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Variation in Charging of Privately-Held PEVs: Implications for Analysis, Markets, and Policy

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Chapter

VARIATION IN CHARGING OF PRIVATELY-HELD PEVS: IMPLICATIONS FOR ANALYSIS, MARKETS, AND POLICY.

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ABSTRACT

As the markets for plug-in electric vehicles (PEVs) and the deployment of electricity infrastructure to charge them are in an initial, dynamic launch phase, there is an absence of stable data on PEV purchase and charging behavior. How then are social, economic, and environmental effects of PEVs being estimated? How are plans for PEV and electric vehicle service equipment (EVSE) production made? How are the effective means to manage that behavior anticipated? In the absence of data, analysts make assumptions. These are often simple assumptions, or perhaps simplifying assumptions. In this chapter we compare PEV charging assumptions to real world measures and assess the implications of changing these assumptions for analysis, markets and policy.

Keywords: Plug-in Electric Vehicle (PEV), charging impacts, utility factor.

INTRODUCTION

Plug-in hybrid and electric vehicles (PHEVs and EVs, collectively referred to as plug-in vehicles (PEVs)) are now being sold in countries around the world. Most large international automobile manufacturers and many regional ones have joined this market launch or are about to join. Concomitant developments in charging infrastructure for these plug-in vehicles are necessarily localized. PEV charging infrastructure development is localized, especially in parts of the world such as the United States of America (USA) where the electrical grid is operated through the coordination of thousands of different jurisdictions and entities ranging in size from a single municipal electric utility to large grid interties spanning multiple states and crossing national boundaries. Within this context ranging from a global market for

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vehicles to local electricity distribution, buyers of PEVs and the electricity to power them are the nexus that determines actual vs. estimated demand as well as social, economic, and environmental impacts. Assuming for a moment the purchase of PEVs, the nexus is literally the act of connecting PEVs to the electric grid, i.e., charging.

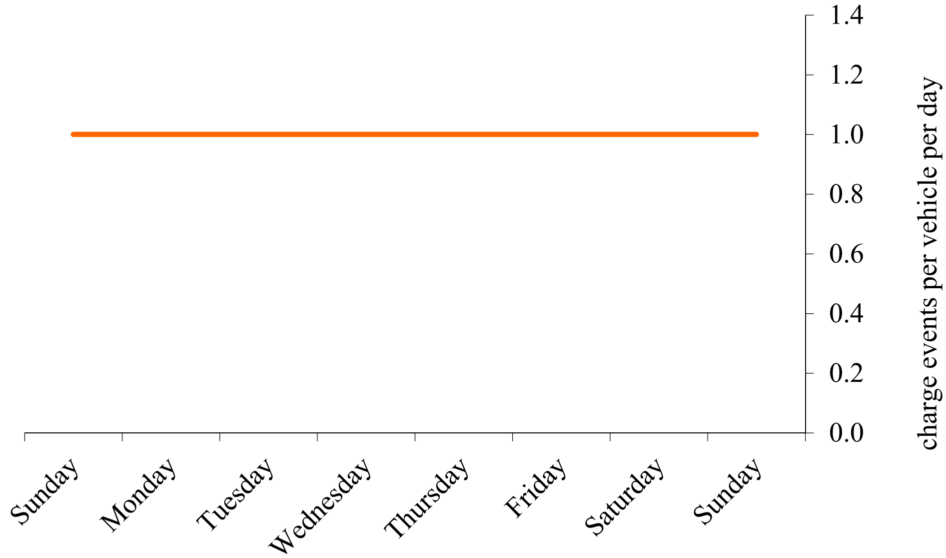
In an effort to characterize the social, economic, and environmental impacts of PEVs, analysts have devised numerous what-if scenarios. Although these analyses vary in context, they generally employ similar travel data from existing internal combustion engine vehicles and assumptions about consumer PEV purchase, driving, and charging behavior. As these analyses aim to simulate lifestyles, vehicle technologies, energy prices, markets, and charging networks that do not yet exist, the scenarios are ultimately limited by the creativity and imagination of researchers. Of all their assumptions, the ones we address here are those for charging behavior, especially assumptions about how many PEVs charge per day and how many times per day. For example, what are we to make of an assumption that all PEVs are charged once per day? More subtly, how do we interpret an *average* charging frequency of 1.0 charging event per day? And if an average daily frequency is assumed, what is the distribution around that mean? What does it matter if we use an assumed average for all PEV charging, or simulate charging by sampling from a distribution?

In this chapter we first briefly describe common assumptions about PEV charging, including commonly assumed data sources. Then we describe some early data on PEV charging. The implications of deviation of these data from the common simplifying assumptions include the question of whether the analytical community would better serve markets and policy by making more complex assumptions when little is known about essential variables.

ONCE-PER-DAY CHARGING AND ITS VARIATIONS

Perhaps the simplest assumption one can make about PEV charging is one of the most often made: each and every PEV is charged once per day, everyday [1-5]. A more restrictive version of the assumption is that all such charging events begin when or after a PEV is returned to the driver's home. In such analyses, the PEV may be assumed to begin to be charged immediately [6, 7] or at some point later in the evening [6-8]. According to such assumptions, over the course of a week, the number of charge events per vehicle per day would be as shown in Figure 1. Anticipating the discussion to come, the line in the figure is not an average; there is no distribution around it.

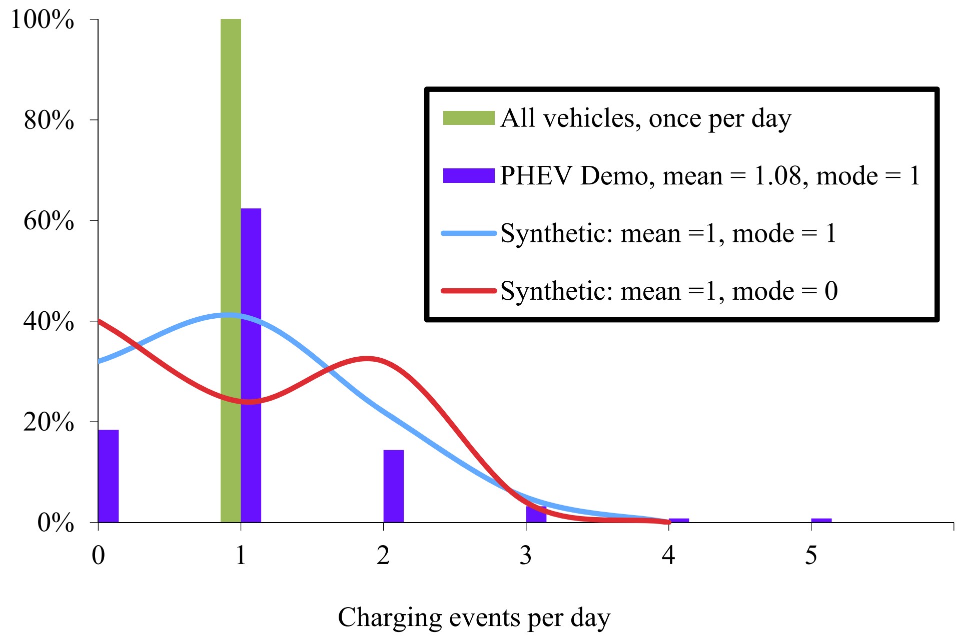
Figure 1: **One PEV charge event per vehicle per day over the course of one week.**



To further foreshadow the discussion below, the EV Project funded by the USA Department of Energy reported that in the third quarter of 2012 the mean number of charges per day of the PEVs in the project across 14 USA cities in which the project is installing charging infrastructure was 1.1 charge events per day for the Nissan Leaf [9] and 1.4 for the Chevrolet Volt [10]—on days the vehicles were driven. Across the cities, the mean for Leafs varied from 1.0 in Tuscon, AZ to 1.3 in Washington, DC and for the Volt, from 1.3 in San Diego, CA to 1.6 in Oregon.

We might reasonably ask whether an average 1.1 per day is sufficiently close to 1.0 to allow the once-per-day assumption to stand. However, a mean number of charging events per day near 1.0 is not the same as an assumption that all PEVs are charged once on every driving day. To illustrate the possible differences, four distributions of daily charging frequency are shown in Figure 2. Each distribution has an average 1.0 charging event per day per vehicle. The synthetic distributions merely illustrate two of all the possible shapes that charging distributions with means of 1.0 could take. The fourth distribution shown is from observed consumer PHEV charging behavior described below in the observed PEV charging section of this chapter.

Figure 2: **Examples of daily charging frequency distributions, mean =1**



Further, recognizing that as practical matter of scale, i.e., a maximum number of chargers per day of 3.0 is likely to be in the high 90th percentiles, an average of 1.4 charge events per day cited for the Chevrolet Volt is not as close to 1.0 as it might seem. Related to correlation between vehicle capability, travel behavior, and charging, the further question is raised by the reported difference between the means for the Volt and the Leaf: why is the car that does not have to be charged being charged, on average, more often than the car that does?

THE GENERALIZATION AS AVERAGE

If a numeric average focuses our attention on some centroid of a distribution, statements of generalizations also tend to focus our attention on specific cases. From an interview with a representative of the EV Project we have this statement:

"While we still expect the majority of charging to take place at home, we're excited to see that in the past three months [3rd quarter, 2012], public charging has increased by 25 percent. This shows that *drivers are becoming more and more comfortable with stretching the range of their vehicles and utilizing the public infrastructure available* [emphasis added]." [11]

During the third quarter of 2012, we spoke with PEV drivers in one of the EV Project's initial cities. While some drivers say they are utilizing the increasing public charging infrastructure, others have taken the position that if they are unable to complete their day's trips in their EV with the charge it has when they leave home, they don't leave home in their

EV. The generalization obscures the distribution of responses to (even the growing) away-from-home charging infrastructure.

WHAT CAN WE KNOW ABOUT VARIABILITY IN CHARGING?

A critique of any charging assumption must acknowledge the limits on what it is possible to know about PEV charging during the dynamic launch of both the vehicles and charging infrastructure. In general though, we argue that what we can't yet know appears to limit the variability that can presently be observed, i.e., as the conditions we describe below are relaxed, the variability that it is possible to observe will increase.

Some PEV driving and charging data are available from short term vehicle trials in which households drive—but do not have to buy or lease—PEVs for periods of days or weeks, e.g., [12]. Other data comes from households who have purchased or leased PEVs and have to-date driven and charged them for periods ranging from a few to several months. Regarding access to charging infrastructure, the data we will discuss includes only households who can charge a PEV at home. The data are also from a period when away-from-home charging was free.

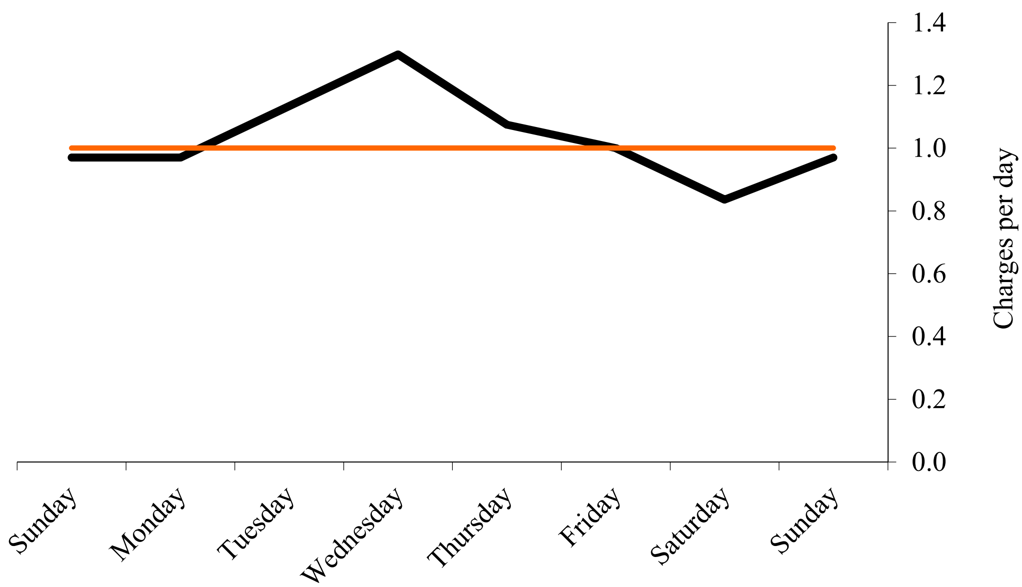
What are missing are data from households who have purchased or leased more than one PEV from a wide variety of design and performance capabilities and charged them within anything like the competing or complimentary versions of charging infrastructures imagined by, for example, Project Better Place's battery swap stations [13], Tesla's "superchargers" located to facilitate longer trips between regions [14], or any other models of away-from-home networks. Further, the makes, models, and body styles of vehicles that are offered as PEVs are limited at present to generally smaller sedans and crossover vehicles. The limited vehicle offerings may shape the types of travel, e.g., trip purposes and distances that can be presently observed. The variability of PEV driving range—whether the total driving range per charge for EVs or the electric-equivalent driving range for PHEVs—is increasing and one manufacturer has introduced an EV for which driving range is a buyer-selectable option.

OBSERVED PEV CHARGING

We illustrate variability in PEV charging, starting with data from a household PHEV trial. Seventy households in northern California were provided with a Toyota Prius PHEV-conversion to drive for periods varying between four and six weeks. Details are available in [12]; notably, in addition to second-by-second driving data and charging data, each household completed entry and exit questionnaires and three in-home interviews. We do assume that the structure of weekdays/weekends imposes enough regularity to sum all 67 weeks into a single week despite the fact the actual individual weeks occurred over the period from summer 2008 and to summer 2010.

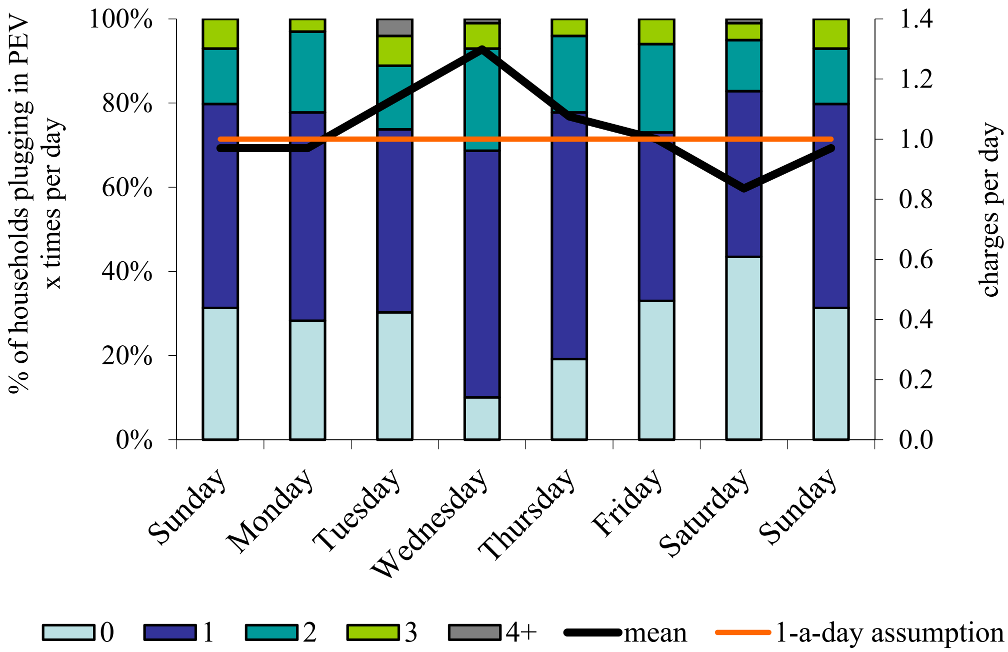
In Figure 3 we overlay the average number of daily charging events from the last week of 70 of these PHEV demonstration households on the every-vehicle, once-per-day assumption from Figure 1. These daily averages show a mid-week maxima (1.30) and a weekend day minima (0.84). Again, one might ask, is the deviation from once per day so severe as to warrant complaint? The problem is we are still arguing about averages with averages. In general, but especially during such a dynamic phase as we are in regarding PEV sales and infrastructure deployment, the quality of any average is assessed by how well it summarizes a distribution—and by the prior question, is any summary the most informative and useful measure?

Figure 3: **Mean number of charges per day (67 one-week data sets from the last week of a one-month household PHEV trial)**



To begin to unpack the summary view of charging in Figure 3, we overlay the daily distribution of number of charging events by household in Figure 4. At the level of disaggregation in Figure 4, we can begin to query the data about why the daily mean values vary and whether any "central-measure" of daily charging behavior is suitable. For example, the highest weekday average (Wednesday) occurs primarily because it is the day the fewest households don't charge the PHEV at all and Saturday's low average is because it is the day the most don't charge the PHEV at all. From interviews with all the households we know the reason that so many vehicles are not charged on Saturday is the greater likeliness that trips involving an overnight stay away from home are made on weekends. Underneath this general cause, we hear from these households that the reasons for not charging the PHEV on Saturday are both that the PHEV is the vehicle taken on these overnight trips and the PHEV is the vehicle left home for these trips. In the first instance, the PHEV is taken away from its primary or sole charging location. In the second, the PHEV would have been plugged in upon its return to home on Friday evening (and thus that charge event was recorded as occurring on Friday) and no one was home to drive and charge the vehicle on Saturday. In the first instance, a growing infrastructure of charging opportunities would lead to increased charging opportunities for PEVs taken for overnight trips. In the second instance, the PEVs would continue to not be charged on Saturday.

Figure 4: **Distribution of number of charges per day (67 one-week data sets from the last week of a one-month household PHEV trial)**



Just as averages, obscure the distributions of observed charging behaviors, so do generalizations about which group of consumers would be interested in purchasing a PEV. For example, EVs are often described as good cars for "commuters," i.e., people with (an assumed) regular in time and distance workday travel pattern. But from these PHEV demonstration households, the answer to who is charging multiple times per weekday is both commuters and non-commuters. A few of the households that used the PHEV for commuting found an electrical outlet in their workplace parking lot. They regularly plugged in the vehicle upon arriving at work in the morning, and almost as regularly, plugged it in again upon returning to work after any lunchtime errands. Returning home at the end of the day, they would plug in again, for the second or sometimes third time that day. Households in which the PHEV was used by a homemaker, self-employed person who worked at home, or retired person also charge the PHEV multiple times throughout the day. The generalization "EVs are good for commuters" obscures that—stripped of specific location and time of day data—the same pattern of multiple charges per day and charges throughout the day rather than only at night are shown by a wide variety of the demonstration drivers.

SERIAL CORRELATION IN DRIVING AND CHARGING?

The National Household Travel Survey (NHTS) [15] data has been used in many analyses of PEV markets, charging, and their impacts in the USA. As there are no PEVs in the NHTS data as yet (the most recent are from 2009), the data cannot describe how PEVs are driven. More typically, the data are used to attempt an answer to how much existing travel done by gasoline-fueled vehicles could be done by PEVs if PEVs engender no changes in travel. Further, the NHTS contains only one day of data per household. The use of such one-day data to represent what are fundamentally behaviors over time is another form of averaging.

One of the essential features of the demonstration household data presented in Figures 3 and 4 is that they are for sequential days from the same households. Interviews of these households reveal how one day's PEV charging can depend on that day's driving, as well as past days' and expectations of driving and charging over future days. Sunday is illustrative: charging on Sunday depends not only on the driving done that day, but on expectations about driving to be done on Monday. Further, and especially for those households who were away-from home Saturday night, Sunday's charging depends on whether they plugged in the prior Friday night, or in anticipation of leaving the PHEV home on Saturday, left it unplugged. The question that arises is the extent to which these dependencies across days are idiosyncratic to individual households or common across households, i.e., observing serial correlation within behavioral units, do we observe the similar correlations across behavioral units. These questions cannot be answered by any data set, no matter how large, that contains only one day of date per behavioral unit.

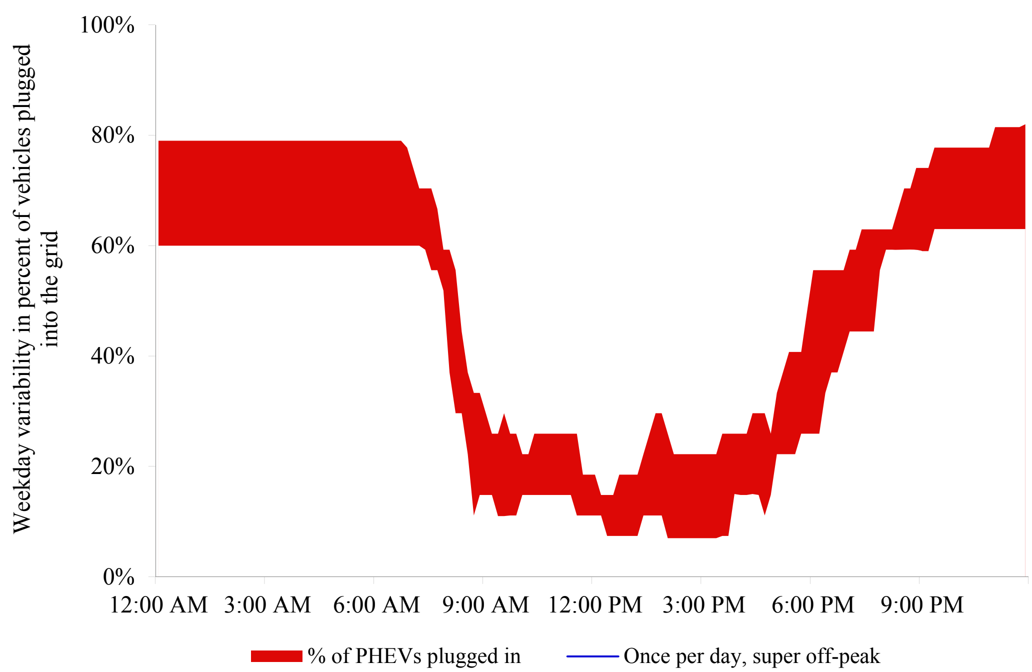
WEEKDAY CHARGING VARIABILITY ACROSS HOUSEHOLDS

If the once-per-day assumption masks variation and possibly correlation across days, how well does the assumption and some stricter variants do in describing charging during the course of a day? [1, 6, and 8] assume that all PEVs charge everyday and off-peak. The definitions of "off-peak" vary. Taking one region as a specific example, in the service area of San Diego Gas & Electric (SDG&E) in southern California, the time-of-use electricity price schedule has three levels: highest prices during the "peak" electricity demand period of noon to 8pm, lowest prices during the "super off-peak" period from midnight to 5am, and intermediate prices during the "off-peak" periods between the prior two. For now, we borrow only the definition of the super-off peak period from midnight to 5am. Figure 5 plots the SDG&E definition of the super off-peak period with the data from the 67 PHEV demonstration households (none of whom were in the SDG&E service area). The top of the red area indicates by time of day the maximum percentage of the PHEV demonstration households that had their PHEV plugged into the electrical grid across the five weekdays; the bottom of area is the lowest percentage of vehicles plugged in at that time.

At no point during the amalgamated weekdays in Figure 5 does the percentage of PHEVs plugged into the grid approach one hundred percent of all vehicles at the same time, as required by the assumption that all the PEVs charge everyday during the super off-peak period. The observed variation during this time period is from 60 to 80 percent. A less restrictive assumption regarding time-of-day, i.e., all PEVs charge every day, but don't all charge during the same time period would allow for different lines and areas to be drawn showing more variability, but the observed variability by time of day shown in Figure 5 and the observation in Figure 4 that at least 10 percent of households didn't charge the PHEV at all on any given day clearly show the assumption that all PEVs charge every day, and the special case that they all charge off-peak or super off-peak, is violated.

That far from all households will plug in their PEV every day is borne out by analysis of 1,000s of PEVs in several regions across the USA [16, 17]. For cities across the USA, only a few match as high a percentage of PEVs plugged into an EVSE at the PEV driver residence as shown for the PHEV demonstration households in Figure 5. Averaged across the cities that are part of the EV Project, 50 to 70 percent of the participating PEV drivers have their vehicle plugged into the grid between midnight and 5am on any given weekday night. In some of these cities, the observed low is 35 percent and in none does it exceed 80 percent [17].

Figure 5 **Once-per-day, off-peak recharging vs. Time of day variability in PHEV charging, weekdays (67 one-week data sets from the last week of a one-month household PHEV trial)**



Additional forces acting to increase or decrease the incidence of charging and Time-of-day variability of Charging

Deploying an away-from-home charging network increases the likelihood of violating the once-per-day charging assumption. On the other hand, imposing time-of use (TOU) electricity pricing and other mechanisms to prompt off-peak charging reinforces the assumption. Initial observations from drivers of PEVs suggests the effects of these countervailing forces may be to increase variability in charging behavior across days and drivers.

Interviews were conducted with buyers and lessees of Nissan's Leaf EV in San Diego, CA during Spring 2012 and focus groups were conducted with different people from the same population in Fall 2012 [18]. During this time (and continuing through 2013) SDG&E is conducting a TOU experiment, randomly assigning a sample of EV drivers to one of three different TOU rate schedules. (SDG&E expects to release their report in early 2014.) Our sample includes some PEV drivers who are participating in SDG&E's experiment and some who are not. These interviews did not measure EV driving and charging behavior, but engaged drivers in a conversation about why they acquired a PEV, how they drive it and charge it, whether they see the EV as an opportunity to enter into a community of like-minded people or to otherwise enact specific values.

EV drivers who have charged their EV away from home generally describe doing so in addition to charging at home. Exceptions included people who could routinely charge their EV at a workplace on weekdays and did not require charging at both home and work to complete their daily travel. In general though, the reports of these EV owners echo some of the charging behaviors reported by the PHEV demonstration drivers: people who charged multiple times per weekday included commuters and non-commuters; overnight, away-from-home trips on weekends may suppress the number of charging events on Saturday; those who stay home on the weekend may charge more often than once per day as they are more likely to be in and out of the house multiple times than they are on weekdays.

Differences from the behaviors reported by the PHEV demonstration drivers include a more concerted effort to charge (at home) everyday and a greater likeliness by more EV drivers in San Diego to explore away-from-home charging opportunities. Their exploration of away-from-home charging is facilitated by the different context from the PHEV demonstration—for which the only away-from-home charging was whatever 110V electrical outlets drivers might find. Coincident with the launch of PEV sales in San Diego, the deployment of Level 2 (up to 7.68kW) charging in public places, workplaces, public parks, and other destinations started, too.

However, the "technological" launch of PEV charging at away-from-home locations has not had as strong effect on increasing the incidence of EV charging as it might have had, and still may have. Though EVSEs continue to be installed at an increasing number of locations, EV drivers report the absence of a concomitant development and practice of "charging etiquette": rules to guide PEV drivers expectations of what to encounter in an away-from-home charging interaction with other PEV drivers [19]. These reports generally conform to stories of charging opportunities missed, not sought, or even avoided, i.e., the lack of etiquette appears to be suppressing away-from-home recharging.

If the deployment of away from home PEV charging infrastructure facilitates increased opportunity for charging throughout the course of a day, the imposition of TOU pricing on electricity for charging PEVs attempts to confine such charging to a specific time period: midnight to 5am, and thus to reduce the number of (home) charge events to one per day. The reports from the EV drivers are varied as to the effectiveness of TOU pricing [18]. For those EV drivers whose home EV charging is on a TOU price schedule, many report they do attempt to strictly adhere to charging during the desired period. In addition to pricing, timers on both the vehicles and the EVSEs allow drivers to plug-in their EV whenever they arrive home, but to initiate charging after midnight. Pricing is also reinforced by long-standing social marketing efforts by electric utilities in California to exhort electricity users to curtail their demand (for all purposes) during the afternoon-to-evening peak demand period. The combined effect of pricing, timers, and exhortation is appears to be broadly, but not universally, successful.

Households who had both an EV and a home solar energy system (SES) are among those EV drivers who reported they did not adhere to the desired pattern of reducing home recharging to once per day, starting at midnight. These households are also on a TOU electricity tariff. However, many of them seem to have a broken mental model of the relationship between their SES and the grid: they believe their SES 1) provides electricity directly from the sun to their home and EV and thus, 2) the grid is insulated from the effects of their EV charging. These people do understand and seem to be sympathetic to the calls for moderating peak period electricity demand. They just think their charging behavior doesn't affect the grid. These EV+SES owners often report charging their EV whenever they return home, including multiple times throughout the day.

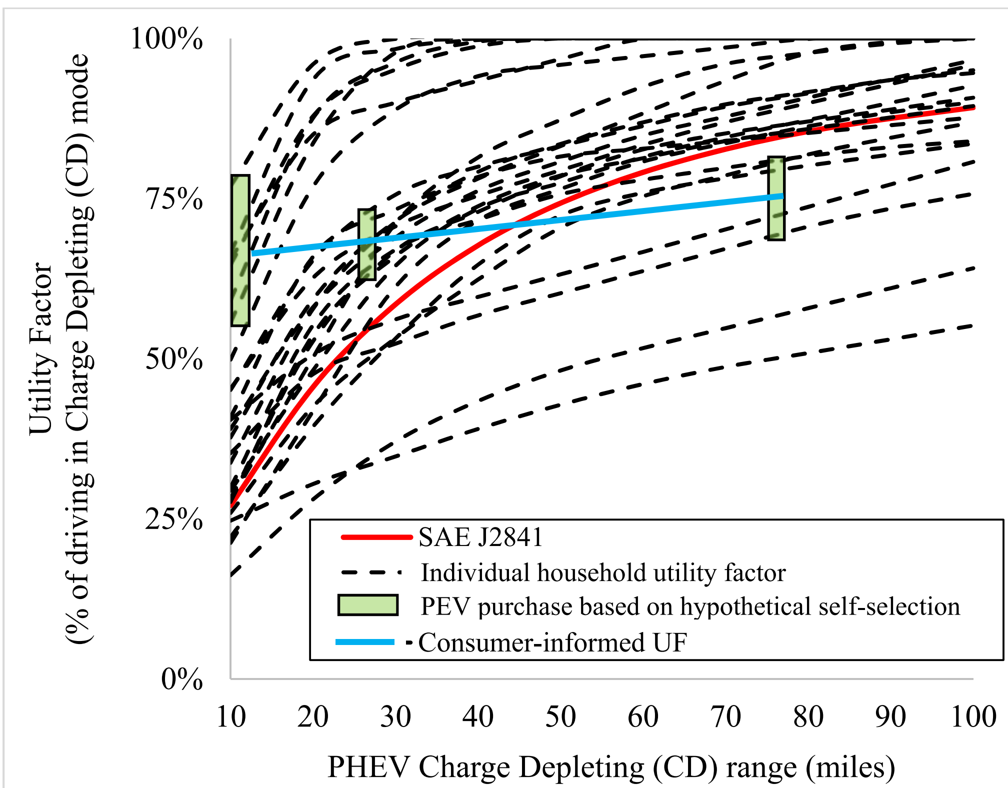
IMPLICATIONS

Deviation from "all PEVs charge once-per-day, everyday" has implications for estimating total electricity demand, electric miles driven, gasoline displacement, emissions, and all other outcomes. An example from the USA is the use of the "all PEVs, once-per-day" charging assumption in the Society of Automotive Engineers (SAE) standard J2841. Illustrated in Figure 6, the standard is meant to represent the "utility factor" (UF): the fraction of the total driving done by a PHEV (with a given electric range) that are electric-powered. (The SAE standard also assumes PHEV driving can be represented by the NHTS data.) The California Air Resources Board (ARB) uses the standard to calculate zero emission vehicle (ZEV) credits to award to PHEVs in comparison to the "full credit" given to EVs and Fuel Cell Hybrid Electric Vehicles (FCHEVs).

Analysis of the driving from our PHEV demonstration households' data indicates 1) that even in matched vehicles the achieved UF varies across drivers and within drivers across days [12]. Further, with experience, PEV drivers are likely to learn what electric range capability is suitable for them. The SAE J2841does not allow for consumers to self-select into vehicles that match their travel and charging behaviors. In Figure 6, the black dashed lines show individual household's UF from simulations based on the PHEV demonstration data. J2841 does not provide a good measure of the centroid of the space defined by the PHEV demonstration households—who all drove closely matched PHEVs.

The distribution and slopes of individual household's UF indicate that neither households nor society would benefit equally from additional electric range for the PHEVs; for each household there is a threshold beyond which the marginal effects of adding range decreases markedly. The three green boxes identify specific electric ranges and the households whose driving and charging behaviors match those vehicle ranges (in the sense that additional electric range and thus additional cost bring reduced marginal benefits in terms of electric-miles driven). Fitting a line to the averages of the UFs within the green boxes produces the blue line which we refer to as a consumer-informed UF.

Figure 6: **SAE J2841 and potential for self-selection in PHEV purchase range to affect utility factors**



CONCLUSIONS

Contrary to simplifying assumptions, observations of incipient and initial PEV charging shows wide variation in charging behavior within a single PEV driver's life over time, between PEV drivers, and across types of PEVs. If some drivers routinely charge their PEV more than once a day, some don't charge every day. Frequency and timing of charging throughout a day are affected by PEV electric-driving range capabilities, drivers' (and their households') travel and access to other mobility tools, fuel prices (gasoline and the cost to charge), the localized recharging infrastructure in the region in which they live, and the efforts (or lack thereof) of their local electricity provider to confine charging to a specific time of day (and through the correlation between time-of-day and most people's diurnal patterns, to a specific location, i.e., home). The continued introduction of more PEVs and more kinds of PEVs are likely to increase variability in charging behavior beyond what is already observable. The continued deployment of away-from-home infrastructure is likely to increase both variability and the number of charge events per PEV per day. These effects will be amplified if 440v "quick charging" is widely deployed. Further, if quick charging differentially facilitates long distance travel, then we can expect the effects to be more pronounced on weekends when this travel is more likely to occur. Reservation systems could alleviate some of the reluctance many PEV drivers show to rely on away-from-home charging—further increasing the effect of such infrastructure on charging frequency and variability.

If PEV charging is more frequent and variable than has commonly been assumed, what are the implications for estimates of social, economic, and environmental impacts—good or bad—of PEVs? What else might analysts do than make simplifying assumptions? The implications for impacts estimates are that spatial and temporal electricity demand to charge PEVs has been mischaracterized. Furthermore, total electricity demand for charging PEVs has been underestimated because either or both 1) charging events are simply being undercounted (as the mean of observed number of charges per PEV per day has been higher than 1.0 in both demonstration households and households of buyers and lessees of PEVs) and 2) calculations of correlations between charges per day and miles driven are likely to be positive. The ongoing tension between increasing PEV charging by building more away-from-home infrastructure and limiting charging to once per day at home during a few hours late at night is correlated both with emissions effects—as emissions in many electrical grids are dependent on time of day—and the additional costs electricity providers face from having to upgrade local distribution and the additional benefits electricity producers stand to gain from increasing the efficiency of their production base.

A prior condition for improvement in the analysis of the effects of widespread sales of PEVs and deployment of PEV charging infrastructure is improved quality of data during this dynamic period. At present, in the USA there is no widely available, comprehensive view of PEV driving and charging. The EV Project data cited in this chapter is helpful, but it focuses on the PEVs and the charging infrastructure within the project. The accrual and availability to analysts of comprehensive (across household, vehicle and infrastructure contexts) data are central to testing assumptions and building understanding of the societal, environmental, and economic implications of PEVs.

As described in [20] and again here, unless and until we have such data, and if the limits of our analytical scenarios are the analytical community's imagination and creativity, then in times such as this early phase of a PEV market launch, the authors encourage more complicated assumptions about PEV driving, charging and purchase behaviors: rather than independent point values, sampling from correlated distributions of behaviors and in the case of charging behavior, distributions of temporally correlated behavior. In such a way, estimates of social, economic, and environmental impacts can be tested for their robustness in the face of our understandable but undeniable ignorance of the nascent nexus of PEV driving and charging behaviors of future PEV drivers. Premature simplification is already having long-term consequences for standard setting and designs of performance based incentive programs.

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