

Will Smart Prices Induce Smart Charging of Electric Vehicles?

By Ahmad Faruqi, Ryan Hledik, Armando Levy, and Alan Madian¹

Contents

Introduction

- 1: Electric Vehicles and TOU Rates
- 2: A Model of Charging Behavior
- 3: Will Price Response Avoid Transformer Overload?
- 4: Experimental Design
- 5: Issues for Future Consideration

Conclusion

Appendix

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The societal and environmental benefits of plug-in electric vehicles (PEVs) have been well documented. However, the near-term impact of PEVs on the distribution grid has yet to be fully explored. Whether PEVs will help or hinder electricity provision will depend on how customers charge their vehicles, which will be driven in part by the rate structures that are offered by utilities and the associated customer response. In this discussion paper, we explore the relationship between PEV charging behavior and time-of-use rates, and offer suggestions for conducting a well-designed pricing experiment that will determine whether such rates will help reduce future grid reliability problems as PEVs penetrate the vehicle market.

Introduction

In his State of the Union speech on January 25, 2011, President Obama recognized the societal benefits of plug-in electric vehicles and set a national goal of putting one million PEVs on the road by the year 2015. Most of the benefits of PEVs arise from reduced dependence on imported oil and lower carbon emissions in areas where marginal power generation comes from combined cycle natural gas or renewable energy power sources. Additional benefits arise from the ability of PEVs to act as a bridge toward greater use of renewables, such as wind, by building load during periods of high renewable generation output. We have previously estimated the present value of these gross societal benefits at \$340 billion over the next four decades for the United States as a whole.²

The near-term impact of PEVs will be felt most significantly by the distribution grid, and specifically by distribution transformers that exist on each neighborhood block and cul-de-sac as customers charge their PEVs. That impact is unlikely to be positive. Since PEV adoption is initially expected to cluster in neighborhoods where demand for PEVs is strongest, the new load may overload transformers and sap much-needed distribution capacity. Consider that the typical transformer serves anywhere from four to ten homes. In an area where the pre-PEV household load is about 3 kilowatts (kW), the post-PEV load could easily double and become 6 kW per house. In areas where it is currently 6 kW per house, it could rise by 50 percent and become 9 kW per house (or more). Thus, the national goal of putting one million PEVs on the road by 2015 could easily become the bane of distribution engineers.³

Will Smart Prices Induce Smart Charging of Electric Vehicles?

Whether PEVs will help or hinder electricity provision will depend on how customers charge their vehicles. This behavior will be driven in part by the rate structures that are offered by utilities, as well as the price responsiveness of PEV owners to those rate structures. In this discussion paper, we demonstrate that even those rate structures that significantly favor off-peak charging, such as heavily time-differentiated rates, will save customers less than \$50 per month on charging costs.⁴ Will that financial incentive be sufficient to induce PEV charging regimens that avoid overloading the distribution grid? The answer depends on the price elasticity of demand. If the price elasticity is consistent with what has been observed in whole-house applications of time-of-use (TOU) pricing, then the outcome may be disappointing.⁵ On the other hand, if price elasticities are substantially higher, then positive outcomes can be envisaged.

Presently, we just do not know enough about the relationship between PEV charging behavior and TOU rates. It is time to stop guessing and start conducting scientific experiments to garner such insights.

Section 1 ELECTRIC VEHICLES AND TOU RATES

Current incarnations of the PEV, which include both battery and hybrid, have begun to appear on American roads this year.⁶ While there is no consensus on the amount of PEVs that will be sold in the next year or two, it is likely that they will begin making significant inroads into the new vehicle market within the decade. By 2030, the most optimistic projections suggest that as many as half of all new vehicles produced could be PEVs.⁷

The numerous potential benefits of widespread PEV adoption have been highly publicized.⁸ Most notably, PEVs have the ability to lower greenhouse gas emissions due to reductions in the amount of gasoline burned by the vehicles' internal combustion engines.⁹ PEV owners benefit from lower vehicle costs by fueling with electricity rather than gasoline, a particularly valuable option with the rise of gasoline prices. Additionally, if PEV owners choose to charge their vehicles late at night, PEVs could represent an ideal off-peak load that would complement new intermittent renewable energy sources such as wind power.¹⁰

How and when PEV owners charge their vehicles can change these impacts from a blessing to a curse for electric utilities. Contrary to many expectations, PEVs are not likely to produce unmanageable demands on generation resources (see sidebar "PEV Load: What's the Problem?"). The real challenge will arise at the distribution level. What would happen if half of the residents of a small neighborhood purchased PEVs and charged their vehicles at the same time in the evening? The resulting local spike in demand could blow the transformers feeding those homes and wreak havoc on the distribution system. Not only is this a serious concern, it could be an imminent reality if early adopters of PEVs cluster in specific neighborhoods.¹¹ In other words, this problem could materialize long before significant numbers of PEVs are on the road.

Will Smart Prices Induce Smart Charging of Electric Vehicles?

This concern has induced utilities to encourage off-peak charging behavior by allowing customers who own PEVs to take all or part of their electric service on some form of TOU pricing, often at higher voltages to facilitate faster charging. Many have approved TOU tariffs specially dedicated to PEVs. TOU rates for a few representative utilities are summarized in Table 1.

Table 1 Example PEV TOU Tariffs

Utility	Period	Price (cents/kWh)	Timing	Source
Consumers Energy	Peak	19	2 pm - 6 pm	[1]
	Mid-peak	12	7 am - 2 pm, 6 pm - 11 pm	
	Off-peak	6	11 pm - 7 am	
Detroit Edison	Peak	18	9 am - 11 pm (Mon-Fri)	[2]
	Off-peak	8	11 pm - 9 am (Mon-Fri), All Day (Sat, Sun)	
Hawaiian Electric	Peak	18	7 am - 9 pm (Mon-Fri)	[3]
	Off-peak	11	9 pm - 7 am (Mon-Fri), All Day (Sat, Sun)	
Pacific Gas & Electric	Peak	28	2 pm - 9 pm (Mon-Fri)	[4]
	Mid-peak	10	7 am - 2 pm, 9 pm - 12 am (Mon-Fri), 5 pm - 9 pm (Sat, Sun)	
	Off-peak	6	12 am - 7 am (Mon-Fri), 9 pm - 5 pm (Sat, Sun)	
San Diego Gas & Electric	Peak	26	12 pm - 6 pm	[5]
	Mid-peak	17	5 am - 12 pm, 6 pm - 12 am	
	Off-peak	15	12 am - 5 am	
Southern California Edison	Peak	33	12 pm to 9 pm	[6]
	Off-peak	16	9 pm to 12 pm	

Sources:

- [1] Consumers Energy website: <http://www.consumersenergy.com/content.aspx?id=3367>
 [2] DTE website: <http://www.dteenergy.com/residentialCustomers/productsPrograms/electricVehicles/pevRates.html>
 [3] HECO website: <http://www.heco.com/vcmcontent/StaticFiles/FileScan/PDF/EnergyServices/Tariffs/HECO/HECOSchEV-CPilot04-13-2011.pdf>
 [4] PG&E website: <http://www.pge.com/about/environment/pge/electricvehicles/fuelrates/index.shtml>
 [5] SDG&E website: <http://www.sdge.com/environment/cleantransportation/evRates.shtml>
 [6] SCE website: <http://www.sce.com/CustomerService/rates/residential/electric-vehicles.htm>

Notes:

- Several of the utilities offer different rates depending on whether the metering is done for the whole house or separately for the electric vehicle. For simplicity, we have only presented the separately metered rate.
- Some utilities offer rates that vary by season; for simplicity, only the summer rate is shown. Winter rates are lower.
- It is somewhat common for utilities not to have created an EV-specific TOU rate, but to recommend that EV owners enroll in an existing residential TOU rate (Portland General Electric is one example).
- Prices represent only the variable portion of the rate and do not reflect, for example, customer charges.

In theory, TOU pricing would appear to be a *sine qua non* for charging PEVs efficiently since their owners can lower their electric bills by charging during off-peak hours. But how important is this economic element in motivating charging behavior? To what extent would customers change how they charge when enrolled in a TOU rate? A time-varying rate structure may strongly affect some customers, but what about PEV owners who bought their cars because they are more “green” and/or more affluent than other customers? The answers to these questions require sound empirical work that is currently only in the embryonic stage.

To guide our answer, we examine the Nissan LEAF¹² as an example, along with three illustrative TOU rates based on tariffs being considered by a utility serving a medium-size urban area.¹³ We also suggest ways in which utilities can design experiments to quantify the impact of TOU prices on charging regimens.

PEV LOAD: WHAT'S THE PROBLEM?

If PEV owners were to simultaneously charge their vehicles in a small geographic area, the increased demand could cause major problems for the utility that must reliably serve that load. While some believe that simultaneous charging of PEVs at system peak could result in supply shortages or create a need for large new investments in generating capacity, we find these scenarios to be unlikely. Rather, we believe that PEV charging will be a problem at the distribution level for most utilities. To illustrate these points, we provide the following illustrative calculations for a utility with one million residential customers.

First, consider the effect of PEV adoption on system peak demand. We begin with a very aggressive assumption that one in every four homes owns a PEV, or roughly 250,000 residential customers with an electric vehicle for our hypothetical utility. Assume that half of these customers are simultaneously charging their vehicles at the time of the system peak (other owners may not yet be home from work or could already have a full charge). Assuming a charging demand of 3.3 kW per vehicle, the resulting increase in peak demand would be roughly 400 megawatts (MW) (calculation: 250,000 customers x 50% peak-coincident charging x 3.3 kW). While not an insignificant number, a mid-sized utility with, for instance, 5,000 to 10,000 MW of existing load would have the capability to address this load growth over a long-term forecast horizon.

Now, consider what could happen at the distribution level. There is evidence to suggest that adoption of PEVs will be geographically "clustered." Research has shown that this is the case with hybrid vehicles (for example, one is much more likely to see several Priuses parked on a residential street in Berkeley, California than in a farming town in California's central valley).*

Let's assume that of the residents living on a street that is served by a single transformer and in a "green" neighborhood, half own a PEV. A charging demand of 3.3 kW could double the daily demand of these homes. As a result, if the PEV owners were all to plug in their vehicles when returning home from work in the evening, the load on that street's transformer could increase by 50 percent (calculation: 50% PEV ownership x 100% increase in load per PEV owner). If the transformer was already being loaded at 70 percent of capacity, then this increase would be enough to overload the transformer and create serious problems in the distribution system.

Certainly, PEV adoption rates will vary from one service territory to the next, and the vehicles will be charged at varying rates and at different times of day. However, it is becoming clear that our generation resources will be in a much better position to accommodate future PEV market penetration than our distribution systems.

* Kahn and Vaughn, "Green Market Geography: The Spatial Clustering of Hybrid Vehicles and LEED Registered Buildings," *The B.E. Journal of Economic Analysis & Policy*, 2009.

Section 2 A MODEL OF CHARGING BEHAVIOR

In order to measure the response of LEAF drivers to alternative TOU prices, we begin by formulating a model of driver charging behavior. The LEAF purchase decision reveals important aspects of driver psychology. Compared to the average utility customer, we hypothesize that LEAF owners are likely to have at least some of the following characteristics: innovative, risk taking, affluent, cost conscious, and/or environmentally conscious.

The LEAF can be charged during an eight-hour period if the car owner has a dedicated 240 volt socket. The charging rate is 3.3 kWh per hour.¹⁴ Under normal driving conditions, a fully charged LEAF has a range of 100 miles (according to the manufacturer), or 73 miles (according to the U.S. Environmental Protection Agency's estimate based on kWh per 100 miles). The range varies considerably depending on driving style, traffic, and weather conditions. Assuming that the LEAF has a 100 mile range, that drivers always discharge the battery completely, and drive 15,000 miles a year, the LEAF would be charged 12.5 times a month. However, owners will rarely, if ever, fully discharge their LEAF before re-charging it, essentially leaving a certain amount of reserve power, just as they do with a typical gasoline fueled car. For discussion purposes, we assume they will charge the vehicle 25 times during the month based on 1,250 monthly miles traveled, with each charge lasting four hours.

To estimate the economics of charging, we use the three TOU rates shown in Table 2. Each rate has three pricing periods: peak, mid-peak, and off-peak. The peak period is from noon to 5 pm, the off-peak period is from midnight to 5 am, and the mid-peak period is all other hours. These prices apply on all days of the year (including weekends, with no seasonal changes). They are roughly revenue-neutral to a flat rate of 21 cents/kWh.

Table 2 Illustrative TOU Rates Used in Simulation (cents/kWh)

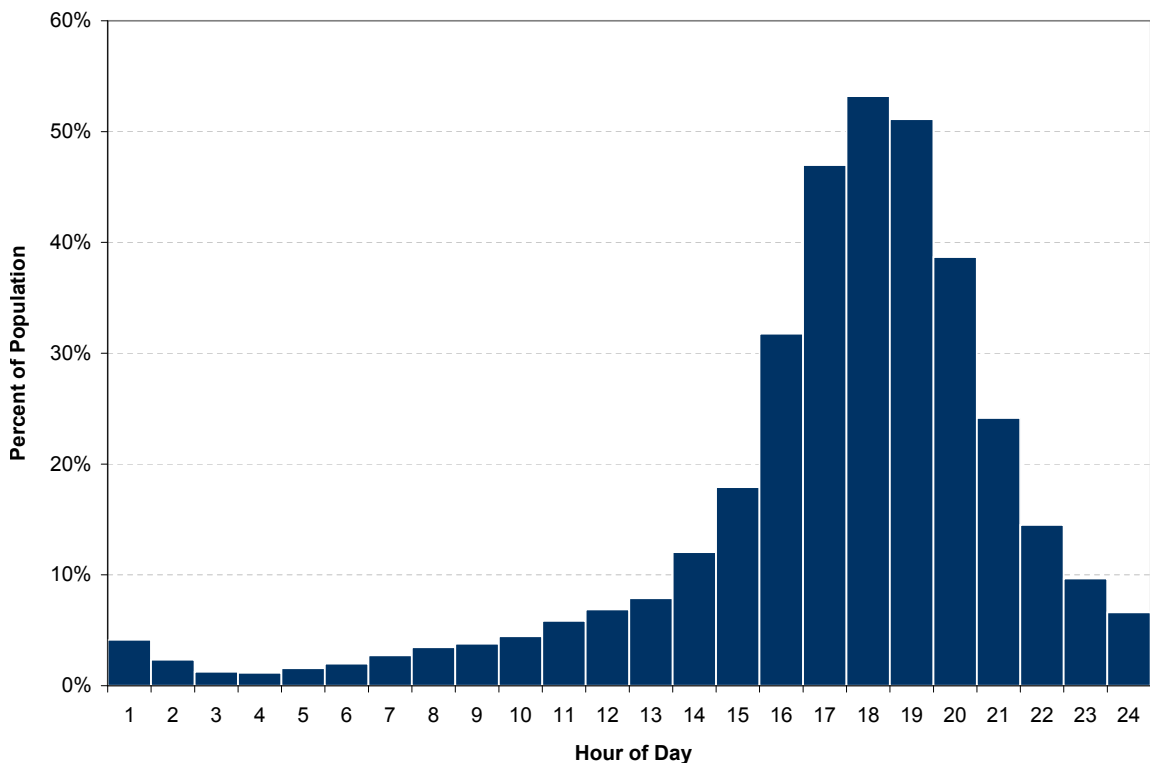
	Peak (Noon - 5 pm)	Mid-peak (5 am - noon, 5 pm - midnight)	Off-peak (Midnight - 5 am)
Low TOU	27	16	14
Moderate TOU	29	18	8
High TOU	38	15	7

Next, we model customer charging behavior, conditional on the given TOU rate and the charging characteristics of the LEAF. Within each rate, however, LEAF owners have an opportunity to charge based on convenience (default charging profile) or only during those times when electricity costs are lowest (best charging profile). Saving money will motivate some drivers to charge when costs are lowest. However, some may charge when costs are lowest because they are socially conscious and want to "do the right thing." Others may do the same because they are image-conscious and want to be seen as doing the right thing, and still others may do so because they are intrinsically "green."

Will Smart Prices Induce Smart Charging of Electric Vehicles?

Without the incentive of a TOU rate, the “typical” customer is likely to plug in their car when they get home from work at 6 pm and charge it to full capacity so that it is ready the next morning. However, other customers might find it more convenient to start their charge earlier or later, depending on their work schedules, the availability of charging stations outside the home, the presence of a control on their home charging station, their tolerance for a less than fully charged battery, or the regularity of their driving, among other factors. An aggregate charging profile for a hypothetical population of PEV owners is illustrated in Figure 1.¹⁵

Figure 1 Share of Hypothetical PEV Owners Charging Vehicle During Any Given Hour of Day



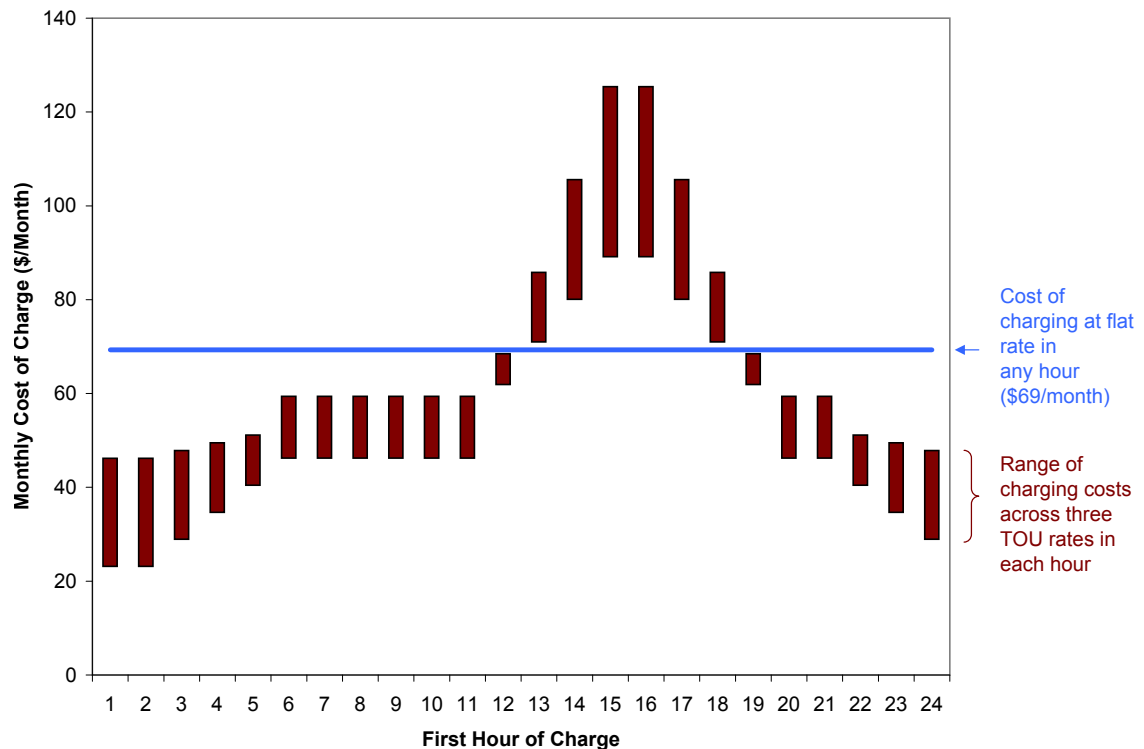
The question, then, is to what extent will the collective charging behavior change if these customers are enrolled in a TOU rate? The answer will be driven in part by the ability of customers to reduce their electricity bills on the TOU rate. To bracket the potential bill savings created by the TOU rates, we ask the following:

- ◆ *What is the charging cost when the PEV is plugged in at various times of day under the three TOU rate regimes (assuming a continuous four-hour charge)?¹⁶*
- ◆ *How does this compare to the cost of charging at the 21 cents/kWh flat rate?*

Will Smart Prices Induce Smart Charging of Electric Vehicles?

Using a straightforward spreadsheet model, we find that charging the PEV will cost about \$69 per month on the flat rate.¹⁷ The charging cost varies under each TOU rate, depending on when the charge is initiated and which TOU rate is being used. The range of charging costs from the three TOU rates is displayed as the red bars in Figure 2.

Figure 2 Range of Charging Costs Across TOU Rates, by Time of Day



A driver on the low TOU rate has the least incentive to charge during the cheapest periods, since their cost exposure is much less than that of an owner on either the medium or high TOU rates. *A priori*, one would expect drivers on the high TOU rate to display the largest price responsiveness and drivers on the low TOU rate to display the least.

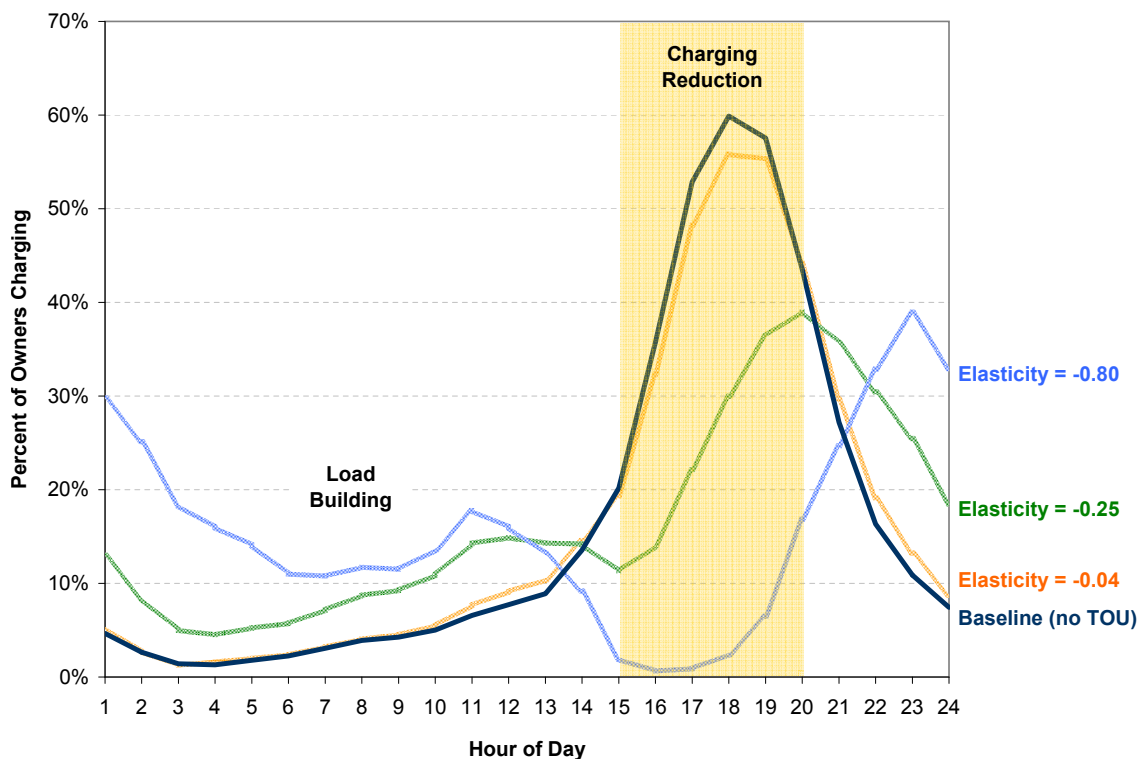
Even in the high TOU rate case, the savings are modest. The difference between charging at 6 pm (the default charging profile) and 1 am (the least-cost charging profile) is about \$60 a month. Will a LEAF owner pay much attention to saving this sum of money? While one might be tempted to say no, there is, in fact, research from related fields that suggests that the answer may not be so obvious. Our research with other dynamic pricing and TOU pricing pilots suggests that despite the modest savings that accrue to customers on such pricing designs, people do move their load profiles in response to higher prices.¹⁸ Drawing upon empirical evidence from more than 100 tests with dynamic pricing, we would expect a peak-to-off-peak price ratio of 8:1 to produce a drop in peak load of around 15 percent. The implied arc elasticity is fairly small (around -0.04) but is still capable of producing significant demand response with a potent rate design.

Section 3 WILL PRICE RESPONSE AVOID TRANSFORMER OVERLOAD?

Simulation modeling will help us better understand the level of price responsiveness that could produce meaningful impacts on charging regimens. Already, we have established illustrative TOU rates (Table 2) and an aggregate charging profile for a hypothetical population of PEV owners (Figure 1), but we still need a measure of how responsive PEV owners are to TOU rates. A starting point for this measure is the already noted arc price elasticity of demand of -0.04.

Using this price elasticity with the high TOU rate shown in Table 2, we find that the percent of customers charging during the peak period would drop from 60 percent to 55 percent. This is not likely to be a meaningful impact for grid operators who are trying to mitigate the adverse impact on the distribution system. However, one could expect the price elasticity to be higher for a single, discretionary end-use such as PEVs. How much higher would it need to be to make a dent in the transformer overload problem? We have run simulations with a wide range of price elasticities to answer this question.¹⁹ At the extreme, a value of -0.80 will be needed to effectively eliminate peak time charging. A value of -0.25 will be needed to eliminate half of the normal peak time charging load. The results of these simulations are shown in Figure 3.

Figure 3 Simulated Changes in Charging Profile due to TOU Rate



Which of these price elasticities is realistic? That can only be resolved by conducting well-designed pricing experiments. How should such an experiment be carried out? The next section attempts to answer this question.

Section 4 EXPERIMENTAL DESIGN

The best way to estimate the parameters of a model for predicting charging behavior is to conduct a social experiment in which a large number of volunteers, perhaps a thousand or more, are surveyed to study their charging behavior under alternative TOU rates.²⁰ These customers are then randomly allocated to a control group and three “treatment” groups corresponding to the three rate types. Customers in the control group continue to drive their existing vehicles throughout the study, while those in the treatment groups acquire, or are provided with, a LEAF after a relatively short interval.

Random allocation, similar to that carried out in medical clinical trials, ensures that the treatment and control groups will be comparable both in observable and unobservable characteristics. The driving behavior and lifestyles of the experimental participants are then observed for several months before the LEAFs are delivered to them. This is necessary to establish a baseline since the best experimental designs feature both before and after measurement and side-by-side measurement.

It would be a mistake not to include a control group in the design, nor factor in a pre-treatment period. The temptation to only include a treatment group and measure their usage only after they have been given the LEAF should be resisted at all costs. Although it may yield results, those results could be subject to serious biases whose magnitudes may be incapable of being inferred from the experiment. The absence of a control group is also likely to lead to imprecise parameter estimates.

The design described above would yield both longitudinal and cross-participant data, i.e., it would constitute a cross-section of time series at the individual owner level. Such a panel data set would lend itself to econometric estimation by using either the fixed-effects or random-effects models that have successfully been used in the literature on dynamic pricing.

Because saving money is only one motive for charging at a particular time, we must examine other driver attributes before a predictive model of charging behavior can be developed. The most salient attributes are likely to be: (a) the “normal” driving habits of each driver, presumably gleaned from an analysis of their behavior with gasoline-powered or hybrid-electric vehicles, and (b) the driver’s reasons for buying the LEAF (risk-taking, affluence, “greenness,” etc.). Such data is now beginning to be collected by organizations such as the University of California, Davis’ Institute of Transportation Studies.

Section 5 ISSUES FOR FUTURE CONSIDERATION

There are several critical decisions that will need to be made about the scope and design of the pilot.

TOU rate design. The peak period price of a TOU rate reflects both the marginal cost of energy and capacity. Typically, in existing TOU rates, this peak price is largely driven by the marginal cost of generating capacity. However, PEV charging is likely to drive new investment in the distribution system. It could make sense to base the peak price on the cost of upgrading the distribution system when designing a TOU rate for PEVs.

Provision of charging control technologies. Another viable option for influencing PEV charging is through the use of technologies that control the timing of the vehicle's charge. This could be simply a timer on the plug or outlet, or a more sophisticated technology that is controlled by the utility and is capable of optimizing charging across a local network of PEVs. Control technologies could be included as additional "treatments" in the PEV pilot.

Participant recruitment. Recruiting pilot participants in a way that avoids "self-selection bias" will be a challenging aspect of the pilot design. In order for the pilot results to reflect the likely preferences of the broader future population of PEV owners, the sample of pilot participants will need to be representative of that broader population. If participants are limited to the very early adopters of PEVs, then this principle could be violated. Alternatively, providing PEVs to a random group of customers will introduce its own challenges, such as larger budgetary requirements to cover the cost of the vehicles.

Charging outside the home. Pilot participants may have the option to charge their vehicle away from their home at any of a growing number of public charging stations. It will be important to address the interaction of this option with the participants' home charging behavior before and after enrolling in the TOU rate.

Conclusion

The results of our analysis suggest that TOU rates may help reduce future grid reliability problems as PEVs penetrate the vehicle market. However, the extent to which properly designed rates could assist in maintaining grid reliability will remain unknown until we are able to empirically test PEV owners' price responsiveness through experimental pilots. Given that PEVs can be expected to present significant challenges to the distribution system over the next few years, this is a question that we cannot afford to leave unanswered.

Appendix: Model Building

To demonstrate one approach to quantifying PEV charging behavior, we have formulated the rudiments of a predictive model. Let $U(m, z | v, \varepsilon, u)$ represent the utility function for a typical household owning a LEAF, where m are the miles driven in a period of time (say a month), and z is a numéraire good. Let v denote the observable characteristics of the household and ε and u be unobservable characteristics. Here u denotes unobservable characteristics related to use of the LEAF while ε denotes individual preferences for driving relative to the numéraire good. For example, the frequency, length, and time of day for the individual trips that make up m will be represented in u while the individual need for transportation is represented by ε .

For simplicity, let us assume there are only two pricing periods, peak and off-peak. Miles of travel require electrical power from charging which can occur at either peak or off-peak rates. Hence, the household is constrained by $m = \alpha t$ where t are the number of hours of recharging and α represents the technical transformation of miles per hour of charge. Because $t = t_o + t_p$ where the subscripts denote off-peak and peak hours, we can write $U(\alpha(t_o + t_p), z | v, \varepsilon, u)$. This represents a separable utility in three goods: on-peak and off-peak charging hours and a numéraire, where charging hours are weakly separable from the numéraire.

Furthermore, because the electricity delivered off-peak and on-peak are perfect substitutes for each other, the indifference curves for the subutility of charging will be parallel lines at 45 degrees. On the other hand, the budget constraint for charging will be kinked due to the time limitation on off-peak charging. This is represented in Figure A-1 below. In the figure, B1 and B2 represent different expenditures on charging with a kink at the maximum of four hours of off-peak demand. This illustrates that absent any other constraint, the optimal charging behavior exhausts off-peak charging before any on-peak charging takes place.

Figure A-1 Charging Budget and Preferences



Will Smart Prices Induce Smart Charging of Electric Vehicles?

Besides the price of electricity, the charging behavior model will need to include other variables, such as customer driving habits and reasons for buying the LEAF. Driving habits, in turn, are a function of a host of socio-demographic variables, such as number of drivers, age of drivers, income, number of cars in a household, size of house, wealth, identifying as “green,” or having a solar panel on a roof. Such data would be collected through surveys.

Additionally, a simulation model can be used to predict the impact of various levels of price responsiveness. Let U_t be the indirect utility of charging beginning in hour t where $t = 1, \dots, 24$, and U_0 be the indirect utility for not charging at all. Let $U_t = \alpha(I - p_t) + \theta_t + \varepsilon_t = V_t + \varepsilon_t$ where ε_t are independent draws from the type I extreme value distribution, p are prices for each of the alternatives, I is income, and θ_t are the unobserved average utilities for charging at the given hour. The values will reflect the convenience of a charge beginning in hour t to a randomly drawn member of the sample population. Given this model, choice probabilities will be conditional logit:

$$P(t=j | x) = \frac{e^{V_t}}{\sum_{t=0}^{24} e^{V_k}}$$

Assuming a simple logit for the charge/no charge decision with the same utility structure, we can estimate the elasticity of demand (ε) with respect to the charging cost as:

$$\varepsilon = -\alpha p [1 - P(\text{Charge})]$$

Hence, given an estimate of the fraction of households that would charge at price p and the elasticity of demand, we can calibrate α as:

$$\alpha = \frac{-\varepsilon}{p [1 - P(\text{Charge})]}$$

Will Smart Prices Induce Smart Charging of Electric Vehicles?

Endnotes

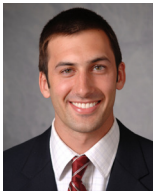
- ¹ The authors would like to acknowledge the helpful contributions of *Brattle* colleagues Joe Wharton, Peter Fox-Penner, Phil Hanser, Hannes Pfeifenberger, Doug Mitarotonda, and Onur Aydin. Comments can be directed to Ahmad.Faruqui@brattle.com.
- ² Faruqui and Hledik, "Sizing up the Smart Grid," presented at Connectivity Week, San Jose, California, June 11, 2009.
- ³ The Obama Administration's goal is described in *One Million Electric Vehicles By 2015: February 2011 Status Report* by the U.S. Department of Energy. Available at: http://www.energy.gov/media/1_Million_Electric_Vehicle_Report_Final.pdf.
- ⁴ Specifically, we focus on time-of-use rates that provide a constant price signal during peak and off-peak periods, rather than dynamic pricing rate structures in which the price signals are event-based.
- ⁵ A recent study by PJM and Better Place has suggested that wholesale electricity prices could even increase with TOU rates for PEVs. This further highlights the need to study and understand this issue in more detail. See *An Assessment of the Price Impacts of Electric Vehicles on the PJM Market*, Better Place, Inc. and PJM, May 2011.
- ⁶ For example, the Chevy Volt is expected to be available in all 50 states by Q4 of 2011 according to the *Car and Driver* website. Available at: <http://blog.caranddriver.com/chevy-volt-to-be-available-nationwide-in-2011-responding-to-high-demand/>. The Nissan LEAF is now commercially available in the U.S. as well.
- ⁷ This is presented in an optimistic scenario by the Electric Power Research Institute (EPRI). See Duvall and Knipping, *Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions*, Report No. 1015325, Electric Power Research Institute, 2007.
- ⁸ See, for example, the U.S. Department of Energy's website describing the benefits of PEVs. Available at: http://www.afdc.energy.gov/afdc/vehicles/electric_benefits.html.
- ⁹ This assumes that the generation of electricity to charge the PEV's battery results in lower emissions than burning gasoline, which is usually the case. For further discussion, see Murphy, Chupka, Aydin, and Chang, "Plugging In: Can the Grid Handle the Coming Electric Vehicle Load?" *Public Utilities Fortnightly*, June 2010.
- ¹⁰ Note that we are referring to the ability of PEV charging to mitigate conditions where renewable generation is in over-supply – more advanced means would be needed for PEVs to contribute to ramping issues associated with renewables integration (e.g., by providing ancillary services).
- ¹¹ This phenomenon has been observed with hybrid vehicles. See Kahn and Vaughn "Green Market Geography: The Spatial Clustering of Hybrid Vehicles and LEED Registered Buildings," *The B.E. Journal of Economic Analysis & Policy*, 2009.
- ¹² Nissan capitalizes LEAF because it is sometimes used as an acronym for Leading, Environmentally friendly, Affordable, Family car.
- ¹³ We chose the LEAF because it, along with the Chevrolet Volt, is one of the first two PEVs to be produced by a major automobile manufacturer. The LEAF went on sale in four western states – California, Washington, Oregon, Arizona – as well as Tennessee in December 2010. Because the LEAF requires charging to operate (the Volt may use an onboard gasoline generator/engine to maintain operation when the battery becomes depleted) it was a natural choice for our analysis.
- ¹⁴ The Nissan LEAF's specifications are provided on the Nissan website. Available at: <http://www.nissanusa.com/ev/media/pdf/specs/FeaturesAndSpecs.pdf>.
- ¹⁵ This assumes that each owner charges for four hours and that a majority of customers plug in their vehicles around 6 pm. For discussion of alternative charging profiles, see "PUF, June 2010."
- ¹⁶ While a full charge would take slightly over seven hours, it is assumed that customers are not entirely depleting their charge before plugging in.
- ¹⁷ $3.3 \text{ kW} \times 4 \text{ hours /charge} \times 25 \text{ charges /month} \times 21 \text{ cents / kWh} = \69 .
- ¹⁸ Faruqui and Sergici, "Household response to dynamic pricing of electricity: a survey of 15 experiments," *The Journal of Regulatory Economics*, 2010, and Faruqui and Malko, "The Residential Demand for Electricity by Time-of-Use: A survey of twelve experiments with peak load pricing," *Energy: The International Journal*, October 1983.
- ¹⁹ See the Appendix for details of our simulation model.
- ²⁰ In this paper, we do not address the very important modeling question of who will buy the LEAF and under what conditions. That problem is a research topic in itself, requiring a different modeling approach and data set. We hope to address it in a future paper.

Will Smart Prices Induce Smart Charging of Electric Vehicles?

About the Authors**Ahmad Faruqui**
Principal**Phone:** +1.415.217.1000
Email: Ahmad.Faruqui@brattle.com

Dr. Faruqui is a leading expert on the customer-facing aspects of the smart grid. He has performed cost-benefit analyses for electric utilities in two dozen states and testified before a dozen state and provincial commissions and legislative bodies. He has designed and evaluated some of the most innovative pilot programs involving dynamic pricing, block rate design, demand response, and energy efficiency.

Dr. Faruqui received his Ph.D. in Economics and his M.A. in Agricultural Economics from the University of California, Davis.

**Ryan Hledik**
Senior Associate**Phone:** +1.415.217.1000
Email: Ryan.Hledik@brattle.com

Mr. Hledik specializes in assessing the impacts of smart grid programs, technologies, and policies. He has assisted electric utilities, regulators, research organizations, wholesale market operators, and technology firms in the development of innovative demand response and energy efficiency portfolios and strategies. He has been the lead developer of several energy market simulation tools for the purposes of wholesale price forecasting, asset valuation, and emissions analysis.

Mr. Hledik received his M.S. in Management Science and Engineering from Stanford University.

**Armando Levy**
Senior Associate**Phone:** +1.415.217.1000
Email: Armando.Levy@brattle.com

Dr. Levy specializes in microeconomics, econometrics, and statistics. He consults to a variety of clients on issues related to statistical and econometric issues as well as sample design. Recently, he has consulted on the forecasting of enrollments and load impacts of a portfolio of demand response programs for a large utility. He was a lecturer in econometrics at UC Berkeley in 2008 and 2009 and has published nearly a dozen papers in peer-reviewed academic journals.

Dr. Levy received his Ph.D. in Economics and his M.A. in Statistics from the University of California, Berkeley.

**Alan Madian**
Senior Advisor**Phone:** +1.617.864.7900
Email: Alan.Madian@brattle.com

Mr. Madian is a leading expert on the costs and impacts of nuclear and green electric generation technologies and conservation strategies. He has authored widely cited forecasts of the impact of plug-in hybrid vehicles (Brookings 2009) and the competitive economics of new nuclear generation worldwide (Brattle 2011). He held academic appointments at the London School of Economics, The University of Rochester, New York University, and Columbia University.

Mr. Madian pursued D.Phil studies in Economics and Political Economy at Oxford, received an M.A. from Yale, and an A.B. Phi Beta Kappa from the University of California, Berkeley.

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