, with nightly demand balanced at 212 MW. The specific balancing strategy to flatten out overall off-peak demand used in this scenario would likely vary by electric utilities. Our scenario merely demonstrates the potential for shifting and minimizing peak demand.

4. Discussion

Allowing potential consumers to participate in PHEV design creates important differences in energy impacts from prior analyses that assume a single PHEV—and typically a PHEV capable of all-electric operation in CD mode. First, the majority of gasoline reduction is due to increases in CS fuel economy, not in the displacement of gasoline with electricity in CD mode. Second, in the unconstrained "plug and play" recharge scenario, recharging follows a far more dispersed pattern throughout the earlier part of the day than anticipated by previous studies, due to allowing heterogeneity in driving and parking behavior as well as PHEV designs. Third, we demonstrate that PHEV electricity use could be increased through policies increasing non-home recharge opportunities, but most of this increase occurs during daytime hours and could contribute to peak demand (depending on a given region's definition of "peak"). This study also demonstrates how deferring all recharging to off-peak hours could eliminate all additions to daytime electricity demand from PHEVs, but less electricity is used and less gasoline is displaced due to the elimination of daytime recharge opportunities.

This analysis provides one measure of potential threat and opportunity for electric utilities. The threat is that without control, the majority of recharging may occur during peak hours (6 am–8 pm), with a peak at 7:00 pm during weekdays. This spike coincides with seasonal peak electricity demand periods in some California regions and with a large enough PHEV market, total electricity generation requirements may be increased. However, the observed 12 am–6 am recharge potential presents an opportunity for strategies in which PHEV recharging (as well as any other electrical load) can be shifted to off-peak periods subject to varying levels of control by electricity users and suppliers.

This scenario analysis remains susceptible to threats endemic to such efforts. Radically changing travel behavior—in response to fuel prices, competition from other alternatives, or in response to PHEVs themselves—could invalidate the use of data on present-day real travel. Rapid technology development and cost reductions, or their delay, may render these PHEV design games under- or over-optimistic. And as discussed in the description of recharging scenarios, none of them likely capture precisely what will happen with workplace recharging, efforts to control time of day of recharging, or efforts to provide home recharging to the over half of new car-buying households in California who do not now find access to electricity where they park their cars.

Acknowledgements

The authors thank the California Energy Commission, the Social Sciences and Humanities Research Council of Canada, and the households who completed our multi-day questionnaire.

References

Axsen, J., Kurani, K.S., 2009. Early US market for plug-In hybrid electric vehicles: anticipating consumer recharge potential and design priorities. Transportation Research Record: Journal of the Transportation Research Board 2139, 64–72.
Axsen, J., Kurani, K.S., Burke, A., 2010. Are batteries ready for plug-in hybrid buyers? Transport Policy 17, 173–182.
Bettman, J., Luce, M., Payne, J., 1998. Constructive consumer choice processes. The Journal of Consumer Research 25 (3), 187–217.
Bunch, D.S., Bradley, M., Golob, T.F., Kitamura, R., Occhiuzzo, G.P., 1993. Demand for clean-fuel vehicles in California: a discrete-choice stated preference pilot project. Transportation Research Part A – Policy and Practice 27, 237–253.
Duvall, M., Knipping, E., Alexander, M., Tonachel, L., Clark, C., 2007. Environmental Assessment of Plug-In Hybrid Electric Vehicles, vol. 1. Nationwide Greenhouse Gas Emissions. EPRI, Report #1015325.
Heffner, R.R., Kurani, K.S., Turrentine, T., 2009. Driving plug-in hybrid electric vehicles: reports from US drivers of hybrid electric vehicles converted plug-in hybrid vehicles. Transportation Research Record 2139, 38–45.
IWS (Internet World Stats), 2007. United States of America: Internet Usage and Broadband Usage Report. <http://www.internetworldstats.com/am/us.htm> (accessed January 27th).
Kalhammer, F., Kopf, B., Swan, D., Roan, V., Walsh, M., 2007. Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007. Prepared for State of California Air Resources Board, Sacramento.
Kromer, M., Heywood, J., 2007. Electric Powertrains: Opportunities and Challenges in the US Light-Duty Vehicle Fleet. Sloan Automotive Laboratory, Massachusetts Institute of Technology, LFEE 2007-03 RP.
Kurani, K.S., Turrentine, T., Sperling, D., 1994. Demand for electric vehicles in hybrid households: an exploratory analysis. Transport Policy 1, 244–256.
Lemoine, D.M., Kammen, D.M., Farrell, A.E., 2008. An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles. Environmental Research Letters 3, 10.
Markel, T., Brooker, A., Gondor, M., O'Keefe, M., Simpson, A., Thornton, M., 2006. Plug-In Hybrid Vehicle Analysis. National Renewable Energy Laboratory (NREL), NREL-MP-540-40609.
Potoglou, D., Kanaroglou, P.S., 2007. Household demand and willingness to pay for clean vehicles. Transportation Research Part D 12, 264–274.
Samaras, C., Meisterling, K., 2008. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. Environmental Science and Technology 42, 3170–3176.
Williams, B.D., Kurani, K.S., 2006. Estimating the early household market for light-duty hydrogen-fuel-cell vehicles and other "Mobile Energy" innovations in California: a constraints analysis. Journal of Power Sources 160, 446–453.