Patterns of Electric Vehicle Charging with Time of Use Rates: Case studies in California and Portland

Mustafa Biviji, Canan Uçkun, Gilbert Bassett, Jianhui Wang, *Senior Member, IEEE,* and Dan Ton[1]

***Abstract*-- This paper presents patterns of electricity consumption for charging electric vehicles when customers can select flat or time of use pricing. The data consist of hourly charging profiles for two utilities whose customers were offered alternative rate schedules with rates different for weekdays and weekends as well as for seasons. The extent to which TOU customers' daily load profiles differ from customers who opted for flat rates is presented for both weekdays and weekends. The on-peak and off-peak consumption for flat rate and TOU customers is compared to show that total consumption and timing of consumption varied by rate structure. Data show large differences in charging profiles for the varying rate structures. This paper discusses the different patterns observed between electric vehicle load and the rest of the residential load. Substitution and own-price elasticities are computed. In addition, issues related to self selection of pricing structures are discussed.**

***Index Terms*—Electric vehicles, load management, smart grids, utility programs,**

I. Introduction

THIS paper analyzes the charging patterns of plug-in electric vehicles (PEVs) under basic and time of use (TOU) rates by using data from service territories in California and around Portland, Oregon.

The U.S. government has a stated goal of 1 million PEVs on the road by 2015. PEVs are likely to play an important role in energy and environmental sustainability, such as by helping to reduce greenhouse gas emissions and dependence on foreign oil. Some of those benefits may be enhanced through demand response (for example, shifting PEV charging from on-peak hours to off-peak hours). An efficient way to achieve this may be through dynamic pricing, e.g., TOU pricing. However, the following questions arise regarding PEV charging under TOU pricing. Will PEV owners respond to TOU pricing? Is the response going to be different than the general residential response?

Few studies discuss the coupling of PEV impacts with price-responsive demand response. Reference [1] investigates the possibility of smart charging of EVs and analyzes the potential impacts under different elasticity scenarios. It also proposes an experimental design for computing the potential demand response from PEVs. Reference [2] presents charging patterns for PEVs using data from the same source as this paper; the data are a year older, however, and is missing pricing information and TOU rates. This paper is based on explicit data on pricing structures, and thus provides insights on charging behaviors related to varying rates.

The next section summarizes data for the two utilities (based on pricing schedules) and for different customer groups. The final section summarizes the results and identifies topics for further study.

II. Electric Vehicle Charging

A. The Data: EV Project

In 2009, ECOtality started the EV project with a grant from the U.S. Department of Energy, partnering with Nissan North America, General Motors, Idaho National Laboratory (INL), and others to deploy and collect charging data [3].

The data for this study, which were collected by ECOtality and the INL team, consist of hourly average charging profiles under different pricing schemes for two different utilities (Portland General Electric [PGE] and Pacific Gas and Electric [PG&E]) for the year starting in July 2012 and ending in June 2013. The team also conducted a survey to collect data about pricing rates of PEV owners. Price rates and number of customers under each rate are summarized in Table I. The dataset does not identify charging load by individual household.

TABLE I
Number of customers in the study and associated price structures

Utility	Rate	Number of residential consumers
PGE	Basic	46
	TOU	15
PG&E	Basic	27
	TOU	118
	EV rate	71

The customers voluntarily selected different pricing rates from the utilities, which creates a potential issue with regard to

[1] This work was supported in part by the U.S. Department of Energy - Office of Electricity Delivery and Energy Reliability under Contract Number DE-AC02-06CH11357.

M. Biviji is with Energy & Environmental Resources Group, LLC, Pittsburgh, PA 15237 (e-mail: mustafa@e2rg.com).

C. Uçkun, G. Bassett and J. Wang are with Argonne National Laboratory, Lemont, IL 60439 (e-mails: canan.uckun@anl.gov, gbassett@anl.gov and jianhui.wang@anl.gov).

D. Ton is with the U.S. Department of Energy, Washington, DC 20585 (e-mail: dan.ton@hq.doe.gov).

978-1-4799-3653-3/14/$31.00 ©2014 IEEE

estimating demand elasticity. As Reference [1] states, the best way to estimate parameters of a model for predicting charging behavior is to conduct a social experiment in which a large number of volunteers are randomly allocated to a control group and a treatment group. The random allocation ensures that the treatment and control groups are comparable in both observable and unobservable characteristics. Reference [4] shows that higher demand flexibility may increase a customer's propensity to select dynamic rates. The remainder of the paper compares the charging profiles for different pricing rates. It also shows the computation for the substitution and own elasticities. Note that the computed elasticities may be overestimated due to the selection bias.

B. Pricing Schedules

Portland General Electric: PGE offers two rate structures: basic and TOU. The basic standard service schedule has a tiered structure, wherein customers are charged 6.8¢ per kWh for up to 1,000 kWh consumption and 7.5¢ per kWh for that above. Annual consumption per PGE residential customer averages 10,375 kWh [5]. Given that the monthly average consumption is 864 kWh, 6.8¢ per kWh is used as the basic rate in the computations.

The TOU rate has three time periods (on-peak, mid-peak, and off-peak) for which the prices vary. On-peak, mid-peak, and off-peak times differ on weekdays, Saturday, and Sunday. Fig. 1 shows the time periods and associated prices. Holidays are treated the same as Sundays. The weekend schedule stays the same in summer and winter, while the weekday schedule changes. Two peak periods are in place during winter.

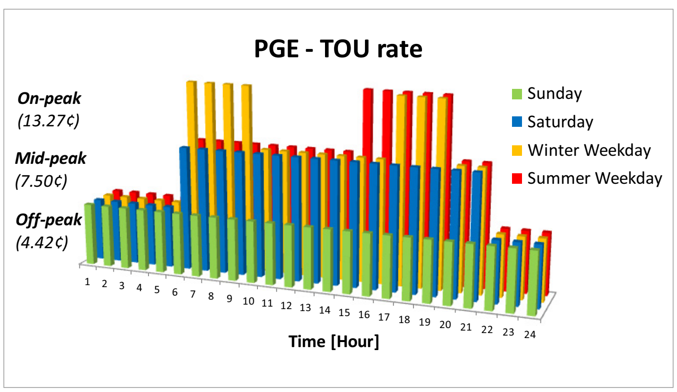

Fig. 1. PGE TOU off-peak, mid-peak, and on-peak schedules and associated prices for weekdays, Saturday, and Sunday.

Pacific Gas and Electric: This paper considers three rates offered by PG&E: basic (E-1), residential TOU (E-6), and EV-rate (E-9A).

PG&E adds another dimension to time-based pricing by charging differently based on consumption levels [6]. In this tiered or inclining block rate structure, the marginal price of electricity consumed in a given hour increases as the consumption level increases through five different tiers. The first tier comprises consumption up to a "baseline" quantity of kWh. Each customer within a climate zone is given the same baseline, which is 50-60% of average consumption in the zone. Tiers 2 through 5 correspond with consumption levels up to 130%, 200%, 300%, and over 300%, respectively, of the assigned baseline. The baselines differ in summer and winter.

The PG&E website publishes prices for all rates [7]. This paper uses 18.85¢ per kWh for summer and 18.89¢ per kWh for winter, for the basic rate, E-1. These summer and winter average basic rates are computed using the published average basic rates for the time periods Jul–Dec 2012, Jan–Apr 2013, and May–Jun 2013.

It is complex to compute elasticities for tiered rates. Therefore, as a proxy for E-6 and E-9A, a simple TOU rate (without tier structure, that is, constant across quantity) is computed with times corresponding to on-peak, partial-peak and off-peak, such that the bills match those under the tiered rate. For the computations, publicly available residential load data are used for the period studied [8]. First, the daily baselines for summer and winter are approximated by using the residential load data and assuming that the baseline is 55% of the average daily load. The average customer's seasonal bill is computed using the tiered rates based on the percentage of total daily consumption during the on-peak, partial-peak, and off-peak periods. Then, the average price paid per kWh for each period is computed under E-6 and E-9A rates, which are used as TOU and EV-rate prices, respectively, for computing elasticities. The resulting prices for summer are represented in Figs. 2 and 3.

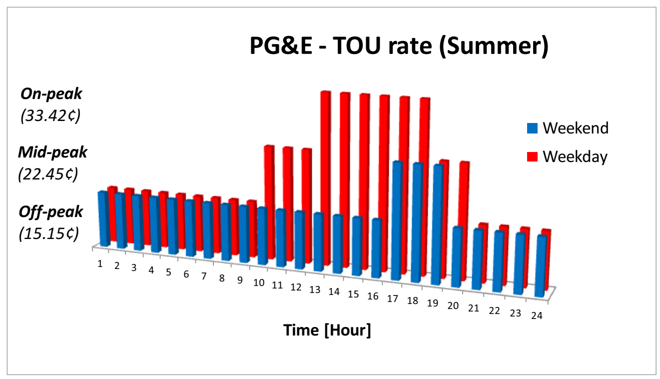

Fig. 2. PG&E TOU rate, E-6, and associated off-peak, mid-peak, and on-peak times and prices for summer weekdays and weekends.

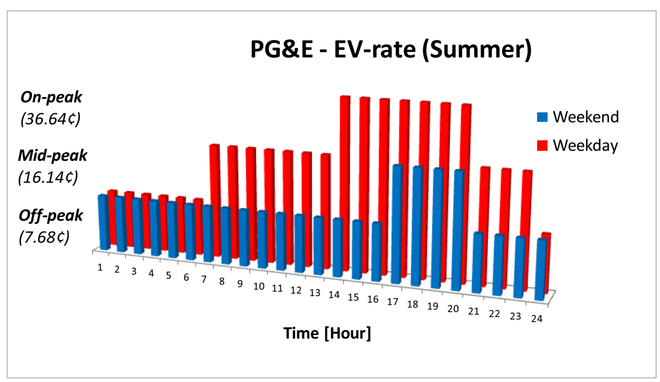

Fig. 3. PG&E EV-rate, E-9A, and associated off-peak, mid-peak, and on-peak times and prices for summer weekdays and weekends.

As the figures show, both rates set average prices high compared to the flat rate of 18.9¢. Further, the EV rate penalizes peak consumption and rewards off-peak consumption more substantially than does the TOU rate.

Winter rates are summarized in Table II. The TOU and EV rates do not have a peak period in winter and are much lower than summer rates. The EV rate has a longer partial-peak period and also a weekend partial-peak period.

TABLE II
Time schedules and estimated rates for PG&E for Rates E-6 and E9-A

		Schedule	Rate (¢/kWh)	Schedule	Rate (¢/kWh)
		Partial-peak		Off-peak	
PG&E TOU	Weekdays	5PM-8PM	17.12	All other	15.5
	Weekends	-			
PG&E EV-rate	Weekdays	7AM-12AM	16.09		8.30
	Weekends	5PM-9PM			

In general, PG&E rates are much higher than PGE rates, and the difference in rates between summer and winter for PG&E is substantial.

C. Data Features and Characteristics

a. Monthly Consumption.

The average daily EV charging load for every month from July 2012 to June 2013 for PGE and PG&E under different pricing structures is shown in Fig. 4. The figure shows a seasonal pattern in which consumption peaks during the winter months. It also shows that basic rate customers tend to consume less than TOU customers throughout the year. TOU and EV customers with PG&E were found to have similar results, with a higher than average daily consumption during winter months, and a higher overall average consumption.

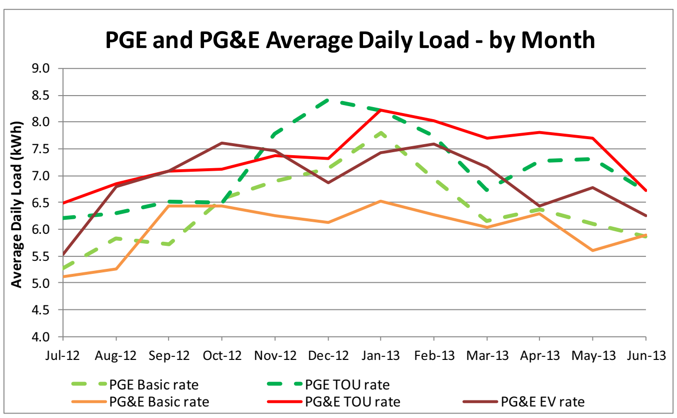

Fig. 4. PGE basic and TOU, and PG&E basic, TOU, and EV rate average daily EV charging load by month and year.

b. Consumption by Day of the Week.

Total EV charging load for the days in a week during summer months is shown in Fig. 5 for PG&E. Even though the pricing structure incentivizes a different schedule, total daily consumption is higher from Tuesdays to Saturdays and lower on Sundays and Mondays. This might be explained by common usage of EVs for planned trips, generally including the weekday office commute. Evidently, most EVs are charged after the Friday commute from late Friday night to Saturday morning; hence, there is less scope for charging on Sunday and early Monday mornings.

Fig. 5 also shows that average consumption by basic rate customers is lower than that of TOU and EV-rate customers, with less variation among the days of the week. This might be attributed to self-selection (that is, customers might have selected the base rate because their consumption was lower ex-ante). Their load might also be lower for other reasons, such as availability of solar energy or other battery options, or some other unobservable characteristic. A similar pattern is seen for the winter months.

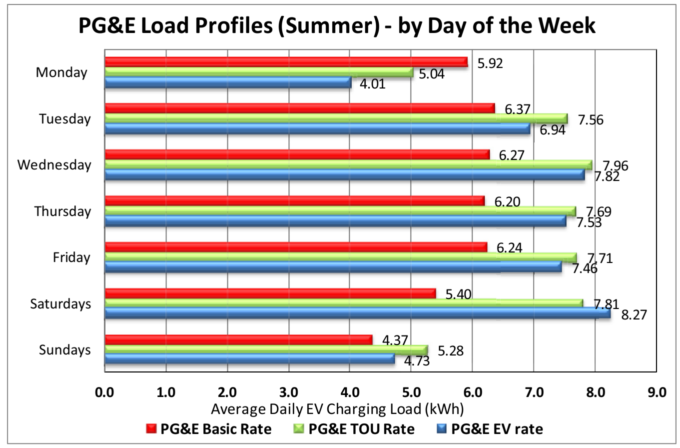

Fig. 5. PG&E basic, TOU, and EV rate average daily EV charging load by day of the week.

For PGE, a slightly different pattern is seen for the summer months (Fig. 6). TOU customers consume significantly less on Mondays (5.25 kWh) than any other day of the week (6.79 kWh). This difference could be due to an absence of time-varying pricing on Sunday as per the PGE TOU rate structure, suggesting that customers do take advantage of a low off-peak rate on Sundays.

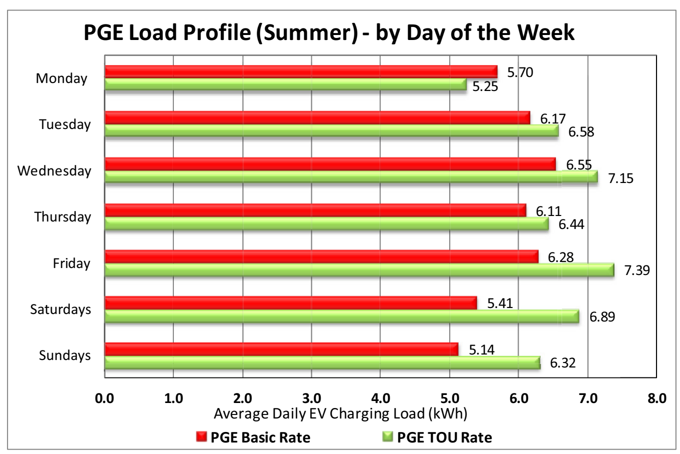

Fig. 6. PGE basic and TOU rate average daily EV charging load by day of the week.

c. Daily Load Profiles by Period.

The daily EV charging load profiles by period for the PGE customer groups during the summer months are presented in Fig. 7, which also depicts the pricing periods. The sharp fall and rise in consumption appears to inversely correlate with the fall and rise in TOU prices. This suggests that TOU customers make a more deliberate effort to avoid the higher priced evening charging peak (compared to the basic group, with constant prices). Also, charging on Saturdays (which has no peak period) follows a similar pattern as weekdays, but with a lower quantity. Sundays (without load profiles shown, given the single off-peak rate) have a similar load curve to Saturdays (and the other days of the week), suggesting customers follow the weekday off-peak period charging habit on weekends also, regardless of the liberal weekend TOU schedule.

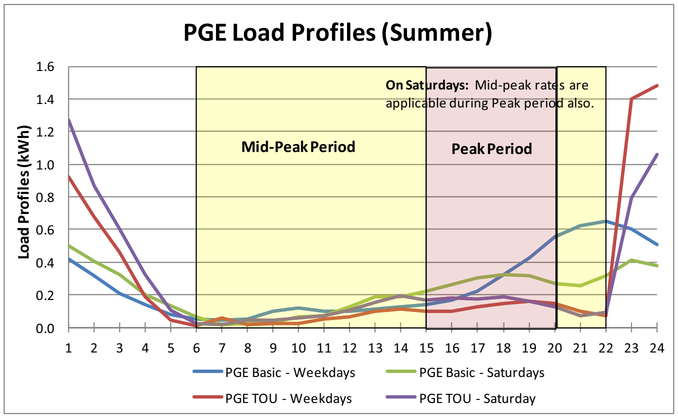

Fig. 7. PGE average hourly EV charging load curves for weekdays and Saturdays (along with peak and mid-peak shaded regions).

Fig. 8 shows load profiles for the three PG&E customer groups on weekdays and weekends. As mentioned, PG&E customers can choose a special EV rate that demands longer peak periods and higher peak rates, while offering lower off-peak rates for greater potential bill savings. Similar to PGE customers, PG&E TOU and special EV-rate customers charge car batteries primarily during off-peak periods. PG&E customers also avoid charging during peak and mid-peak periods, and follow weekday charging patterns on weekends as well (despite a different weekend rate structure).

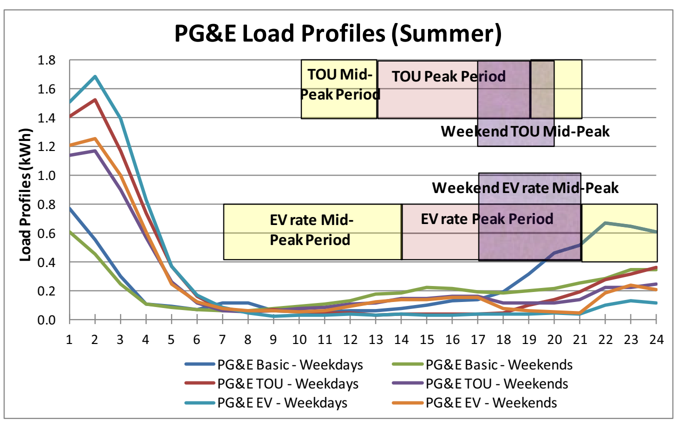

Fig. 8. PG&E average hourly EV charging load curves for weekdays and weekends (along with peak and mid-peak shaded regions).

Winter month results are similar to those shown above for summer months, with the big difference in consumption being a winter increase of 7–17%, depending on the utility and pricing schedule.

d. Statistics for Peak versus Off-Peak Consumption.

Let Q_{it} denote average hourly consumption during the peak period, and Q_{jt} denote average hourly consumption during the off-peak period on day t (for a given customer class and pricing structure). The recorded data indicate (see Table III) that the daily average of $\ln(Q_{it}/Q_{jt})$ for PGE during summer weekdays is 0.155 for basic customers and –1.643 for TOU customers. These values indicate that for basic rate customers, peak hourly consumption is about 16% higher than off-peak consumption. For TOU customers, consumption shifts significantly, with peak consumption being only one-fifth of off-peak consumption.

This change in peak/off-peak consumption can be compared to the peak/off-peak rates in the TOU schedule. Let P_{it} denote the peak period rate and P_{jt} denote the off-peak period rate on day t (for a given customer class and pricing structure). The $\ln(P_{jt}/P_{it})$ for TOU customers is -1.098 as compared to a $\ln(P_{jt}/P_{it})$ value of 0 for a basic rate (as P_{jt}/P_{it} is 1). Assuming basic-rate consumption patterns would be the same as those of TOU customers (if faced with basic rates) allows for an estimate of the elasticity of substitution. (Note that an inverted price ratio is used so the resulting elasticity value is positive for a shift in load from the peak to off-peak period in response to TOU pricing.) Table III shows the substitution elasticity calculation for PGE summer months (excluding Sundays).

TABLE III
Elasticity of substitution calculation for PGE

	$Q_r = \ln(Q_{it}/Q_{jt})$	$P_r = \ln(P_{jt}/P_{it})$
Basic rate	0.155	0.000
TOU rate	–1.643	–1.098
Elasticity	$(Q_r[TOU] – Q_r[Basic])/(P_r[TOU] – P_r[Basic])$	
Value	1.637	

Note that ideally, a control would be established for the selection effects mentioned and other factors that alter peak to off-peak consumption patterns. Examples include availability of solar power, ability to store power via batteries, and flexibility in ability to time charging. The Excel-based tool described in Reference [9] provides a straightforward way to estimate these elasticities and to control for additional, non-price factors that might affect load. The remaining elasticity estimates have also been found by using the tool [10].

Table IV contains estimates of substitution elasticity and the supporting statistics for summer and winter periods separately for the different pricing schemes offered by both utilities.

TABLE IV
Elasticity of substitution values for PGE and PG&E

SE Value (t-test, R^2)	**SE (P1&P2)**	**SE (P1&P3)**	**SE (P2&P3)**
PGE TOU–Basic (Summer)	-0.593 (-3.49, 0.05)	1.637 (26.16; 0.74)	3.761 (25.00; 0.68)
PGE TOU–Basic (Winter)	0.359 (2.32, 0.02)	1.929 (26.47, 0.74)	3.468 (27.88, 0.72)
PG&E TOU–Basic (Summer)	0.606 (2.88, 0.03)	2.047 (19.78, 0.61)	3.040 (18.81, 0.49)
PG&E TOU–Basic (Winter)	NA*	NA*	12.864 (23.81,0.69)
PG&E EV–Basic (Summer)	0.727 (5.61, 0.11)	2.114 (35.29, 0.83)	3.242 (30.73, 0.73)
PG&E EV–Basic (Winter)	NA*	NA*	4.477 (50.61, 0.91)

Note that in Table IV, SE = substitution elasticity, P1 = peak period, P2 = mid-peak period, and P3 = off-peak period.

Values in brackets are supporting statistics (t-test value, R^2 value). Some elasticity estimates are not applicable (NA*) because no peak period was present for that rate structure.

In general, less substitution is taking place from peak to mid-peak periods. Hence, all charging seems to be postponed (shifted) to off-peak periods by TOU customers.

Table V below provides estimates of own-price elasticity (which is a measure of load conservation) for different rate structures during the summer and winter pricing periods.

TABLE V
Own-price elasticity values for PGE and PG&E

OPE Value (t-test, R^2)	**OPE (P1)**	**OPE (P2)**	**OPE (P3)**
PGE TOU–Basic (Summer)	-1.471 (-16.24, 0.52)	NA**	-1.874 (-28.76; 0.73)
PGE TOU–Basic (Winter)	-1.896 (-16.98, 0.54)	NA**	-1.980 (-29.24, 0.74)
PG&E TOU–Basic (Summer)	-2.010 (-14.64, 0.46)	-4.358 (-13.26, 0.33)	-2.321 (-17.06, 0.45)
PG&E TOU–Basic (Winter)	NA*	NA**	-0.362 (-1.13, 0.00)
PG&E EV–Basic (Summer)	-3.303 (-25.65, 0.73)	NA**	-1.215 (-27.51, 0.68)
PG&E EV–Basic (Winter)	NA*	NA**	-0.452 (-3.16,0.03)

Note that in Table V, OPE = own-price elasticity, P1 = peak period, P2 = mid-peak period, and P3 = off-peak period. Values in brackets are supporting statistics (t-test value, R^2 value). There is no peak period (*) and the change in prices is too small (**).

III. Discussion and Summary

The residential EV charging load profiles show different characteristics than does a normal residential load profile. Minimal consumption occurs during morning and early afternoon hours. With TOU rates, EV charging mostly takes place late at night during off-peak hours. Also, TOU customers do not seem to differentiate between peak rates and mid-peak rates for charging EVs. These characteristics, along with low consumption on Mondays, make EV load profiles significantly different from normal household load profiles.

The difference can also be observed in customer responses to pricing-elasticity values. For residential customers, short-term own-price elasticity values generally range from –0.2 to –0.6, while short-term substitution elasticities range from 0.07 to 0.21 [11]. While this dataset suffers from self-selection issues, it would not be surprising to see higher elasticity values for EV charging loads (as seen in this paper). EV charging is generally more flexible and easier to manage than shifting multiple residential loads. The charging time might be set up in advance by using EV supply equipment (EVSE). This higher flexibility seen in EV loads would enable designing for more varied pricing programs, hence allowing utilities to better manage EV charging-induced spikes in residential locations. An example of this is seen in PG&E's special EV rate (a more aggressive TOU pricing structure); these customers are willing to take advantage of the savings from lower off-peak rates (in shorter off-peak periods). Shifts in demand can be expected to become even more pronounced as technology (for example, smart phones) evolves, thus allowing for greater flexibility in timing consumption to take advantage of cheaper off-peak rates.

Consumption between household and EV charging also differs according to season, with EV charging consumption peaking during winter, as opposed to residential consumption peaking during summer. Since most utilities peak during summer months, more EVs could to a certain extent help balance load demand over the entire year. Utilities can take advantage of the differences in residential and EV charging load profiles with attractive TOU programs, while the end-customer can take advantage of lower off-peak rates in an effort to reduce bills.

IV. Acknowledgments

The authors gratefully acknowledge the contributions of John Smart and his team from Idaho National Laboratory and Steve Schey and his team from ECOtality for providing the data and addressing questions related to the data.

V. References

[1] A. Faruqui, R. Hledik, and A. Levy, "Will Smart Prices Induce Smart Charging of Electric Vehicles?" The Brattle Group, Inc., July 2011.

[2] S. Schey, D. Scoffield, and J. Smart, "A First Look at the Impact of Electric Vehicle Charging on the Electric Grid in the EV Project," EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, May 2012.

[3] *The EV Project » Overview*. [ONLINE] Available at: http://www.theevproject.com/overview.php. [Accessed 14 August 2013].

[4] T. Ericson, "Households' Self-Selection of a Dynamic Electricity Tariff," Discussion Paper No. 446, Statistics Norway, Research Department, February 2006.

[5] *PGE at a Glance: Quick Facts | PGE*. [ONLINE] Available at: http://www.portlandgeneral.com/our_company/pge_glance/quick_facts.aspx. [Accessed 13 August 2013].

[6] *Understanding Baseline Quantities*. [ONLINE] Available at: http://www.pge.com/myhome/customerservice/financialassistance/medicalbaseline/understand/. [Accessed 14 August 2013].

[7] *Pacific Gas & Electric – Tariffs*. [ONLINE] Available at: http://www.pge.com/tariffs/electric.shtml. [Accessed 14 August 2013].

[8] *Pacific Gas & Electric – Tariffs*. [ONLINE] Available at: http://www.pge.com/tariffs/energy_use_prices.shtml. [Accessed 14 August 2013].

[9] D. Ton, M.A. Biviji, E. Nagypal, and J. Wang, "Tool for Determining Price Elasticity of Electricity Demand and Designing Dynamic Price Program," in Proceedings of 2013 IEEE Innovative Smart Grid Technologies Conference.

[10] *Argonne National Laboratory, Decision and Information Sciences - Tool for Designing Dynamic Rates*. [ONLINE] Available at: http://www.dis.anl.gov/projects/TDDR.html. [Accessed 14 August 2013]

[11] B. Neenan and J. Eom, "Price Elasticity of Demand for Electricity: A Primer and Synthesis," Electric Power Research Institute, January 2008.