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**Households' Plug-in Hybrid Electric Vehicle Recharging Behavior:
Observed variation in households' use of a 5kWh blended PHEV-conversion**

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs), which run on both electricity from the grid and gasoline, are touted as providing some of the societal and environmental benefits of electric vehicles for a large portion of motorists' daily travel, while also acting as a transitional technology toward fully electric vehicles. To test analysts' assumptions about how PHEV users will recharge their vehicles, the observed recharging behaviors of forty households that participated in a PHEV demonstration in Northern California are reported. Recharging behavior is summarized across all households' last week of their four-week PHEV trial period with regards to the time-of-day, frequency of plugging-in, and electricity demand to recharge the vehicles. While the means of the frequency distribution of plug-in events among demonstration households is similar to prior recharging assumptions made by analysts, the distributions are not symmetrical about the mean and there exists a large variation in both the average number of times households plugged-in per day and the average energy per plug-in event. Further, there is no strong correspondence between the number of daily plug-in events and total daily electricity demand. The range of behaviors reported here support the contention that the success of PHEVs in meeting energy and emissions goals relies on PHEV users' recharging and driving behavior as much or more as on PHEV designs.

INTRODUCTION

Electric drive vehicles (EVs) promise societal and environmental benefits, such as reductions in the use of fossil fuels, improved local air quality, decreases in greenhouse gas emissions (GHGs) (1), and possible increases in the overall efficiency of the electrical grid (2, 3). Plug-in hybrid electric vehicles (PHEVs) which run on electricity from the grid and gasoline are claimed to provide some of the societal and environmental benefits of all-electric vehicles, while offering consumers the option to use gasoline on extended trips or during periods of high top speeds and aggressive accelerations, thus creating a path by which light-duty vehicles can be incrementally electrified (4).

However, given the public's general unfamiliarity with electricity as a transportation "fuel," it is unclear to what extent consumers will choose, given the option, to recharge PHEVs from the electrical grid rather than refuel them with gasoline. The issue is germane to policy makers and analysts since the incremental economic, societal, and environmental benefits of PHEVs (beyond the gasoline fuel economy benefits of hybrid drivetrains) depend on users driving and recharging behaviors, as well as on vehicle designs. Furthermore, the distribution of time-of-day electricity used to recharge PHEVs and EVs could have serious implications for electricity providers, as they try to meet the additional distributed demand. Depending on electricity production and distribution infrastructures, various regions of the country might be affected differently by PHEV recharging (5). Time of day effects also vary: nighttime recharging will help level demand and can increase the overall efficiency of the system, day time charging may exacerbate existing demand peaks. Regardless of region or time of day, a growing PHEV fleet will be part of an increasing electricity demand that will require new power plants in most regions by 2030 (5). In addition to power plants, transmission and local distribution infrastructure may need to be updated and expanded. Accurate information about how PHEVs are driven and recharged can help planners manage the grid to accommodate PHEVs and EVs. Vehicle manufacturers and air quality and energy regulators also stand to benefit from a better understanding of recharging behavior, as standardized test procedures do not yet exist for air quality, fuel economy, and safety (6). Finally, armed with information about recharging behavior, battery manufacturers may more accurately model battery life and cost.

Assumptions About Recharging Behavior

To address basic questions about PHEVs' impacts on the U.S. electricity grid, as well as on environmental and climate policy, analysts have assumed driving and recharging behaviors, e.g., the day-to-day frequency and time of day of recharging. As demonstrated by (7), differences in assumptions as to time of day recharging produce very different estimates of electricity grid impacts. Table 1 summarizes some recent PHEV analyses and their recharging assumptions. These assumptions represent educated guesses or possible scenarios of aggregate behavior. However, and to the extent these assumptions are averages, they do not take into account the possible distribution of behaviors. To start the process of replacing assumptions with data from real people who drove and recharged a PHEV in the context of their daily lives, this paper reports on the observed PHEV recharge behavior of households participating in four-week PHEV trials in northern California.

From Table 1, analyses by (10) and (11) don't assume time of day and daily frequency, but use daily travel data (though each very differently) to determine the actual arrival times of vehicles at recharging locations assumed in each scenario. However, these analyses do assume where PHEV drivers will recharge and whether or not they would recharge their vehicles at any

particular location (and time). To explore the implications of their assumptions, these studies posit recharging scenarios in which all PHEV users are assumed to exhibit the same behaviors, e.g., everyone recharges at work, users can only recharge at home and do so every time the vehicle stops there, users only charge off peak, etc.

TABLE 1 Summary of Past PHEV Recharging Assumptions

Report	Battery Capacity	Recharge Profile	Charging Frequency
PNNL (8)	13kWh	100% of PHEV battery capacity, all between 10pm and 6am	Every vehicle, once a day.
EPRI (9)	5.8 kWh & 17.9 kWh	76% of PHEV battery capacity recharged between 10pm and 6am 24% of PHEV battery capacity recharged between 6am to 10pm	Every vehicle, once a day.
NREL (10)	7.2 kWh	Based on GPS travel data from conventional vehicles. Used multiple scenarios to create an array of recharging profiles including plug-in frequencies	<p>Uncontrolled Charging: Charge only at home; plugged-in immediately after the vehicle arrives home until it is fully charged or driven again.</p> <p>Delayed Charging: All charging occurs at home, but only after 10 p.m.</p> <p>Off-peak Charging: All charging occurs at home overnight, but utility matches vehicle charging precisely to periods of minimum demand.</p> <p>Continuous Charging: The vehicle charges whenever it is parked, limited by the battery capacity.</p>
ITS (11)	1.5 kWh to 15 kWh	Vehicle start and stop charging times based on travel diary data from conventional passenger vehicles. Used multiple scenarios to create an array of recharging profiles including plug-in frequency	<p>Plug and Play (P&P): The vehicle is recharged every time it is parked within 25ft of an outlet.</p> <p>Off-peak only: Vehicle is recharged every time it is parked within 25ft of an outlet, between 10 p.m. and 6 a.m.</p> <p>Enhanced worker access: P&P plus, recharging occurs while vehicle is parked at work (even if the vehicle is not now parked within 25 ft of an outlet at work).</p>

While assumptions such as these about individual recharging behavior have been applied to estimate the impacts of a PHEV fleet, there is little data on how PHEV users recharge their vehicles, given the opportunity to do so. The observation of PHEV recharging behavior allows for comparison to prior assumptions and the exploration of differences in weekend vs. weekday travel and recharging, lifestyle, and access to places to recharge.

PHEV HOUSEHOLD DEMONSTRATION AND MARKET RESEARCH

The recharging behaviors reported in this paper were observed in a PHEV demonstration and research project in which households drove a PHEV for four weeks. The project is described in more detail in (12). This paper presents the data from the first forty households, gathered between August 2008 and June 2009. Households were asked to completely substitute a PHEV-conversion for one of their pre-existing vehicles. Households within the geographic study region were invited to participate in the PHEV demonstration through a mailer sent out by their automobile insurer. Households that wanted to volunteer for the study completed an online screening questionnaire. Participants were non-randomly selected based on a number of characteristics such as age, life stage, vehicle holdings, and geographic location to ensure a variety of household types, vehicle market segments, and vehicle use types. Households were required to have access to a standard electrical outlet (110-120V/10A) at their home where they could recharge the vehicle—if they chose to recharge it. Geographically, the participants lived in the cities and towns along Interstate 80 in Northern California, including Solano, Yolo, Sacramento, and Placer counties. As intended, the sampling method recruited households that varied in their prior understanding of electric drive vehicles, beliefs about political and environmental issues, and vehicle ownership (12).

At the beginning of each household's PHEV trial, participants received no information about when to recharge the vehicle, how often they should recharge, or if they should recharge at all—though the clear implication was that since the car *could* plug in and use both gasoline and electricity, there must be some reason to recharge. Throughout each household's PHEV trial, researchers were careful to place recharging in the context of an act of discovery by the household—something the household could do. Participants were told the approximate charge depleting range of the vehicle, assured that the vehicle would still run on gasoline if they chose not charge or depleted the battery's charge through the course of the day, and how to read the in-vehicle supplemental battery gauge.

Vehicles

The PHEVs used in this project are conversions of Toyota's Prius hybrid vehicle. The conversion adds a 5 kWh lithium ion battery that can be recharged from a standard 110-120v/10A household outlet. A fully discharged battery will recharge completely within five to six hours. As PHEVs, the conversions can operate in charge depleting (CD) and charge sustaining (CS) modes. The conversion does not change the underlying engine management or control strategies; while in CD operation far more electricity is substituted for gasoline than in a stock Prius, but the car still uses gasoline and electricity more or less continuously under real-world driving conditions. Driving on electricity only, i.e., all-electric operation, is limited to modest accelerations and speeds less than ~35 mph (13). Starting with a full charge, demonstration drivers achieved 25 to 35 miles of CD blended operation. Once the supplemental battery is discharged, the vehicle switches to CS operation, in which the vehicle reverts to operating as a hybrid (4).

On-board data loggers recorded information about the vehicle, including data about gasoline consumption, the vehicle's location, and battery state of charge (SOC). Vehicle use and recharging data were recorded at one second and one minute intervals, respectively. Throughout their PHEV trial, participants were given access to a website where they could track their vehicle, including gasoline and electricity use, as well as estimates of costs, trip and daily driving distances, recharging times, battery SOC, and estimates of carbon emissions.

Comparative Data on Recharging

PHEV recharging behavior analyzed here is based on the last week of each household's trial. This provides a common period over which the same number of days and days of the week can be compared. Further, since households had developed their recharging habits by this last week (or had developed their habits as much as they were going to in the course of a four week long experiment), their final week with the PHEV is most representative of how these vehicles would be recharged by the households if the households actually owned these PHEV-conversions. The households generally confirmed this in their final interviews with researchers, often describing recharging as normal or routine (12).

Context to Interpret Results

Frequency of recharging is perhaps the daily behavior that most affects the energy, social, and environmental benefits of PHEVs (14, 15). Other important behaviors include the purchase of a PHEV with a CD range that will allow the household to accomplish the greatest proportion of miles driven in CD mode (constrained by the expense of buying too much CD driving range) before their next recharge opportunity, as well as driving behaviors which affect overall efficiency, notably accelerations, top speeds, and choice of routes (16, 17). The context for interpreting the PHEV recharging behavior observed to-date in this demonstration project is as follows.

First, the participants were able to recharge a PHEV at their home. Second, as households reported they lacked a sense of the etiquette that would shape recharging at away-from-home locations, less away-from-home recharging was observed than may otherwise occur in a world where the rules and conventions are known. Households who noticed "EV parking" and recharging spaces often asked us whether they could park and charge their PHEVs in such spaces. The few bolder individuals who attempted this discovered that such spaces lacked 110-volt outlets suitable to recharge the PHEVs they were driving. Many households also said they were uncertain of the propriety of asking friends, acquaintances, employers, and business-owners if they could plug-in. In one household, plugging in at work would have required a participant to take her boss's reserved parking space. Third, no household paid time-of-day electricity tariffs which might encourage or discourage recharging at different times of day (and therefore possibly different locations). Fourth, participants had to find recharging within the existing network of electrical infrastructure. In addition to being restricted to existing electrical outlets, this limit was experienced by participants in terms of the length of the provided electrical cord (50 feet; 15.24 meters), its risk as a tripping hazard, and participants' fear of the theft of the cord.

The location and time-of-day of recharging are related in that some away-from-home recharging opportunities, e.g., workplaces, would most often occur during the day for most employees at times when electricity prices would presumably be higher under time-of-day tariffs, especially during afternoons and early evenings. Such tariffs will present PHEV drivers

with countervailing signals—maximize their CD miles by recharging, but incur higher electricity costs to do so.

In summary, the recharging frequency data reported here is from households who can recharge at home, whose recharging frequency is constrained by a general lack of away-from-home recharging opportunities (as created by the lack of both physical infrastructure and social norms) and perceived risks, but unconstrained by differential electricity prices or other signals.

In addition, PHEV recharging behavior may also be shaped by the relationship between personal travel and vehicle design, in particular, CD type—all-electric or blended—and CD range. If these same households had been given PHEVs with a different CD range or all-electric CD range, the frequency with which they recharged might be different than observed.

In the discussion that follows, weekdays and weekend days are examined separately. Weekdays may provide routines to daily life, including vehicle travel, e.g., daily commutes that influence observed recharging behavior. Weekends may lack these routines or have their own, e.g., trips for worship or recreation. Hence, driving and recharging behavior, access to a recharging location, and the time of day power demand, may differ between weekdays and weekend days.

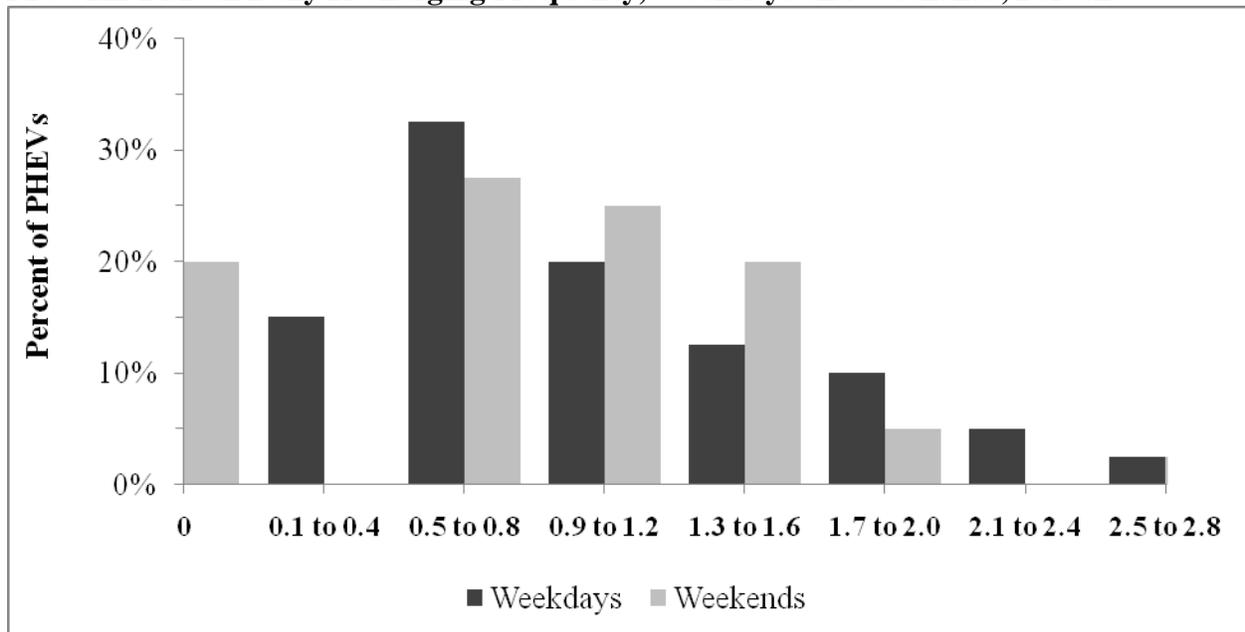
RESULTS

How Many Times Do PHEV Drivers Plug-in?

From here forward, the phrase “plugging-in” refers to all acts of connecting the vehicle to the electrical grid, regardless of the initial state of charge when the vehicle is plugged-in or the final state of charge of the battery when the vehicle is unplugged. This definition creates a more general category of vehicle recharging that contains both “recharging” with its connotations of returning the battery to 100 percent SOC, and “partial recharging” in which the vehicle is unplugged and driven before the battery reaches 100 percent SOC.

The mean number of times per day that each household plugged-in their PHEV on weekdays and weekend days was calculated; the frequency distributions of these means are plotted in Figure 1. The weekday distribution of mean daily plug-in events ranges from zero to 2.6. Two households recharged zero times during their final week. One believed that recharging made too little difference—compared to the substitution of an HEV into their household fleet—to make recharging worthwhile. The other believed that leaving the vehicle plugged-in unattended posed a fire hazard. The distribution of the mean number of daily plug-in events on weekend days ranged from zero to 2.5 per day.

Plugging-in occurs less frequently on average on weekend days than on weekdays largely because about one-fifth of households did not plug in at all on the weekend days observed in their last week driving the PHEV. The PHEVs were often taken on out-of-town trips on weekends, but were rarely if ever charged during these long, and often overnight, journeys. This is supported by the fact that the average number of daily plug-in events per household was higher on Sundays (0.94) than Saturdays (0.71)—consistent with some PHEVs returning on Sunday from an overnight trip that started on Saturday (or Friday). Such differences between individual days are provisional, and must be regarded as supportive but not conclusive evidence. Further, the households that did not plug in at all on the weekend also charged less frequently on weekdays, on average 0.5 times less. Therefore, those households that had not developed a frequent weekday recharging routine tended to carry that lack of recharging into the weekend, even if they had access to an electrical outlet.

FIGURE 1 Mean Daily Recharging Frequency, Weekdays and Weekends, Percent.

Overall, the mean of the weekday distribution is slightly more than one plug-in event per day (1.05). However, the number of times each household plugged in per day varied widely across households: 16 households (40 percent) plugged in their PHEV more than once per weekday, and over 25 percent plugged in more than 1.5 times per weekday. Across weekdays, the difference in households' mean frequency of daily plug-in events ranged from a high of 1.24 per PHEV on Wednesday to a low of 0.88 on Thursday. Presently, these observations for individual days are regarded as provisional. With regards to weekends, households plugged in on average 0.7 times per day, and 12 households (30 percent) plugged in their PHEV more than once per weekend day.

Households varied in their prior knowledge of electric drive, understanding of how the PHEV worked, and motivation and opportunity to recharge away from home. Most respondents who recharged less than once a day lacked an understanding of when they were driving in CD mode, their CD range, and the effect that recharging had on the performance of the vehicle (12). Among those participants who did regularly plug-in the PHEV at least once a day, recharging was described as a daily household task or chore, "like feeding the dog or taking out the garbage." In these households, failure to recharge on a given day was often caused by a disruption to their routine, e.g., returning home later than usual in the evening and forgetting to plug-in. The interviews revealed that the act of recharging was seldom seen by these households to be bothersome or difficult. Rather, most households, except for the two already mentioned who did not recharge at all during their last week, found recharging easy, convenient, and worthwhile. While many respondents expressed the value of plugging-in by commenting how much longer they were able to forgo trips to gasoline stations. Households did vary in their motivation to recharge, touching on themes of national security, air quality, resource use, saving money, convenience, and opposing the politics of oil (12).

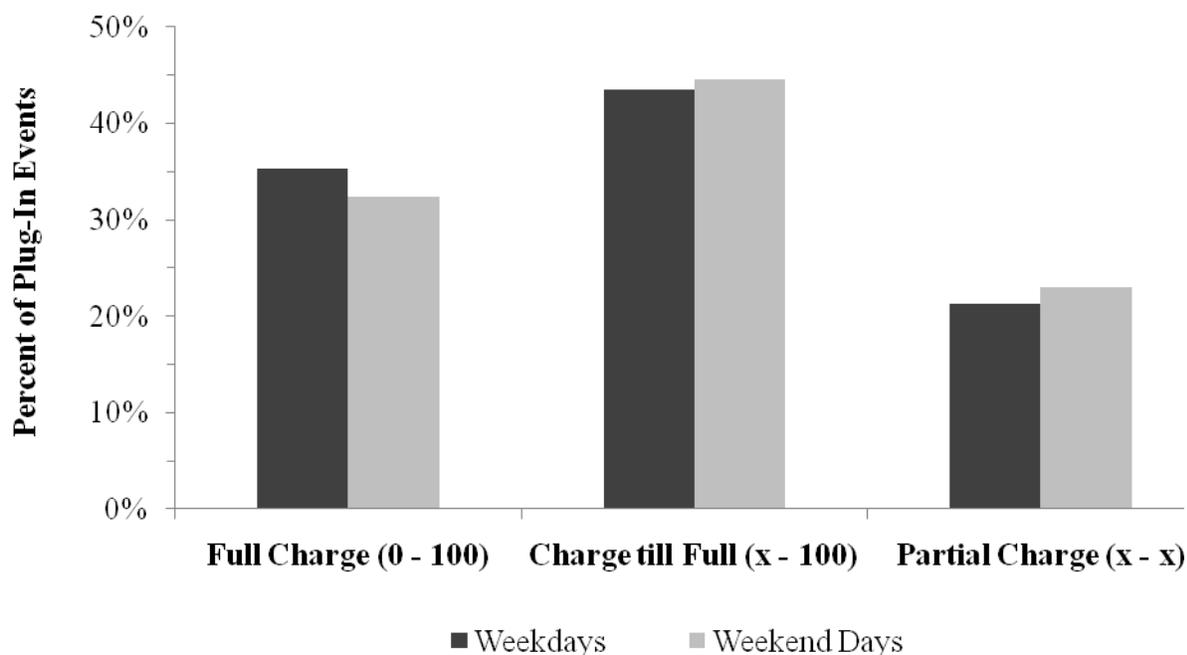
Those participants who plugged their PHEV in more than once a day included those that had access to a plug at work and those that recharged the vehicle multiple times per day at home. The two households that recharged at work plugged-in on average 2.0 and 2.6 times per

weekday. They plugged-in as soon as they arrived at work, and if they used the car to leave work during the day they would plug-in again after returning to work. They typically would recharge again at home in the evening. For those households that plugged-in at home more than once a day, some were able to do so because the PHEV remained at home for most of the day. These included households of retired individuals, households in which a homemaker was the PHEV driver, and households in which an employed person worked from home. Households that did use the vehicle for a daily commute and that recharged more than once a day on average, made conscientious use of opportunities, such as plugging-in when the vehicle arrived at home in order to receive a partial charge before going out again later in the evening—sometimes even delaying evening trips to allow the vehicle to be partially recharged.

How Often do People Fully Recharge the PHEV?

The observed plug-in events differed not only in location and frequency, but also in the amount of energy stored in the supplemental battery per event. Figure 2 shows all plug-in events for weekdays (n=210) and weekend days (n=68), classified in three categories: 1) a full charge from the minimum to maximum state of charge (SOC); 2) a charge to 100 percent SOC from higher than the minimum SOC; and, 3) a partial charge from something higher than the minimum SOC to something less than fully charged.

FIGURE 2 Distribution Of Plug-in Events.



Less than forty percent of all plug-in events were of the first type, i.e., full charges. Recharging the battery until it was full, i.e., the sum of the first two types of plug-in events, was by far most common. Full charges, as identified here, required on average of just over 4.6 kWh per event. The second category—partial charges from more than 0 percent to 100 percent SOC—consumed an average 2.4 kWh per event. These partial recharges were due to households that travel less than their CD range in the PHEV on a daily basis and recharge once a day, and those households that exceed their CD range every day and plug-in more than once a day. The last

category—partial charges consumed from more than 0 to less than 100 percent SOC—consumed 1.5 kWh, on average. These partial charges occurred in households that plugged-in more than once a day, including, households in which the PHEV driver was based at home and would plug-in throughout the day, and households that drove the PHEV to work during the day, plugged-in the vehicle upon returning home in the evening, and then took the car out again before parking and plugging-in for the last time that day upon their re-arrival at home.

Electricity Availability and Power Demand

To describe PHEV plug-in and recharge behavior over the course of a day, two measures are summarized: electricity availability and power demand. Electricity availability is the time of day during which the vehicle was plugged into an electrical outlet. Conceptually, this means that the supplemental battery could be at any SOC or the vehicle at any location—so long as it is connected to the grid, electricity is available to the vehicle. Power demand refers to the electricity drawn from the grid to recharge the PHEV battery. Therefore the time over which power demand is accumulated is a subset of the time during which electricity is available to the vehicle. The observed average recharging rates for these PHEV-conversions generally fell within the range of 900 and 1,200 Watts. In order to compare and summarize across households, power demand is standardized (by assumption) to be 1,000 Watts. Additional loads for the battery cooling system (in the range of 30 to 50 Watts), brief periods of higher demand during the initial phases of battery charging, and longer periods of lower demand at end of the charging cycle have been ignored. Electricity availability and power demand are represented as the range in the percentage of PHEVs plugged in and the power demand required to recharge the vehicles, at a specific time of day, for a 24-hour period, across all weekdays and weekend days. The households' data are treated as if they had occurred during the same calendar week.

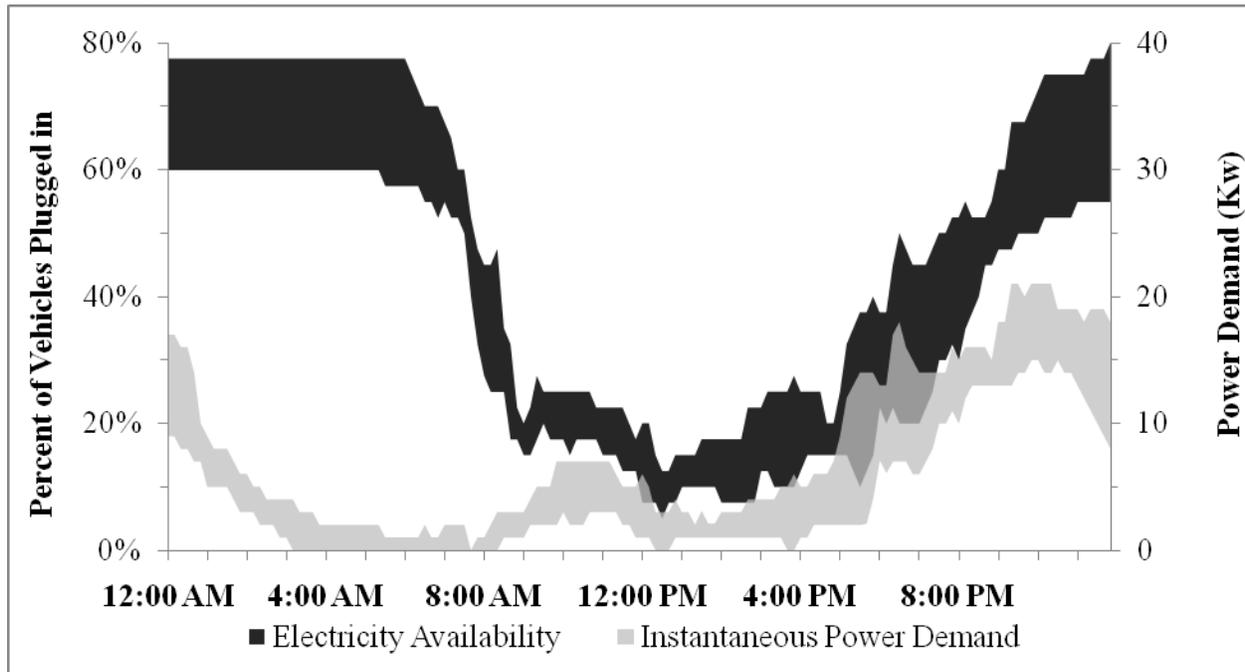
Electricity Availability & Power Demand: All Weekdays

Figure 3 shows daily variability in electricity availability as the percentage of vehicles plugged in at a given time, for all weekdays (in red, and on the left axis) and the power demand to recharge the vehicles (in blue, and on the right axis). Since daily electricity availability and power demand varied within each household from day to day, the bottom edge of the red and blue areas represent the lowest values observed at each point in time on any weekday, and the top edges the highest values.

As the red area shows, across the 200 weekdays represented in Figure 3 (40 households times 5 weekdays each), electricity was available to 60 to 75 percent of households' PHEVs between 10:00 pm and 6:00 am. By 9:00 am only 20 to 23 percent of households had their PHEV connected to the grid. This is explained by the number of drivers in the demonstration that have full time jobs and typically leave home in the morning to go to work. While there were two households that charged during the day while at work, the remainder of the PHEVs that plugged into the electrical grid during midday are due to retired individuals, participants that worked at home, and those who otherwise were typically at home during the day. At 4:00 pm, when households start to return home from work, vehicles begin to be plugged in, until 10:00 pm by which time the percentage of households connected to the grid stabilizes again at about 70 percent. The greatest difference—in excess of 30 percentage points—between lowest and highest percentages of households plugging in their PHEV occurs during the early evening, and reflects the variability both 1) within and across households in when they plug in the vehicle during the evening and 2) variation across different days of the week. The lower boundary of the electricity

availability during the evening is largely defined by Friday night when more people tended to plug in the PHEV later in the evening than they did on other weekdays. For the time period between midnight and 6:00am, the lower values are predominantly due to the recharging behavior on Monday nights.

Figure 3: Observed High and Low values for Weekday Electricity Availability and Power Demand for 40 Households



As the red area shows, across the 200 weekdays represented in Figure 3 (40 households times 5 weekdays each), electricity was available to 60 to 75 percent of households' PHEVs between 10:00 pm and 6:00 am. By 9:00 am only 20 to 23 percent of households had their PHEV connected to the grid. This is explained by the number of drivers in the demonstration that have full time jobs and typically leave home in the morning to go to work. While there were two households that charged during the day while at work, the remainder of the PHEVs that plugged into the electrical grid during midday are due to retired individuals, participants that worked at home, and those who otherwise were typically at home during the day. At 4:00 pm, when households start to return home from work, vehicles begin to be plugged in, until 10:00 pm by which time the percentage of households connected to the grid stabilizes again at about 70 percent. The greatest difference—in excess of 30 percentage points—between lowest and highest percentages of households plugging in their PHEV occurs during the early evening, and reflects the variability both 1) within and across households in when they plug in the vehicle during the evening and 2) variation across different days of the week. The lower boundary of the electricity availability during the evening is largely defined by Friday night when more people tended to plug in the PHEV later in the evening than they did on other weekdays. For the time period between midnight and 6:00am, the lower values are predominantly due to the recharging behavior on Monday nights.

Electricity availability tells us when the vehicles were connected to the grid; the blue area in Figure 3 shows actual power demand to recharge the vehicles. Given the households' PHEV

driving and recharging behaviors, electricity demand to recharge their vehicles starts to rapidly increase at 5:00pm, and peaks just after 10:00pm. It then declines steadily through the night and into the morning, reaching practically zero by 5:00am. While there were a few households that charged during the day at work, most of the demand to recharge these vehicles was between 9:00am and noon. The most variability in power demand occurs in the evenings between 5:00pm and midnight. The lower boundary of the power demand between 4:00pm and 8:00pm is primarily a result of the increased probability of households plugging in the PHEV later in the evening on Fridays. The upper boundary is shaped by a higher percentage of people recharging earlier on Wednesday nights. Regardless of the absolute power level at 5:00pm, there is a rapid increase in the power demanded between 5:00pm and 6:00pm.

By comparing electricity availability and power demand in Figure 4, a picture of aggregate recharging behavior and electricity grid impacts emerges. In the absence of any signals, e.g., prices, etiquette, or supporting systems such as timers, on weekdays households tended to plug in their PHEVs in the early evening, usually upon arriving home, and unplugged them when they left home in the morning. This means that, on weekdays, the period between 5:00pm one day and 9:00am the next morning is the period with the highest average likelihood of a PHEV being plugged in. While the prospect of increases in electricity demand to recharge PHEVs (or any EV) during peak hours is frightening to electricity providers, as well as to energy and environmental analysts, it is clear from a comparison of the red and blue areas in Figure 4 that there is potential to shift electricity demand for these particular PHEVs in these households from early evening until after 10:00pm, since electricity demand to recharge these vehicles declines rapidly after 10:00pm and all recharging is completed by 5:00am the following morning.

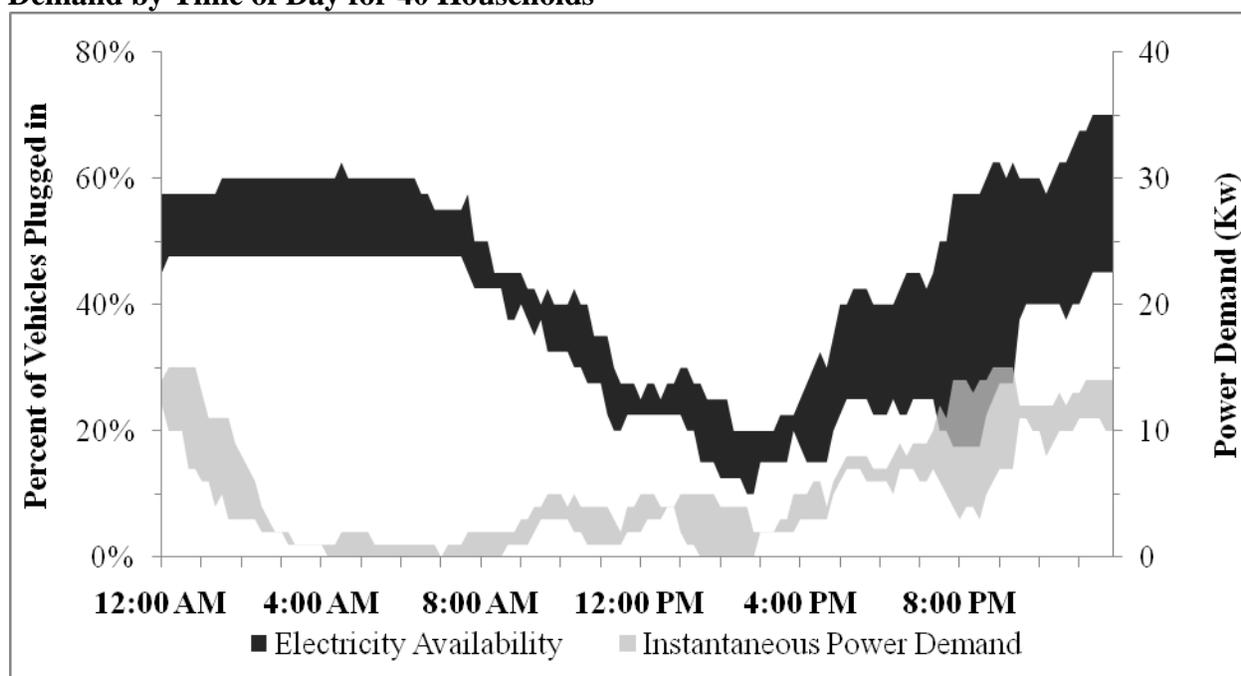
Electricity Availability & Power Demand: Weekend Days

Figure 4 shows weekend electricity availability (in red, on the left axis) and power demand (in blue, on the right). Fewer PHEVs are plugged in during the weekend high availability period than during the weekday high availability period: 50 to 55 percent of vehicles were plugged in between 11:00pm and 6:00am on weekends compared to 60 to 75 percent between 10:00pm and 6:00am on weekdays. The high electricity availability period starts an hour later on weekend nights than on weekdays. While electricity availability decreases toward and into the morning, it does so gradually and does not decline below 15 percent. The incidence of households plugging in their vehicles during the afternoon between 2:00pm and midnight, increases less rapidly than on weekdays. Compared to weekday recharging, it appears as though some individuals, given they had access to an outlet, plugged in their PHEV for longer on the weekend. However, on average, not as many people plugged in their vehicles on the weekend as on weekdays. Overall, there is less variability in the percentage of vehicles plugged in between 8:00am and 4:00pm than between 7:00pm and 12:00pm. The lower boundary during this early night period is defined by Saturday, with people tending to plug in later in the evening. Sunday defines the upper bound of the evening in the figure, with most vehicles plugged in by 8:00pm.

As with weekdays, most weekend electricity demand to recharge the vehicles occurred between 5:00pm and 2:00am. However, much less total energy and lower peak power are required on weekend days than on weekdays. On average, weekend electricity demand increased more slowly over the course of the early evening than on weekdays. In general, this is because, during weekends, the PHEVs are being plugged-in at a higher starting SOC than on weekdays. Essentially, as those vehicles that are plugged in later start recharging, their impact on total

power demand (summed across all households) is less than on weekdays because vehicles that were plugged in earlier have already finished recharging. Unlike weekdays, the greatest difference in electricity demand is in the early morning, around 1:00 am. The upper boundary for the evening electricity demand is due to the demand observed on Saturdays, when people generally recharged later than on Sunday. Again compared to weekdays, on weekends the PHEVs were on average plugged in until later in the morning, recharging took place over a longer time period, and peak power demand was lower in the evening. Since the PHEVs started recharging at a higher SOC and the vehicles were plugged in over a longer period of time, electricity demand increases more slowly over the course of the evening than was the case for weekdays. As with the case of weekday power demand, it appears as though there is an opportunity to shift recharging of these PHEV-conversions by these households to present off-peak electricity demand periods.

Figure 4: Observed High and Low Weekend Day Electricity Availability and Power Demand by Time of Day for 40 Households



DISCUSSION AND CONCLUSION

The results from a demonstration project that provided households of the opportunity to drive a PHEV for four weeks show large variability across households in the incidence of plugging the vehicles into the grid, in terms of the time of day, mean daily frequency, and resulting electricity demand both in total and for each plug-in event. The observed behaviors reported here are based only on the fourth and final week of driving and recharging for 40 households. The final week of driving provides a common number of days and same days of the week and is judged by researchers and households to be the most representative of how these households would recharge the vehicle on an on-going basis. However, this last week is unlikely to be an accurate representation of every week of every household's life. Longer periods of observation will lead to greater observed variation within a household. Furthermore, the participants are all driving

one incarnation of what a PHEV can be—a converted Toyota Prius with 25 to 35 miles of blended-operation CD range provided by a ~5kWh battery. Observed recharging behaviors of other types of PHEVs may reveal correlations between PHEV performance capabilities and driving and recharging behaviors. Finally, it seems likely that PHEV owners may recharge more often than participants in a PHEV demonstration—given that ownership is a much greater commitment. Similar commitment to the “alternative” fuel has been observed among drivers of other types of “dual-fuel” vehicles (20). Thus, the specific numerical results of this research should be interpreted with appropriate caution.

That said, the households in this study are, on average, plugging-in their PHEV conversions about once per weekday, and less frequently on weekend days. More importantly, there is wide variation across the households’ mean frequency of plugging in—from an average of zero to 2.6 times per weekday and zero to 1.5 times per weekend day. While 40 households is a limited sample, the lower and upper observed household weekday means span a wide range of possible behaviors, i.e., it isn’t possible to observe less than no recharging and the maximum observed value is from a household plugging in at home and work everyday. This observed variability is likely to prove more robust than the mean of the distribution, which is likely to change as we learn from more households and the context in which households drive and recharge PHEVs change. The higher frequency of plugging-in on weekdays is because 1) a few households plug-in the PHEV at home and work, 2) multiple plug-in events at home during the day by retired households, homemakers, and telecommuters, and 3) efforts of some households to plug-in multiple times in the same evening. Overall frequency of plugging-in on weekend days is lower because 1) there is no observed workplace recharging, 2) PHEVs are more likely to be away from home and thus away from the primary or sole recharging location, and 3) those households with incomplete understanding of recharging carried their lack of plugging-in through to weekends.

While the average number of plug-in events was observed to be slightly more than the commonly assumed once-per-day on weekdays and slightly less on weekend days, the plug-in frequency among actual PHEV owners could be higher. Dropping the two households who did not recharge at all during their last week increases the mean weekday frequency to about 1.1 plug-in events per day. Dropping the four households who only plugged-in twice during their last week increases the average to 1.2 plug-in events per day for the remaining 34 households. If we believe that people who won’t recharge a PHEV would not buy one in the first place, then this higher value may be more representative of PHEV owners—subject to all the conditions of the demonstration.

Comparing electricity availability and power demand illustrates both when these PHEVs could have been recharged and when recharging actually occurred. It also demonstrates how much power was required to recharge these PHEVs, and when. In general, households plugged in their vehicles after 4:00pm on weekdays and left them plugged in until 6:00am the next morning. While the electricity demand from vehicles being plugged in between 5:00 and 6:00pm creates a relatively rapid increase in grid electricity demand, the differences between “availability” and “demand” areas in Figures 3 and 4 show there is opportunity to shift recharging these PHEVs (with their 5kWh batteries and 110-volt recharging) to present off-peak electricity demand periods. Compared to weekdays, weekends present even greater opportunity to time-shift grid power for the vehicles since 1) fewer are plugged in, 2) those that are plugged in require less electricity to fully recharge, and 3) those that are plugged in tend to remain plugged in longer into the next morning.

The ability to generalize the recharging behavior observed in the PHEV demonstration is limited by several factors. The households in this demonstration were selected in part because of their capability to recharge a PHEV at home. Approximately 52 percent of new car buyers park a car near a suitable electrical outlet at their primary residence (11). For households who lack this basic electrical infrastructure, home recharging would be practically impossible—thus their participation in the market for PHEVs might depend on access to some other location at which they can routinely recharge. In a study of PHEV pioneers, those who lacked both a home and workplace base for recharging were observed to drive their vehicles in CS operation for almost all their miles, i.e., they rarely recharged (19). Interviews with the PHEV demonstration participants revealed factors that affected their recharging behaviors, e.g., whether they had access to workplace recharging, as yet undeveloped etiquette, fear of tripping on the cord, and fire hazards (12). Given the development of away from home vehicle recharging infrastructure, limiting the risk from tripping, and a refined recharging etiquette, it is expected that recharging would be more frequent; by the same token, a wider range of recharging options will lead to an increase in variability in household recharging behavior. The two demonstration households who could recharge at home and work plugged-in more often. As evidenced by these households, and by others in the demonstration who expressed interest in plugging-in at work but lacked access to an outlet there, workplace recharging would increase the average number of plug-in events and the proportion of miles driven in CD mode.

For nighttime recharging, opportunity exists to delay recharging of these PHEVs until well after existing peak electricity demand. While most people plugged in the PHEV between 5 p.m. and 10 p.m., the vehicles remained plugged in until the next morning. To limit on-peak PHEV recharging, it might be predicted that more expensive electricity would be sufficient deterrent. Yet, despite the provision of a tool to track gasoline and electricity costs, most households had little or no understanding of how much it cost them to refuel or recharge the vehicle (12). It is not possible to estimate the impacts of time-of-day (or location-based or power-based) pricing based on this study. Such pricing produces countervailing signals for households seeking to maximize CD operation, avoid trips to gasoline stations, access the symbolic meanings of driving on electricity, or achieve high (gasoline-only) fuel economy (19).

Overall, the PHEV recharging behavior observed in this demonstration project differs from that assumed by some analysts, i.e. once a day and between 10pm to 6am (8, 9). The average of the observed distribution of daily frequency of plug-in events in this PHEV demonstration is close to the assumed frequency of recharging. So is the assumption acceptable? The arguments against this are numerous. First, the distinction must be made between “recharging” and “plugging-in.” At least for the households and PHEVs in this demonstration, most plug-in events are not full recharges. More importantly, there is wide variation across households. The mean of the observed distribution of plugging-in is a biased estimator because the distributions shown in Figure 1 are distinctly non-symmetrical: the distributions are censored at zero and have long tails in the direction of higher recharging frequency. Plugging-in multiple times per day confounds the energy (and thus emissions) conclusions of studies that assume once-per-day recharges to full. For instance, the household that plugged-in 2.6 times per day on average for all weekdays actually used between 4.2 kWh and 9.2 kWh of grid electricity per day (plugging in two and four times per day, respectively). Despite plugging in more than once a day on these days, this household’s daily power demand ranged from 16 percent less to 46 percent more than the nominal 5kwh of electricity from an assumed once a day full recharge. With regards to CD range, on these two days the household drove 30 and 62 CD miles respectively.

For those two households in the demonstration that plugged-in exactly once a day, every weekday, the actual daily energy used to recharge their vehicles to 100 percent SOC varied from 1.5 to 4.3 kWh and 1.9 to 5kWh respectively. Certainly a household could have consumed ~5kWh, every day by recharging a fully depleted battery, however, none of the 40 households that participated in the PHEV demonstration to date have actually met this basic assumption laid out by (8, 9) , or done so based on average plug-ins per day.

While analyses purporting boundary conditions have used daily travel data to incorporate variation in travel and electricity demand (mediated by their models of what a PHEV is) (9,10), they do not address the distributions of observed household recharging behavior, or more generally, the uncertainty of recharging behavior and its interactions with travel behavior and PHEV design. The households in this demonstration illustrate that the world is likely to be far more complicated than the proposed “boundary” conditions. The intellectual hazard in characterizing future scenarios as boundary conditions is the risk that the boundaries are on our imagination rather than on the possibilities of future transportation and energy systems or travel and recharging behaviors. Incorporating distributions of PHEV types, driving, and recharging behaviors in an effort to explicitly incorporate uncertainty and variability into cost, energy, and environmental analyses may lead to better understanding of the implications of PHEVs and other electric-drive vehicles. The present report on observed behaviors is offered as one small step in this direction.

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