Plug-in hybrid vehicle GHG impacts in California: Integrating consumer-informed recharge profiles with an electricity-dispatch model

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Abstract: Estimating greenhouse gas (GHG) emissions of plug-in hybrid vehicles (PHEVs) is challenging because PHEVs are powered by gasoline and grid electricity—in a variety of proportions across individual consumers. Previous GHG estimates emissions postulate consumer behavior and simplify interactions with the electricity grid. We construct PHEV emissions scenarios to address inherent relationships between vehicle design, driving and recharging behaviors, seasonal and time-of-day variation in GHG-intensity of electricity, and total GHG emissions. From a survey of 877 California new vehicle buyers we elicit driving patterns, time of day recharge access, and PHEV design interests. The elicited data differ substantially from those used in previous analyses—including substantial interest in PHEVs with no true all-electric driving. We construct electricity demand profiles scaled to one million PHEVs and input them into an hourly California electricity supply model to simulate GHG emissions scenarios. Compared to conventional vehicles, consumer-designed PHEVs cut marginal (incremental) GHG emissions by more than one third in current California energy scenarios and by a quarter in future energy scenarios—

reductions similar to those simulated for all-electric PHEV designs. Across the emissions scenarios realization of long-term GHG reductions depends on reducing the carbon intensity of the grid.

1. Background

This paper explores the conditions under which plug-in hybrid vehicles (PHEVs) may reduce greenhouse gas (GHG) emissions from the light-duty transportation sector in California. The two primary advances of this analysis are its incorporation of 1) explicit measures of consumer interest in and potential use of different types of PHEVs and 2) a model of the California electricity grid capable of differentiating hourly and seasonal GHG emissions by generation source.

By combining a heat engine powered by gasoline and an electric motor powered at least in part by electricity from the electric grid, PHEVs both directly displace gasoline with electricity and reduce gasoline use through the efficiency gains of a hybrid powertrain. Vehicle electrification improves total energy efficiency of the vehicle (MJ/mile) and may allow society to more easily lower the carbon intensity of the energy used in vehicles (gCO_2/MJ) over time. Policymakers are increasingly turning attention to PHEVs to meet transportation environmental and energy goals (Service, 2009). For instance, President Obama set a national target of 1 million PHEVs on the road by 2015 (Revkin, 2008), and as of the beginning of 2009, a federal tax credit is offered for the first 250,000 PHEVs sold (U.S. Congress, 2009). However, determining the environmental and societal impacts of PHEVs is complex and the benefits are uncertain; they are new technology with a wide diversity of possible designs, driving and recharge patterns, and electricity sources.

A PHEV operates in one of two modes: charge depleting (CD) or charge sustaining (CS) mode (Fig. 1). During CD mode, driving the PHEV depletes the battery's state of charge (SOC), and CD range is the distance a fully charged PHEV can be driven before depleting its battery and switching to CS mode. Over its CD range a PHEV can be designed for either all-electric operation (AE), i.e., using only electricity from the battery, or for blended (B) operation, i.e., using both electricity and gasoline in almost any proportions. We identify CD range and operation with the following notation: AE-X or B-X, where X is the CD range in miles (where 1 mile = 1.61 km). Fig. 1 depicts the battery discharge pattern of a hypothetical AE-X (top graph) and B-X (bottom graph) measured as SOC on the left axis. Holding CD range constant, an AE-X design requires more battery energy and power capacity and is thus costlier than a B-X design (for the same X). Further, at any distance cumulative gasoline use (on the right axis) will be higher in the B-X design for any vehicle trips that include a portion of CD driving. In all PHEVs, CS mode relies solely on gasoline energy as with a conventional hybrid-electric vehicle (HEV); the gasoline energy maintains battery state of charge—but the vehicle does not use grid electricity until recharged. See Axsen et al. (2008) for a more complete description of PHEV operation and battery considerations.

In this paper we analyze potential PHEV GHG impacts in California. We first review the assumptions of previous estimates, which ignore or oversimplify the complexity and diversity of plausible PHEV consumer interests and behaviors and PHEVs' interactions with the grid. We address behavioral complexity using survey responses from 877 new vehicle buying households in California collected in December 2007 (Axsen and Kurani, 2010). To improve the representation of electricity supply, we employ a dispatch model of the electrical grid in California

(McCarthy and Yang, 2010). Our results indicate how PHEVs may reduce GHGs across a diverse set of buyer interests, driving patterns and recharge access. We do not present a full lifecycle analysis—we account for "source-to-wheel" GHG emissions associated with PHEV fuel use, but do not consider the GHG implications of vehicle manufacturing or disposal.

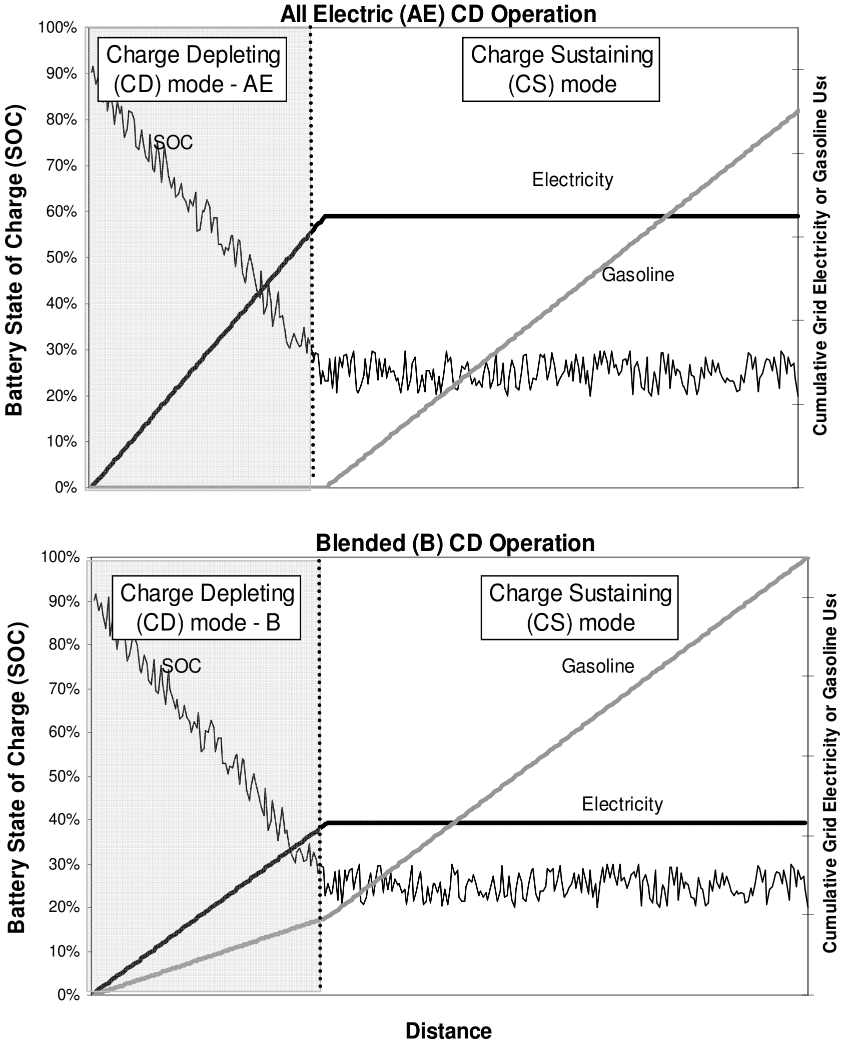

Fig. 1 Illustration of the discharge pattern of a PHEV battery (~65% depth of discharge, adapted from (Kromer and Heywood, 2007)).

2. Literature review

Previous studies of PHEV GHG impacts (Duvall et al., 2007; Hadley and Tsvetkova, 2008; NAS, 2009; Samaras and Meisterling, 2008; Silva et al., 2009; Stephan and Sullivan, 2008) and other energy impacts (Kang and Recker, 2009; Lemoine et al., 2008; Sioshansi and Denholm, 2009) utilize a wide array of input assumptions, which we place into five categories in Table A1. First are the baseline vehicles that are compared with PHEVs: previous analyses typically assume internal combustion engine vehicles (ICEVs) or HEVs, or both, and baseline fuel economies can be based on past, present or future models. Second, assumptions also vary by PHEV design, where most studies assume some variant of an AE-X and neglect the potential for B-X. Third, assumptions of driving behavior have been based on disaggregated details drawn from travel or activity diaries, an aggregated metric calculated from such diaries (e.g. a utility factor), or an assumption that all vehicles are driven the same distance daily. Fourth, recharge behavior assumptions have been based on travel or activity diary data indicating when drivers are parked, as a block of time where all vehicles recharge concurrently, or following some defined off-peak distribution—or in some cases time of day recharging is not addressed. Fifth, prior PHEV GHG emissions estimates also vary as to how the electricity to recharge the vehicle is generated. A more sophisticated approach uses some form of dispatch model, representing the various power plants that are used for different demand loads on a daily and seasonal basis. Other studies use representations of previous demand patterns or forecasts. Simpler estimates apply an annual average rate of carbon intensity for all electricity demanded—not accounting for interactions between vehicle use and hourly, seasonal, or regional variations in electricity generation.

To illustrate the effects of various combinations of these assumptions, Fig. 2 depicts GHG reductions estimated for PHEVs by three of the most influential U.S.-based studies (Duvall et al., 2007; Samaras and Meisterling, 2008; Stephan and Sullivan, 2008). All three conclude that PHEVs can reduce GHG emissions relative to ICEVs, though estimated reductions range from 15 to 65 percent. Fig. 2 depicts how assumptions differ by PHEV design (AE-10, 19, 20, 38, 40, or 56), the carbon intensity of electricity used in the vehicles (200 to 1100 gCO_2/kWh), and the selected baseline (ICEV or HEV). The Electric Power Research Institute's (EPRI) (Duvall et al., 2007) findings of relatively optimistic GHG reductions from PHEVs result largely from assumptions of a low-carbon electricity grid in the year 2050, with greater reductions from longer CD ranges. Samaras and Meisterling (S&M) (2008) consider a wider range of electricity carbon intensities, finding that at higher intensities, PHEVs with shorter CD ranges may reduce more GHG emissions than PHEVs with longer CD ranges recharged in higher carbon-intensive grids. Stephen and Sullivan (S&S) (2008) find greater GHG reductions at higher carbon intensities of electricity production, largely because they assume a less efficient ICEV baseline (19 MPG) and 100 percent CD driving for PHEVs, that is, they model AE-40s that never deplete their batteries and thus never use gasoline.

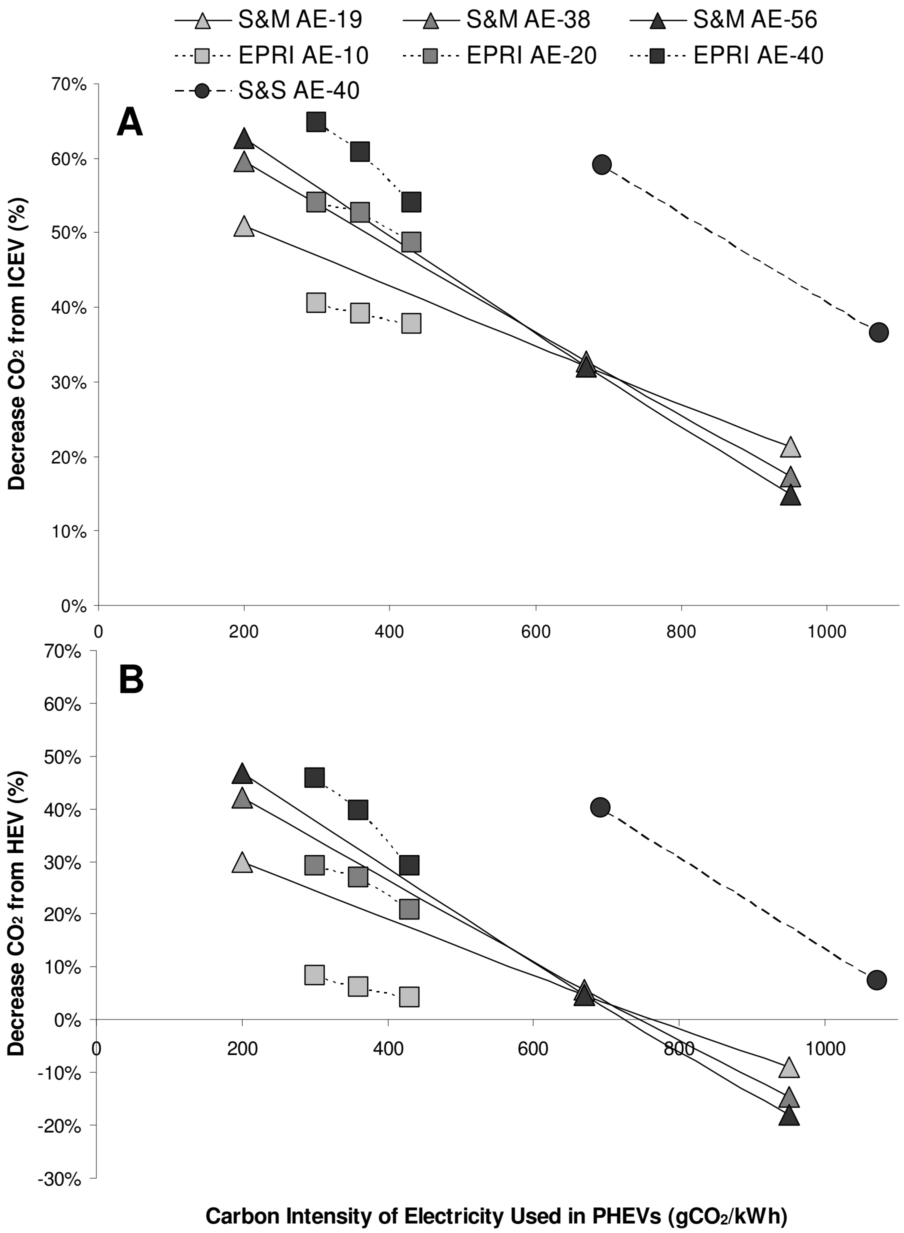

Fig. 2. Comparing CO_2 emissions results of previous studies according to electricity carbon intensity (A: reductions relative to CVs; B: reductions relative to HEVs)

On the demand side, the present study departs from previous research efforts by eliciting distributions of PHEV designs, driving behavior and recharge potential directly from plausible PHEV buyers—that is, collecting all three types of data from the same buyer. On the supply side, we meet the modeled demand for electricity with a dispatch model of the California electrical grid capable of differentiated GHG estimations.

3. Representing the demand-side: A survey of California new car buyers

We used a consumer survey to consult car buyers about their potential interest in, design of, and use of PHEVs. With this data we constructed consumer-informed recharge profiles, that is, representations of time of day electricity demand from the PHEVs they designed. Conceptually, an aggregate vehicle recharge profile is the product of four data components or assumptions in the absence of data: 1) type or distribution of PHEV design(s), 2) PHEV driving patterns, 3) recharge behaviors of PHEV owners—when they plug in, where, for how long and how often, and 4) market penetration of PHEVs. The first three components determine unique energy use and GHG emissions profiles for each driver/vehicle. We use the survey data to inform the first three, but leave the fourth to future studies. Here, for simplicity and to ease comparison, we assume a market of one million PHEVs (~3.6 percent of California's light-duty vehicles) in every scenario we construct (scaling up from the plausible PHEV buyers identified in our survey respondents).

Survey data were collected from a sub-sample of 877 California new vehicle buyers in December, 2007. The full survey included a representative sample of over 2,200 U.S. new vehicle buyers, with nationwide results reported elsewhere (Axsen and Kurani, 2009). We deem the weighted California sub-sample to be generally representative of California new car buyers (Axsen and Kurani, 2010). Respondents completed a sequential multi-part questionnaire over the course of several days, including a 24-hour diary of driving and vehicle recharging potential by time of day and parking location as identified by the respondents. We elicited respondent interests in PHEV designs through a series of design games. Of the 877 total respondents, here we focus exclusively on those we deem to represent the *plausible early market*—the 282 respondents that satisfied two conditions: 1) at their home they parked within 25 feet of an electrical outlet at least once during their 24-hour diary day, and 2) they opted to design and (hypothetically) purchase that PHEV in the higher price design game. In other words, we focus on the one third of California respondents that demonstrate both easy access to home recharge infrastructure and substantial interest in owning a PHEV. The next four sections briefly summarize these respondents' PHEV designs, driving behavior, and recharge potential, and how we used this data to construct aggregate recharge profiles. Further information about this survey are detailed in Axsen and Kurani (2009), with California recharge profiles constructed in Axsen and Kurani (2010)

3.1. Consumer-informed PHEV designs

After receiving a "PHEV buyers' guide" describing basic PHEV design options, respondents completed an online PHEV design game allowing them to upgrade (or not) their next anticipated vehicle purchase to a PHEV, manipulating CD type (AE or B), CD-range (X), recharge time, and CS fuel economy for incremental price increases (Table 1). Although respondents were free to specify any vehicle model as their likely next new vehicle purchase, to represent energy use we simplify their PHEV designs into either 1) cars (and car-like vehicles) or 2) trucks (and truck-like vehicles).

Table 1. PHEV purchase design game options and prices (Axsen and Kurani, 2009)

Attributes	Attribute level	Car	Truck
Base premium over conventional		$3,000	$4,000
Added premiums:			
Recharge time	8 hours	0	0
	4 hours	+$500	+$1,000
	2 hours	+$1,000	+$2,000
	1 hour	+$1,500	+$3,000
CD mpg and type[a]	Blended (B-X)		
	75 mpg	0	0
	100 mpg	+$1,000	+$2,000
	125 mpg	+$2,000	+$4,000
	All-electric (AE-X)	+$4,000	+$8,000
CD range	10 miles	0	0
	20 miles	+$2,000	+$4,000
	40 miles	+$4,000	+$8,000
CS mpg	Conventional mpg +10	0	0
	Conventional mpg +20	+$500	+$1,000
	Conventional mpg +30	+$1,000	+$2,000

[a] Metric conversions: 75 mpg = 3.14 L/100km, 100 mpg = 2.35 L/100km, 125 mpg = 1.88 L/100km, and all-electric = 0.00 L/100km.

The resulting designs sharply contrast with previous PHEV design assumptions. Fig. 3 portrays the distribution of selected PHEV designs according to CD type and range. Most plausible early market respondents opted to maintain the lowest CD options offered in the design game; 67.7 percent selected the least ambitious CD type (B-X, 75 MPG) and 80.6 percent selected the least ambitious CD range (10 miles). CS fuel economy (not shown in Fig. 3) was the most frequently selected upgrade—only 46.5 percent of respondents stayed with the base increase of 10 MPG over the conventional vehicle they specified as their likely next new vehicle, while 24.2 and 29.3 percent opted for the 20 and 30 MPG increases, respectively. Although 69.9 percent selected eight hour recharge time, for the construction of recharge profiles we adjusted recharge times to better match the battery size actually required for the respondents selected CD type and range (Table 2), as estimated in Axsen et al. (2010). Thus, 79 percent of respondents' designs require less than two hours to fully recharge, 18 percent require two to four hours, and 3 percent require more than four hours.

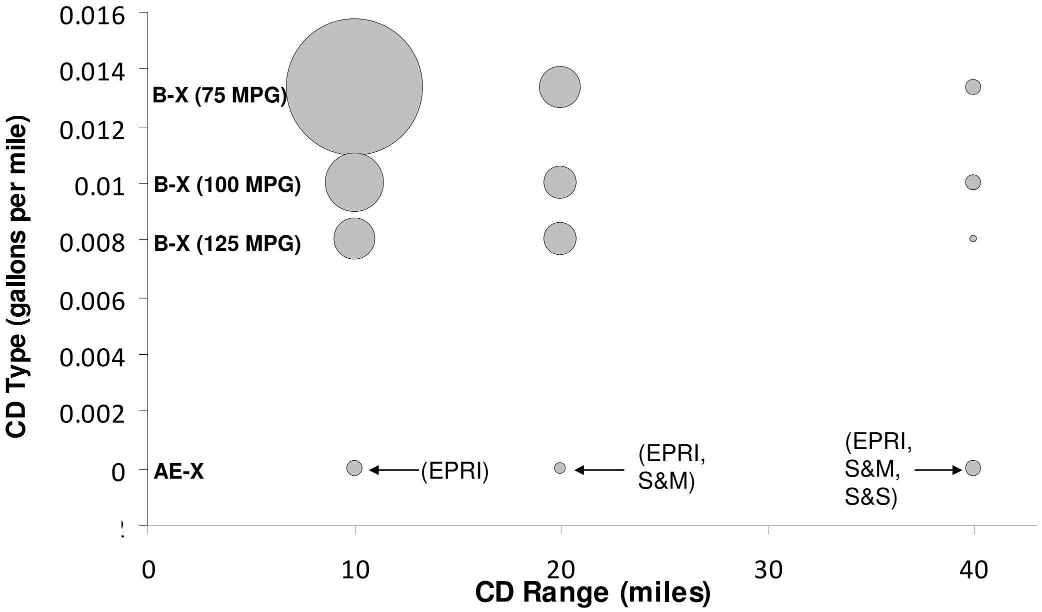

Fig. 3. Comparing the distribution of consumer-designed PHEVs (User) with the AE-X designs assumed in previous analyses (area of each circle indicates the proportion of survey respondents selecting a given PHEV design; arrows point to the PHEV designs assumed in previous analyses).

Table 2. Assumed PHEV energy use (kWh/mile) and required battery capacity (kWh)

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

3.2 Consumer-informed PHEV driving behavior

Each survey respondent also completed a 24-hour driving diary for one of their new vehicles. They were randomly assigned a day of the week, and starting with the first trip of that day, they recorded the time of departure, duration, and distance of each trip made in their vehicle for the next 24 hours. The present study's distribution of travel behavior does not differ significantly from relevant sub-samples drawn from previous travel diary studies (Duvall et al., 2007; Samaras and Meisterling, 2008; USDOT, 2004).

3.3 Consumer-informed PHEV recharge potential

Respondents reported the start time and duration of each parking episode, and the distance to the nearest electrical outlet from the vehicle allowing us to construct a 24-hour profile of recharge potential for each respondent's vehicle for a given outlet distance. We assume an outlet is available for recharging if it was reported to be within 25 feet of the parked car regardless of who owns the outlet. On average for weekdays, over 95 percent of our plausible early market respondents are parked within 25 feet of an electric outlet from midnight to 5am; this reduces to a minimum of 23 percent at midday. The full recharge potential distribution for California respondents is portrayed in Axsen and Kurani (2010).

3.4 Constructing consumer-informed PHEV recharge profiles

PHEV energy use results from the interaction between vehicle designs, travel, and recharge events. For example, shorter cumulative distance between recharge events and longer CD ranges result in a higher proportion of CD driving miles (what is commonly referred to as the utility factor), increased electricity usage, and decreased gasoline usage. We construct distributions of driving and recharging behaviors by matching the disaggregated, temporally explicit data from each respondent's 24-hour diary to their PHEV design.

To further explore the effects of recharging on GHG emissions, we construct three PHEV design conditions of time of day electricity demand:

1. "User" design represents the distribution of PHEV designs as elicited from the plausible early market (Fig. 3).
2. "AE-20" replaces each respondent's selected PHEV design with an AE-20. In this scenario, all PHEVs are assumed to recharge at 1 kW (1 kWh per hour—attainable with a 110-volt outlet), resulting in a total of 6.0 hours to fully recharge a car and 7.7 a truck. Any CS driving is assumed to be done at a fuel economy 15 MPG higher than the respondent's selected conventional vehicle (which was the basis for their PHEV design).
3. "AE-40" in which CD type and CS fuel economy are similar to the AE-20, but with a 40-mile CD range and a faster recharge rate of 2 kW (attainable with a 220-volt outlet or a higher amperage 110-volt outlet). This faster recharge rate is allows a higher proportion of drivers to fully recharge the PHEV at night—at only 1 kW, a depleted AE-40 would require 12 to 15.4 hours to fully recharge. For this AE-40 design scenario, we assume any identified 110-volt outlet can recharge the vehicle at the 2kW.

We add these AE-20 and AE-40 design conditions to facilitate comparison with prior PHEV studies, as well as to explore the potential GHG impacts of a world where consumers more strongly value AE range. For each of the three PHEV design conditions, we construct three different recharge conditions that not only affect timing of vehicle charging but also total amount of electricity used (illustrated in Fig. 4):

1. "Plug and play": Drivers are assumed to plug in and begin recharging immediately whenever they park within 25 feet of an electrical outlet. 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.
2. "Universal workplace access": In addition to whatever recharging they do in "plug and play," all drivers (who commute to a workplace) can and do recharge if and when they park at their workplace.
3. "Off-peak only": No PHEV recharging is allowed during daytime peak hours (6am to 8pm). The timing of electricity use over the off-peak period is represented as a constant load between 8pm and 6am. In reality, a particular electric utility would not desire a constant load, but would instead seek to vary the recharge profile according to their particular demands and needs, e.g. "valley filling." For the present purpose of calculating GHG emissions, however, a constant load is sufficient to generally represent an off-peak scenario.

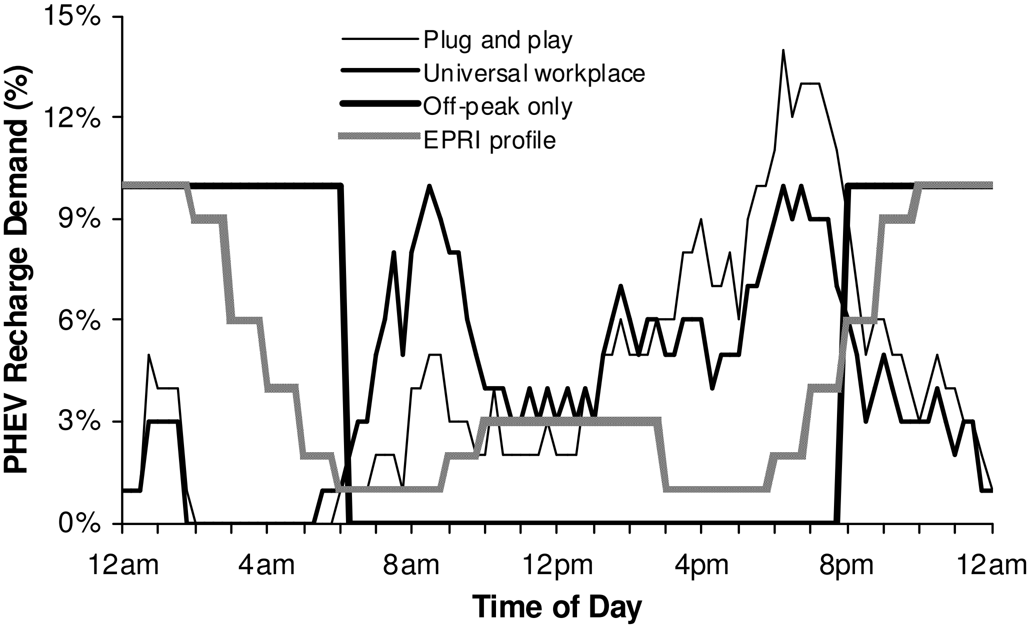

Fig. 4. Comparing consumer-informed recharge profiles (User designs, weekdays only) with EPRI's recharge profile (Duvall et al., 2007).

We use these three PHEV design conditions and three recharge conditions to construct nine recharge profiles for weekday and weekends using a spreadsheet model—thus a total of 18 24-hour recharge profiles. For each recharge profile, we assume that vehicle recharging is 83.3 percent efficient (following Lemoine et al., 2008) and that PHEVs will be driven precisely as were the respondents' vehicles as recorded on their diary day. Further assumptions used in the construction of these recharge profiles are detailed in Axsen and Kurani (2010).

The resulting 18 recharge profiles are portrayed in Table A2 at hourly intervals, as scaled to one million PHEVs. Total daily electricity demand is three to five times higher in the AE-20 and AE-40 PHEV design conditions relative to the User condition. Relative to the plug and play condition (and for all vehicle design conditions), the universal workplace access condition increases total daily electricity demand by 15 to 30 percent, while the off-peak only condition reduces total daily electricity demand by 10 to 25 percent. Increasing vehicle access to charging (from off-peak only to plug and play to universal workplace) increases higher average battery SOC, thus miles driven in CD mode and grid electricity used. Fig. 4 illustrates recharge profiles based on the User design condition and the three recharge conditions, where uncontrolled recharge conditions can result in very different profiles than those assumed by previous studies (e.g. Duvall et al., 2007). If PHEV buyers plug in when they can within the current infrastructure and there is no effort or ability to defer demand, the majority of PHEV recharging will occur during present peak electricity demand hours.

4. Representing the supply-side: Modeling electricity and gasoline GHG impacts

4.1. Simulating electricity GHG emissions: California dispatch models

The carbon intensity of electricity generation is determined by the mix of power plants that are operating, which in turn is influenced by total electricity demand which varies by time of day and time of year. There are three approaches that are frequently used to represent GHG emissions from electricity used by PHEVs:

1. Apply an annual average carbon intensity (gCO_2/kWh) for all electricity used (e.g. Samaras and Meisterling, 2008);
2. Apply an hourly average emissions rate to represent emissions by time of day and year, averaged across the grid mix of power plants; or
3. Represent hourly marginal emissions rates to account for incremental GHG emissions from power plants operating during vehicle recharging that would not be running otherwise (e.g. Duvall et al., 2007; Stephan and Sullivan, 2008).

We estimate both hourly average and hourly marginal GHG emissions to recharge PHEVs. Both hourly allocation methods require modeling the mix of power plants generating electricity over time. The marginal generation mix in California consists of fossil-fired power plants, usually natural gas. The hourly average mix accounts for all electricity generation in a given hour, including hydro, nuclear, and renewable resources—about 35 percent from power plants with almost zero operational GHG emissions. Thus, assuming hourly marginal rather than hourly average rates in California places a disproportionately larger burden for GHG emissions on PHEVs than on all pre-existing electricity uses (though this isn't the case for regions with high fractions of coal-fired generation). On the other hand, assigning the hourly average emissions rate does not emphasize the incremental impacts of recharging PHEVs. We leave it to readers and encourage policymakers to consider societal issues in choosing which emissions to assign to new demand.

We simulate average and marginal emissions rates using the Electricity Dispatch model for Greenhouse Gas Emissions in California (EDGE-CA) to represent a present energy scenario and the long-term version (LEDGE-CA) to simulate the planned 2020 California grid (Table 3). EDGE-CA is a spreadsheet-based accounting tool that represents supply, demand, and energy transfers among three regions in California as well as imported power from out of state. EDGE-CA represents variations in power plant availability based on hourly, daily, and seasonal factors. To calculate hourly marginal GHG emissions, the EDGE-CA model tracks the last power plant dispatched. The data sources, decision rules and supply curves for EDGE-CA are discussed further in McCarthy and Yang (2010).

The LEDGE-CA model is more appropriate for long-term analysis (McCarthy, 2009). LEDGE-CA includes power plant retirements and capacity expansion, but more simply represents dispatch by defining California as a single region and ignoring imports of electricity (though it does include imports from coal-fired power plants from contracts expected to be held by California in 2020). In this way, the costs of all new capacity and generation supplying California electricity demand is attributed to its ratepayers, regardless of where the power plants are located. LEDGE-CA calculates an optimal distribution of new capacity from fossil-fired power plants to complement supply scenarios that dictate the level of hydro, nuclear, and renewable generation in the state. In this analysis, LEDGE-CA is applied to simulate electricity capacity and generation for a "future" energy scenario (year 2020), assuming a 33 percent Renewable Portfolio Standard (RPS) is implemented in California (Douglas et al., 2009). Power plants are dispatched in similar fashion as in the EDGE-CA model.

Table 3. California electricity supply composition in 2010 (EDGE-CA) and 2020 (LEDGE-CA).

	2010 grid (EDGE-CA model results)[e]				2020 grid (LEDGE-CA model results)[e]			
	Total Generation (Used for average emissions rates)		Marginal Generation (Used for marginal emissions rates)		Total Generation (Used for average emissions rates)		Marginal Generation (Used for marginal emissions rates)	
	Annual gen. (GWh)	GHG rate (gCO$_2$e/ kWh)	Annual gen. (GWh)	GHG rate (gCO$_2$e/ kWh))	Annual gen. (GWh)	GHG rate (gCO$_2$e/ kWh)	Annual gen. (GWh)	GHG rate (gCO$_2$e/ kWh)
Nuclear	46,150	16	-	-	36,085	16	-	-
Renewables	25,554	0	-	-	107,424	0	-	-
Coal	39,149	1,154	-	-	48,896	866	-	-
Hydro	53,196	0	-	-	37,557	0	-	-
NGCC & CHP[a,b]	127,221	504	505	690	111,125	486	746	549
NGST & NGCT[c,d]	9,221	760	487	760	5,033	653	247	601
Other	2,556	1,176	2	794	-	-	-	-
GHG rate averaged over one year		403		724		290		562

[a] CHP = (Natural gas) Combined heat and power;

[b] NGCC = Natural gas combined cycle;

[c] NGCT = Natural gas combustion turbine;

[d] NGST = Natural gas dsteam turbine

[e] The LEDGE-CA model excludes imports except for coal-fired power plant import contracts expected to be held by California load serving entities in 2020. Thus, while in-state nuclear and hydro generation are constant in both cases (equal to the 2020 values), generation from those power plants is higher in 2010 because it includes imported hydro and nuclear power from out of state that supplies California electricity demand in the near term

4.2 Modeling gasoline use

For the 2010 baseline of conventional vehicles, we model gasoline use according the respondents' driving day recorded in their diaries. Each survey respondent input an MPG estimate for their anticipated next vehicle purchase. This estimate is applied to each mile travelled during their diary day. In other words, if the vehicle is rated at 20 MPG, we assume a constant rate of fuel use for each mile driven (neglecting potential for varying drive patterns within a trip, among trips, or across drivers, and potential inaccuracies in actual drive cycle). We consider two additional baselines of gasoline-using vehicles: 1) 2010 hybrid-electric vehicles (HEVs) with 53 percent greater fuel economy than conventional vehicles (ANL, 2009), and 2) a 2020 fleet of new vehicles required to meet future fleet average fuel economy standards of 35 MPG (NHTSA, 2009).

GHG emissions from gasoline use are estimated using a flat rate per liter of gasoline. For the 2010 energy condition, we start with 67 gCO_2/MJ (EPA, 2006) and add an upstream emissions rate of 19 gCO_2/MJ from the GREET model (Wang, 2001), totaling 86 gCO_2/MJ. This is the value also used by Samaras and Meisterling (2008). For the 2020 energy scenario, we account for California's Low Carbon Fuel Standard (LCFS), which requires a 10 percent reduction of lifecycle carbon intensity across all on-road transportation fuels (including electricity) used in California by 2020 (Farrell and Sperling, 2007). For the 2020 energy condition we assume gasoline carbon intensity is reduced from its 2010 value by 10 percent, presumably by blending in a low-carbon biofuel. Because of the low carbon intensity of electricity in LCFS calculations, increased vehicle electricity use will offset some of the need to reduce the carbon intensity of gasoline and reductions in "gasoline" carbon intensity are slightly lower in the PHEV conditions (but still very close to 10 percent).

5. Results and discussion

5.1 Comparing User and AE-40 GHG emissions profiles

In Fig. 5 we compare marginal hourly GHG emissions for one million PHEVs distributed as the survey respondents' designs (User) and AE-40 designs under present California energy conditions for the median GHG emissions day modeled for 2010: June 12th. These GHG profiles illustrate the differences among modeled PHEV scenarios. For each graph, the area under the dotted line depicts the day's baseline, that is, total GHG emissions from one million conventional vehicles (with emissions peaks corresponding with peak travel times)—this baseline is identical in all six graphs. The day's total PHEV GHG emissions is the sum of the light grey (gasoline emissions) and dark grey (electricity emissions) areas for each graph.

Because the User PHEV design distribution is dominated by B-10 vehicles, the majority of User miles (56 to 74 percent) are driven in CS mode, and gasoline accounts for the majority of driving energy use (88 to 93 percent) and GHG emissions (78 to 89 percent). In contrast, imposing AE-40 designs onto respondents' driving and the recharge patterns results in less CS driving (21 to 38 percent of miles), a lower proportion of gasoline energy use (34 to 54 percent) and a lower proportion of GHG emissions from gasoline (19 to 40 percent).

Despite these differences, total GHG emissions are similar between the scenarios—in fact slightly favoring the User designs—because of two countervailing components of total vehicle carbon intensity (gCO_2/mile): total vehicle energy consumption (MJ/mile) and total fuel carbon intensity (gCO_2/MJ). Because electricity is used more efficiently in vehicles than gasoline is, the AE-40s' relatively high use of electricity results in 25 percent lower energy consumption on average (1.89 MJ/mile) than User designs (2.50 MJ/mile) in the plug-and-play conditions in Fig. 5. However, because the fuel carbon intensity of gasoline is lower than for marginal electricity calculated by EDGE-CA in 2010 (Table 4), User designs' fuel mix has 29 percent lower total fuel carbon intensity (103 gCO_2/MJ) than AE-40 designs (146 gCO_2/MJ). As a result, User designs emit 6 percent less GHG emissions than AE-40 designs on the modeled day, and 9 percent less averaged across the year.

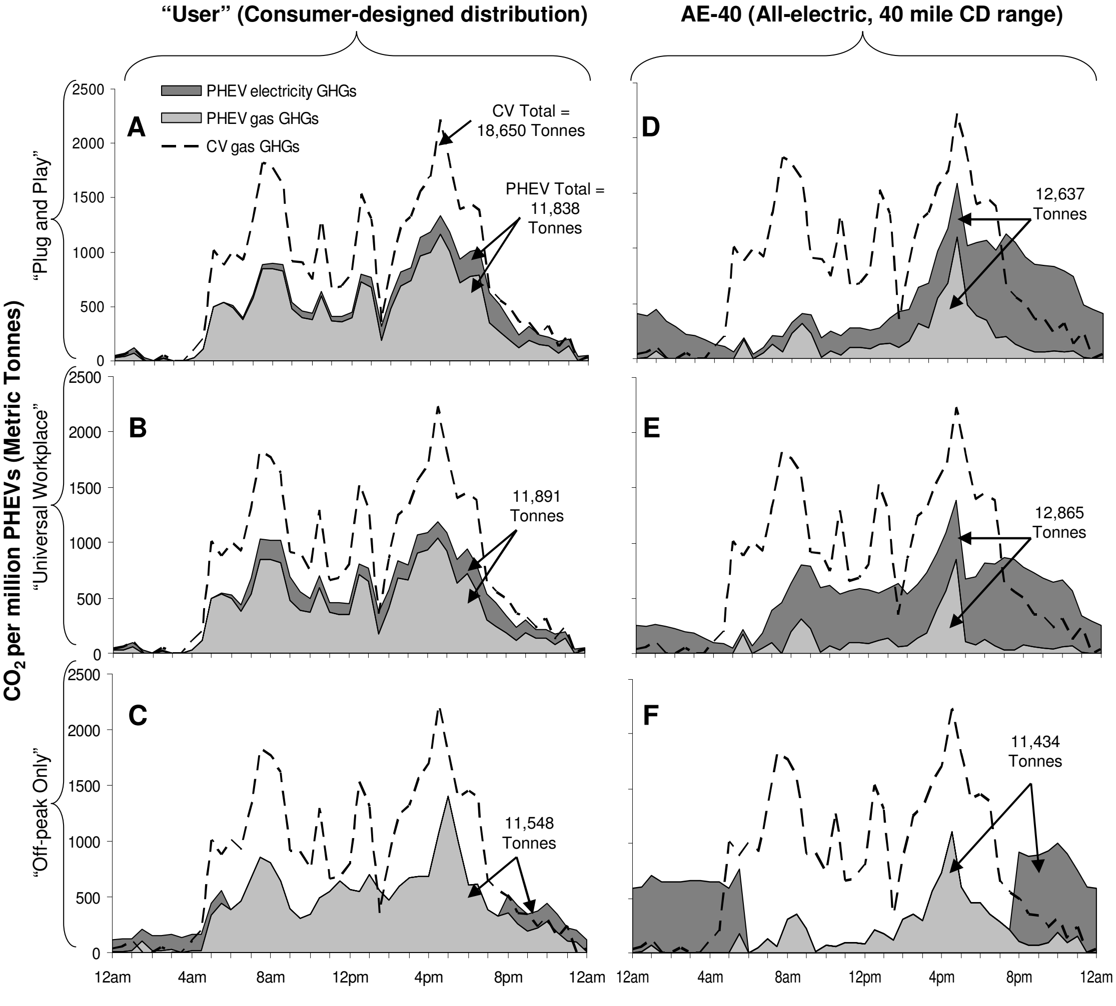

Fig. 5 Time of day GHG emissions from 1 million PHEVs, including gasoline and marginal electricity in 2010 energy scenario (median GHG emissions day, weekday, June 12th)

5.2 Annual marginal and average emissions

Annual PHEV emissions for each scenario are based on seasonally varying hourly marginal and average electricity emissions rates (summarized for plug and play condition in Tables A3 and A4). Fig. 6 only depicts GHG impacts according to hourly marginal emissions rates, while Table 4 also includes hourly average emissions rates. Applying hourly marginal electricity emissions rates from the current California energy scenario (EDGE-CA, no LCFS), we calculate 37 to 38 percent GHG reductions for User designs, and 30 to 35 percent reductions for both AE designs. These reductions do not substantially differ from an assumed fleet of today's HEVs; User designs emit three to five percent less than the modeled HEVs, while AE designs emit one percent less to seven percent more. Under the future energy scenario (LEDGE-CA, with LCFS), User and AE designs reduce marginal GHGs by 20 to 24 percent when compared with a future fleet of higher efficiency conventional vehicles mandated by federal fuel economy (CAFE) standards (which may include a significant proportion of HEVs).

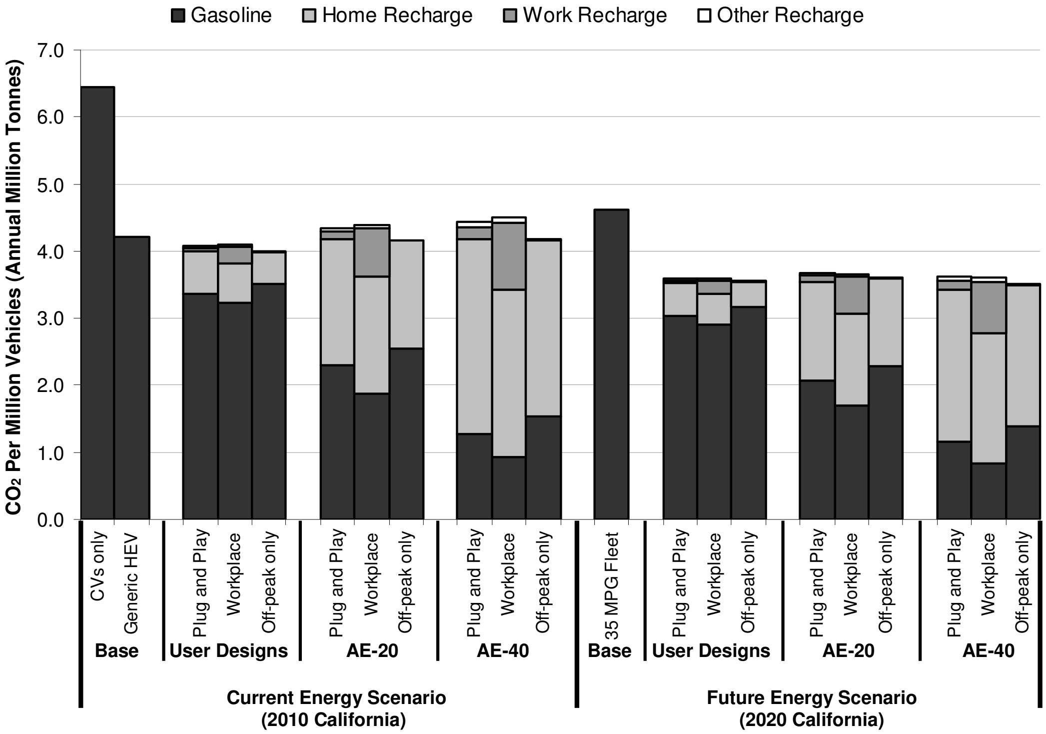

Fig. 6. Annual GHG emissions from 1 million PHEVs, including gasoline and marginal electricity by recharge location: home, work, or other.

Table 4 details several key vehicle and fuel metrics that govern energy use and GHG emissions. CS operation of User designs is more efficient (MJ/mile) than the AE designs, while the opposite is true in CD operation. In 2010 and 2020, the User designs have a lower carbon intensity (gCO_2/mile) that AE designs in both CS and CD modes, when considering marginal emissions. However, when considering average emissions, a more electrified PHEV design (AE-20 or AE-40) is almost always more desirable from a GHG standpoint than the User designs. Further, every PHEV scenario results in lower emissions than the HEV scenario. Thus, when considering hourly average electricity emissions, the use of PHEVs becomes more desirable from a GHG perspective, particularly AE designs that use more electricity.

Although our results portray totals and averages across respondents, all scenarios are based on a wide variety of underlying individual consumer interests and behaviors. For instance, while the first PHEV scenario (User design, plug and play, 2010 grid, marginal emissions rate) indicates an annual average of 256 gCO_2/mile, the distribution of rates modeled for each survey respondent (and their unique combination of PHEV design, driving behavior and recharge potential) can range from one-half below to two-thirds above this value.

Table 4. Energy use and GHG emissions among vehicle scenarios (15,949 million vehicle miles travelled by the distribution of 1 million vehicles over one year of simulation)

	Total energy intensity (MJ/mile)			Total fuel carbon intensity (gCO_2/MJ)		% GHG reductions from base CV		% GHG reductions from HEV	
	CD	CS	Total	Mar.	Avg.	Mar.	Avg.	Mar.	Avg.
2010 Energy									
CVs only			4.31	93.7	93.7				
HEVs			2.82	93.7	93.7				
User designs									
Plug and play	2.05	2.70	2.47	103.4	95.3	37%	42%	3%	11%
Uni. workplace	2.05	2.71	2.43	105.7	95.6	36%	43%	3%	12%
Off-peak only	2.04	2.69	2.51	99.4	95.0	38%	41%	5%	10%
AE-20 designs									
Plug and play	1.45	2.81	2.20	123.7	99.1	33%	46%	-3%	18%
Uni. workplace	1.45	2.81	2.06	133.6	100.8	32%	49%	-4%	22%
Off-peak only	1.45	2.80	2.27	115.1	98.7	35%	45%	1%	15%
AE-40 designs									
Plug and play	1.45	2.87	1.87	148.3	103.8	31%	52%	-5%	26%
Uni. workplace	1.45	2.86	1.76	160.5	105.7	30%	54%	-7%	30%
Off-peak only	1.45	2.83	1.95	134.3	103.2	35%	50%	1%	24%
2020 Energy									
35 MPG fleet			3.43	84.4	84.4				
User designs									
Plug and play	2.05	2.70	2.47	99.4	92.5	22%	28%		
Uni. workplace	2.05	2.71	2.43	100.6	92.2	22%	29%		
Off-peak only	2.04	2.69	2.51	97.1	93.0	23%	27%		
AE-20 designs									
Plug and play	1.45	2.81	2.20	111.1	90.1	20%	36%		
Uni. workplace	1.45	2.81	2.06	117.0	88.8	21%	41%		
Off-peak only	1.45	2.80	2.27	106.3	91.2	22%	34%		
AE-40 designs									
Plug and play	1.45	2.87	1.87	125.0	87.2	22%	46%		
Uni. workplace	1.45	2.86	1.76	131.9	85.5	22%	50%		
Off-peak only	1.45	2.83	1.95	117.6	89.1	24%	43%		

5.3 Comparing recharge conditions

When considering hourly marginal electricity emissions rates in California (Fig. 6), “off-peak only” recharging results in slightly larger reductions in GHG emissions for each vehicle design in present and future energy conditions. In other words, within the range of conditions explored here, to reduce GHG emissions it is better to constrain PHEV recharging to off-peak hours, even if it results in less recharging and electricity use overall. In contrast, applying hourly average electricity emissions rates (Table 4) encourages additional daytime recharging, i.e. universal workplace access, resulting in slightly larger GHG reductions across vehicle design and recharge conditions. However, these variations are slight; overall GHG reductions vary by only one to seven percentage points across recharge conditions for each combination of PHEV and energy condition.

5.4. Sensitivity to electricity and gasoline carbon intensity

We depict the sensitivity of GHG emission reductions to the carbon intensity of electricity supply which varies across regions, with future developments, and with the assumption of hourly marginal versus hourly average emissions rates (Fig. 7). Graph 7A presents a current gasoline scenario, assuming no LCFS is in place and depicting only 2010 baselines (current conventional vehicles and HEVs) for comparison. Graph 7B is a future gasoline scenario, assuming the LCFS is in place, and depicting a future fleet meeting the 35 MPG CAFE standard. The ranking of the three PHEV emissions scenarios relative to each other and to the three vehicle baselines clearly depends on electricity and gasoline carbon intensity. The vertical lines in each graph depict the aggregated electricity carbon intensity applied in each California energy scenario explored above (using marginal and average emissions rates), as well as the present U.S. annual average rate used by Samaras and Meisterling (2008).

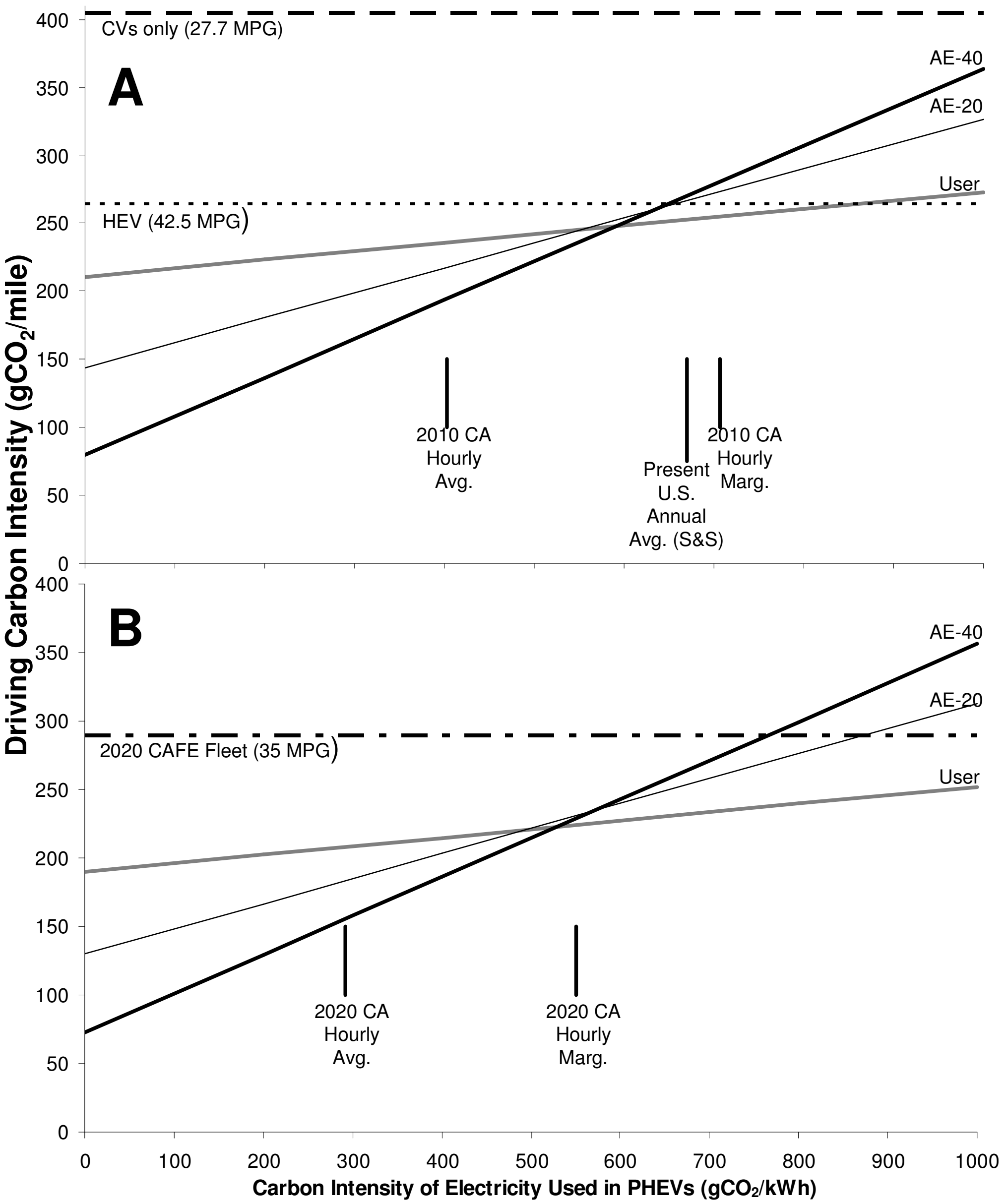

Fig. 7. Comparing GHG emissions across electricity carbon intensity rates under plug and play recharge conditions (A: 2010 energy scenario; B: 2020 energy scenario)

With current gasoline emissions intensity (Fig. 7A), an important pivot point is ~600 gCO_2/kWh (typical of a natural gas-fired combustion turbine), above which User designs result in deeper GHG reductions than AE designs. Another pivot point is ~850 gCO_2/kWh, below which User designs result in deeper reductions than our selected HEV baseline. Of the vehicles we represent here, User designs result in the lowest GHG emissions between these pivot points (a range that includes current marginal CA emissions and the U.S. annual average), though differences between consumers' PHEV designs and HEVs are slight. More dramatic GHG reductions can be realized below 600 gCO_2/kWh, particularly for AE designs. With less carbon intensive gasoline under an LCFS or similar policy (Fig. 7B), User designs produce the most reductions with electricity sources above 550 gCO_2/kWh and have less GHG emissions than a fleet of 35 MPG vehicles even under highly carbon intensive coal-based electricity sources (over 1000 gCO_2/kWh).

6. Conclusions

6.1 Summary of results

Previous analyses of PHEV GHG impacts rely on simplistic representations of the demand side (consumer interests and behaviors), and too simple representations of the supply side (GHG emissions impacts of energy demanded). The present study improves upon previous efforts regarding the former and at least matches the best previous efforts regarding the latter. We highlight several key results.

- Consumer-designed (User) PHEVs—which mainly consist of blended, low CD range designs—can reduce "source to wheel" GHG emissions compared to conventional vehicles in all the recharge and energy conditions we simulated.
- User-designed PHEVs can also reduce GHG emissions relative to AE-20 or AE-40 designs when electricity is generated by sources with emissions above 600 gCO_2/kWh, e.g., most present-day natural gas or coal plants.

- AE-X designs may yield deeper GHG emissions reductions than User designs as the carbon intensity of electricity supply falls (below 600 gCO_2/kWh).
- Constraining recharging to off-peak times results in deeper GHG reductions when using more carbon-intensive electricity sources; in contrast, less carbon-intensive electricity may warrant measures to facilitate increases in daytime recharging, e.g. via workplace recharge infrastructure.

Our estimates of GHG emissions reductions are comparable to previous studies, but our assumptions differ in important ways (Table A1). For instance, EPRI estimates larger reductions due to assumptions of a less carbon-intensive electricity grid, only AE-X designs, and primarily off-peak recharging (Duvall et al., 2007). Stephen and Sullivan (2008) estimate even larger reductions due to a focus only on AE-40 designs driven only in CD mode—thus using zero gasoline. In contrast, the present analysis elicits consumer data to construct scenarios with more gasoline-intensive PHEV use, and more carbon-intensive electricity sources. Thus, our estimated reductions tend to be slightly lower than previous studies.

Further, our general findings are robust to a range conditions, and can be extended beyond the California context. Although we use representations of California consumers and energy supply, elicited distributions of consumer interests in PHEVs, driving behaviors, and access to recharging are similar to those of a nationwide sample (Axsen and Kurani, 2009), and we depict a range of electricity carbon intensities that could approximate other regions (Fig. 7). Of course, we caution that the specific details of each region will differ due to unique interactions between consumer design priorities, driving and recharge patterns, and time of day electricity carbon intensity.

Important limitations remain. Increasing the complexity in our model to represent present consumer interests and behaviors and the present energy system operation does not guarantee a more accurate depiction of the future. Our three recharging conditions span many, but not all, possible conditions and the adoption of PHEVs may change buyers' driving and parking behavior and availability of vehicle charging. Also, the PHEV design exercises risk being more adaptable to individual desires than the actual vehicle market may be, and our fuel economy (MPG) and electricity use (Wh/mile) assumptions do not account for variations in driving behavior. However, we feel that are general conclusions are robust to a variety of conditions.

6.2 Implications of results

Implications of our findings can be framed from two perspectives. A shorter-term focus on GHG emissions reductions suggests that consumer-designed PHEVs can reduce GHG emissions relative to conventional vehicles, but similar (marginal) reductions are also attainable by HEVs. Thus, if one assumes that all the one-million vehicle scenarios explored here are equally probable, HEVs or other high-efficiency gasoline vehicles (averaging 42.5 mpg) may prove a more effective GHG abatement strategy in the short term, say over the next decade, rather than PHEVs.

In contrast, a longer-term perspective suggests a plausible trajectory for achieving deeper GHG reductions from PHEVs beyond the next decade. A logical starting point is to provide consumers with the PHEV designs they presently want (B-X, shorter CD range, higher fuel economy in CS mode). This starting point of cheaper B-X designs could set the stage for future commercialization of AE-X designs by increasing consumer experience with, and exposure to, PHEV technology, increasing consumer valuation of AE-X capabilities and reducing battery and drivetrain costs due to increased manufacturing experience. With the emergence of less-carbon intensive electricity sources, a transition from B-X to AE-X designs could lead to deeper long-term GHG reductions than a strategy that focuses only on HEVs or AE-X designs.

We offer several key conclusions.

- Even if PHEVs do not currently offer larger incremental GHG reductions relative to HEVs, they could with future, less-carbon intensive electricity sources.
- Policymakers and researchers should not overlook the cheaper, lower battery-capacity B-X PHEVs that consumers presently design. Such designs are not only likely to be easier to sell to more consumers than AE-X variants, but we estimate they may also initially yield similar or larger GHG reductions.
- PHEV impact analyses can be improved by explicitly consulting potential users. Survey respondents designed vastly different PHEVs than the AE-X designs assumed by previous studies. Even if the near- to mid-term market for PHEVs contains less variety than the distribution of User designs, uniform assumptions regarding PHEV designs contradict the PHEV designs of our respondents and the forces that create variation across vehicle makes and models.
- Empirically observed recharge potential suggests that without substantial policy intervention, actual recharge behavior is likely to follow a much different and more diffuse recharge profile than previously assumed.

Finally, we acknowledge that our study focuses only on GHG emissions. Consideration of other potential PHEV benefits such as energy security, air quality and promotion of renewable energy are left to other research. In any case, it strikes us as compelling to begin with the PHEV designs consumers want to buy as the starting point of a trajectory toward achieving these benefits.

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Appendix

Table A1. Summary of PHEV impacts literature

Study	Base vehicle (MPG)	Recharge profile inputs			Electricity (gCO_2e/kWh)	GHG reductions from ICEV baseline (from HEV base)
		PHEV type (CD kWh/mile)	Driving patterns (utility factor)	Recharge patterns		
Studies *with* GHG emissions analysis						
EPRI (Duvall et al., 2007)	ICEV (30) HEV (46.3)	AE-10, 20, 40 17 models (0.26-0.31)	U.S. VMT distribution (12-66%)	EPRI profile (74% off-peak)	Marginal, 2050 U.S. dispatch model: (300-430)	38-65% less (4-46% less)
Samaras and Meisterling (2008)	ICEV (30)	AE-19, 38, 56; Toyota Prius (0.32)	2001 NHTS distribution (47-76%)	Daily recharge	Annual avg,, U.S. (200-950)	15-51% less (47% less to 18% more)
Stephen and Sullivan (2008)	ICEV (19) HEV (27)	AE-40; RAV-4 SUV (0.41)	CD only (100%)	Nightly recharge (valley-filling)	Marginal, U.S. elasticities (692-1072)	59% less (40% less)
Hadley and Tsvetkova (2008)	HEV (40)	AE-20; Sedan (0.26-0.30) SUV (0.39-0.47)	CD only (100%)	Evening/ nightly (120 or 220 V)	Marginal, 2020-30 U.S. dispatch model (600-690)	(3% less to 10% more)
Silva et al (2009)	Series (54) Parallel (49)	15 kWh vehicles (0.12 to 0.20)	Drive cycle simulations (U.S., EU,)	Daily recharge	Annual average, U.S. (543) EU (387)	(30-50% less)
NAS (2009)	ICEV (32-41) HEV (45-60);	B-10, AE-40; sedan; (0.08, 0.21)	U.S. VMT distribution (23- 63%)	Nightly recharge	Annual average, 2050 U.S EIA (520) EPRI (210)	(small reductions)
Present Study	User CVs (28 avg.)	User distribution (see Figs. 3 and 4, Table 2)	User diary distributions (see Table 4)	User informed scenarios (see Fig. 5)	Marginal and avgerage, CA dispatch model (see Table 3)	2010: 27-50% less 2020: 35-61% less
Studies *without* GHG emissions analysis					(GHGs omitted)	(Other results)
Lemoine et al. (2008)	CV (37.7) HEV (49.4)	AE-20, compact car (0.25)	CD only	Scenarios	CA on peak day, Aug 3rd, 1999	Grid can accommodate 1 million PHEVs
Sioshansi and Denholm (2009)	n/a	AE-22; car (0.30)	St. Louis Travel Survey	Whenever parked (120 or 240 V)	Texas dispatch model, time of day	V2G can offset grid GHG increases
Kang and Recker (2009)	n/a	A-20, 60; compact (0.21), SUV (0.32-0.37)	2001 California Travel Survey	Scenarios: (120 or 240 V)	Hourly California ISO data	Home charging can power 40-80% for PHEV

Table A2. Recharge profiles for 1 million PHEVs, by hour (MW) and total (MWh), for weekdays (WD) and weekends (WE)

Time	USER Designs						AE-20						AE-40					
	Plug/Play		Workplace		Off-peak		Plug/Play		Workplace		Off-peak		Plug/Play		Workplace		Off-peak	
	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE	WD	WE
0:00	49	95	50	93	212	194	470	412	437	418	703	660	758	711	487	698	1,142	1,066
1:00	63	32	60	31	212	194	373	294	343	302	703	660	614	487	426	427	1,142	1,066
2:00	6	0	6	0	212	194	269	280	237	288	703	660	411	430	337	326	1,142	1,066
3:00	0	0	3	0	212	194	169	204	167	204	703	660	287	322	254	229	1,142	1,066
4:00	0	3	3	3	212	194	124	113	120	108	703	660	176	208	141	163	1,142	1,066
5:00	1	12	15	11	212	194	52	71	68	70	703	660	68	105	82	104	1,142	1,066
6:00	33	12	83	11	0	0	50	31	111	31	0	0	80	62	187	61	0	0
7:00	49	13	212	17	0	0	74	21	289	25	0	0	142	42	538	49	0	0
8:00	88	72	266	117	0	0	87	99	432	147	0	0	138	173	639	269	0	0
9:00	87	56	258	92	0	0	131	167	493	213	0	0	240	127	797	222	0	0
10:00	69	53	151	54	0	0	167	99	520	148	0	0	236	104	711	203	0	0
11:00	59	101	126	101	0	0	161	115	495	166	0	0	234	178	674	280	0	0
12:00	72	164	126	169	0	0	143	200	422	267	0	0	210	324	602	407	0	0
13:00	137	198	198	197	0	0	219	296	472	348	0	0	356	520	678	521	0	0
14:00	152	182	219	179	0	0	242	385	471	434	0	0	416	598	652	593	0	0
15:00	197	158	208	155	0	0	334	432	501	460	0	0	565	621	714	615	0	0
16:00	237	185	198	184	0	0	434	467	539	464	0	0	643	677	703	677	0	0
17:00	259	265	248	262	0	0	543	571	540	568	0	0	784	823	772	822	0	0
18:00	357	258	346	251	0	0	649	571	621	564	0	0	1,011	781	947	771	0	0
19:00	351	127	293	118	0	0	726	591	700	581	0	0	1,244	815	1,107	790	0	0
20:00	198	125	176	125	212	194	720	550	657	529	703	660	1,144	875	966	867	1,142	1,066
21:00	148	131	140	144	212	194	716	525	639	536	703	660	1,061	980	853	994	1,142	1,066
22:00	123	129	120	139	212	194	707	524	640	529	703	660	985	914	758	916	1,142	1,066
23:00	94	86	85	96	212	194	607	485	563	484	703	660	890	792	613	801	1,142	1,066
Total	2,828	2,453	3,590	2,550	2,115	1,936	8,165	7,501	10,477	7,881	7,026	6,605	12,691	11,669	14,638	11,803	11,416	10,660

Table A3. Time of day marginal emissions for User scenario, plug and play, averaged on a monthly basis from 2010 EDGE-CA (gCO_2e/kWh).

Hour	J	F	M	A	M	J	J	A	S	O	N	D	Year
0:00	595	566	573	540	522	575	588	717	714	604	566	610	579
1:00	586	566	566	516	549	572	540	717	595	609	566	597	566
2:00	569	566	540	516	516	544	534	566	544	566	566	553	546
3:00	566	566	566	516	516	535	534	566	566	595	595	553	553
4:00	--	--	--	--	--	--	--	--	--	--	--	--	--
5:00	717	595	717	566	542	566	626	717	717	717	717	717	629
6:00	717	717	717	591	553	626	717	726	726	717	717	717	717
7:00	717	717	717	717	626	717	726	731	720	717	717	717	717
8:00	717	717	717	730	717	726	763	766	763	717	717	717	717
9:00	717	717	717	726	722	726	766	766	763	717	717	717	725
10:00	717	717	726	722	726	763	763	745	763	722	717	717	726
11:00	717	717	726	726	763	763	766	808	763	742	726	717	726
12:00	717	717	726	726	763	740	766	811	763	746	717	722	726
13:00	717	717	723	726	763	745	811	812	766	744	717	723	739
14:00	717	717	722	724	763	763	811	812	766	726	717	723	738
15:00	717	717	726	717	735	745	811	811	763	729	717	726	729
16:00	717	717	722	726	726	745	811	848	763	722	721	726	726
17:00	726	726	717	717	722	740	766	812	748	726	717	725	726
18:00	726	726	718	720	723	763	766	766	745	753	723	726	729
19:00	726	725	726	722	745	739	766	766	763	739	717	726	726
20:00	725	723	726	722	763	763	766	766	763	717	717	717	726
21:00	717	717	717	725	717	739	766	766	726	717	717	718	723
22:00	717	605	711	575	563	717	726	763	743	717	717	725	717
23:00	626	566	717	540	516	623	726	721	717	717	610	717	626
Avg	714	693	710	696	702	736	763	778	750	722	708	718	724

Table A4, Time of day marginal emissions for User scenario, plug and play, averaged on a monthly basis from 2020 LEDGE-CA (gCO_2e/kWh).

Hour	J	F	M	A	M	J	J	A	S	O	N	D	Year
0:00	530	515	482	461	442	432	474	540	530	505	514	524	498
1:00	519	505	471	443	435	421	462	527	511	494	505	522	490
2:00	512	488	434	418	407	382	434	502	482	486	496	496	456
3:00	516	482	448	442	407	369	436	501	495	485	498	501	459
4:00	--	--	--	--	--	--	--	--	--	--	--	--	--
5:00	570	528	498	470	403	395	455	535	567	528	546	552	515
6:00	586	562	500	465	432	407	476	528	558	539	566	574	520
7:00	589	564	500	476	440	440	503	566	569	533	544	571	515
8:00	576	572	511	483	463	467	528	581	589	542	563	560	531
9:00	585	564	522	501	496	493	563	591	597	566	571	564	552
10:00	580	564	526	513	537	522	597	632	615	584	576	564	558
11:00	580	565	528	509	543	550	614	643	611	604	558	565	572
12:00	574	570	512	507	549	556	630	659	633	596	568	567	571
13:00	565	567	520	510	556	567	638	685	597	600	566	543	573
14:00	560	570	510	502	541	563	630	673	606	593	557	541	567
15:00	556	558	519	501	551	564	613	682	627	590	556	546	565
16:00	573	570	509	492	516	549	604	674	619	599	608	578	571
17:00	592	571	516	491	508	562	633	656	619	596	586	613	580
18:00	595	604	513	482	493	514	581	643	622	595	593	601	581
19:00	604	595	539	537	506	529	554	624	623	583	592	610	580
20:00	612	606	561	542	549	521	581	627	624	597	592	612	592
21:00	605	595	527	525	538	554	581	609	612	606	620	610	587
22:00	595	559	504	479	488	493	535	612	584	557	567	589	548
23:00	546	528	489	458	452	441	501	581	545	523	529	548	513
Avg	577	568	521	496	515	520	585	626	607	582	569	582	562