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How Will Tomorrow's Residential Energy Consumers Respond to Price Signals? Insights from a Texas Pricing Experiment

Tomorrow's consumers likely will have the ability to monitor their appliance-specific energy usage, remotely program their HVAC system, live in more energy-efficient dwellings, obtain electricity through rooftop solar photovoltaic systems, drive plug-in electric vehicles, and have a generally higher level of knowledge about household energy usage. How will they respond to electricity price signals? The authors explored this question through pricing experiments at the Mueller neighborhood in Austin where, to some degree, 'the future is now.'

Jay Zarnikau, Shuangshuang Zhu, Ron Russell, Milton Holloway and Michael Dittmer

I. Introduction

In recent years, numerous pilot programs have been undertaken to explore how dynamic pricing could change electricity consumption behavior. Antecedent experiments targeted typical energy consumers or a representative distribution of consumers, such that the results could be extrapolated to a larger utility service area to address

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questions surrounding the impacts, benefits, and costs of wide-scale permanent pricing changes.

The pricing experiments described here explore a very different questions: How would sophisticated energy consumers who are comfortable with advanced energy-related technologies respond to price signals?[1] How might such a combination of future residential sector technologies and price signals help accommodate additional renewable generation on the electric grid? The participants in this pricing experiment were not typical consumers by today's standards. More than half have plug-in hybrid or electric vehicles. Most have photovoltaic systems. All can view the electricity usage of their major appliances and circuits within their home over the Internet. Most have remotely programmable thermostats. Their homes are built to highly energy-efficient standards. Most of the participants have advanced university degrees. In short, these consumers are keenly interested in minimizing their energy use, they understand their energy usage, and can do the math. While participants in this pricing experiment are not typical residential energy consumers, perhaps they will be the norm 20 to 50 years from now. That is what makes this forward-looking pricing experiment different.

To explore how price signals could alter consumption patterns, 62 participants in this pricing program were offered electricity at experimental rates during different months. A discounted price of 2.65 cents per kilowatt-hour (kWh) was charged during a ''wind-enhancement period,'' coinciding with nighttime hours during five winter months, when west Texas wind farms tend to reach their maximum generation. Purchases during up to 15 summer critical peak periods per year were priced at 64 cents per kWh, about five times the prevailing price. Prices during other periods were adjusted to achieve overall revenue neutrality. Thus, if the consumer took no actions to change their consumption pattern, electricity costs over the 18-month period of the experiment would be similar to the bill received from the local utility.

The participants in this pricing experiment were not typical consumers by today's standards.

In response to traditional time-of-use (TOU) pricing, many of the 30 participants with electric vehicles moved their charging to the nighttime wind enhancement periods. Laundry was delayed to the nighttime. The percentage of energy consumption shifted to off-peak periods was in-line with the results from TOU studies targeting more-typical homeowners. Yet, the overall magnitude of the peak demand reduction in response to critical peak pricing (CPP) events was lower than in previous studies involving typical consumers in North America, in part reflecting the lower overall energy use in these energy-efficient dwellings.

II. Research Design

To evaluate how traditional TOU and CPP pricing schemes could be used to alter customer load profiles, 62 homes received price signals over a 20-month period from March 2013 through October 2014. Energy use was also monitored in a control group of 62 homes.

The TOU pricing featured a discounted nighttime price of $0.0265 per kWh to encourage use of west Texas wind generation during the five windiest months of the year: March through May, November, and December. The discounted price was applied to energy consumption in the hours from 10 p.m. to 6 a.m. on all days during those months. To make the experimental pricing approximately revenue-neutral, there was an offsetting surcharge of approximately $0.02 per kWh on the participants' energy consumption during all other hours of those five months.

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A premium price of $0.64 per kWh was applied to the participants' energy consumption during the weekday (Monday through Friday) afternoon hours of 4 p.m. to 7 p.m. on ''critical peak'' days during the four summer months of June through September. To make the experimental pricing approximately revenue-neutral, an offsetting discount of approximately $0.016 per kWh was applied to energy consumption during all non-peak hours of CPP event days.

While there was no temporal overlap between the two pricing schemes, some behaviors formed in response to TOU pricing impacted participant response to later CPP events.

Most of the participants resided in the Mueller development near downtown Austin, Texas. When the Robert Mueller Municipal Airport was closed in 1999, the City of Austin saw an opportunity to develop a mixed-use planned community built to the highest energy efficiency standards. With support from the U.S. DOE and sponsors such as Intel, Whirlpool, Landis + Gyr, LG, Oncor, Oracle, Sony, Sun Edison, and Texas Gas, it has become the nation's premiere test laboratory for energy-related technologies, as seen in Rhodes et al. (2014). Construction of single-family homes began in August 2007. The homes have energy efficient features and a high concentration of installed grid-tied solar photovoltaics and plug-in electric vehicles (PEVs) – features that are likely to become more prevalent in the decades ahead. Basic demographic information and typical features of the homes are listed in Table 1.

Homes within the pricing and the control groups were outfitted with home energy management (HEM) systems to collect whole home and circuit (appliance) level energy use data in one-minute intervals. These energy use data were used to perform comparative analysis between and within the pricing and control groups to characterize and quantify the pricing group's response to the two experimental pricing schemes.

Over the course of this experiment, the pricing and control groups received and continued to pay their usual Austin Energy electric bills, based on the local utility's normal electric rates. A monetary incentive was used to entice pricing group participants to either shift their energy consumption to the ''wind enhancement'' time period or to reduce energy consumption during CPP events. A credit account with an initial balance of $200 was created for each participant in the pricing group. Changes to the initial balance, based on the difference between what the participant actually paid to the utility and what they would have paid if Austin Energy actually charged the pricing trial rates, reflected the participant's degree of response to price signals. Participants were able to view their credit account through an online web portal display, as shown in Figure 1.

The pricing trial electric rates consisted of the following components:

- Customer charge (the same as Austin Energy's charge), which was a flat rate of $10.
- Baseline (existing Austin Energy) rates were applied only to consumption during non-wind hours and non-CPP hours.
- Wind period rates were applied to consumption during wind hours.
- Surcharge rates were applied to total monthly consumption during non-wind hours.
- Discount rates were applied to consumption on CPP event days during hours other than 4 p.m. through 7 p.m.

The pricing trial rate formulas were:

1. Wind enhancement period: Customer charge + [Baseline rates x (consumption between 6 a.m. and 10 p.m.)] + [Wind price × (consumption between 10 p.m. and 6 a.m.)] + [Surcharge rate × (consumption between 6 a.m. and 10 p.m.)]
2. Months during which CPP events could be called: Customer Charge + [Baseline rates × (consumption during all hours other than during called critical peak days, 4 p.m. to 7 p.m.)] + [Critical Peak price × (consumption during 4 p.m. to 7 p.m. on called critical peak days)] + [Discounted

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Table 1: Demographic Data of Participants in Pricing and Control Groups.

Demographic Information (n = count)	Responses
Salary (n = 53)	• 43 survey respondents, or about 81 percent, claimed income above $75,000. • One respondent claimed income between $300,000 and $1 million, and two participants claimed income above $1 million.
Ethnicity (n = 62)	• 51 respondents, or 82 percent, reported Caucasian ethnicity. • Three respondents reported Hispanic ethnicity. • Three reported Asian/Pacific Islander ethnicity. • Five declined to respond.
Education (n = 59)	• All respondents, except for one left blank, reported a college degree or higher. • 42 respondents, or 71 percent, reported a postgraduate degree.
Home during weekdays	• 46 percent of the pricing group and 62 percent of the control group homes can typically be occupied on weekdays (daytime hours).
PEV ownership	• 34 PEVs are owned by the pricing group, consisting of 25 plug-in hybrids and 9 full electric vehicles, compared to only 6 PEVs for the control group.
Cooking appliances	• Predominantly natural gas. • 27 percent have an electric oven.
Laundry appliances	• 1 in 3 has an electric dryer, although natural gas is available.
HVAC systems	• 90 percent have a gas furnace.
Water heaters	• Natural gas.
Average square footage	• Approximately 2,000 square feet for both the participant and control groups.
Percent of homes with remotely programmable thermostats	• 100 percent of homes in both groups.

PERIOD	USAGE	PRICING TRIAL BILL	AUSTIN ENERGY BILL	ADJUSTMENT CREDIT
Mar 1, 2013 - Mar 31, 2013	674 kWh	$59	$62	$3
Apr 1, 2013 - Apr 30, 2013	703 kWh	$58	$67	$9
May 1, 2013 - May 31, 2013	658 kWh	$54	$58	$3
Jun 1, 2013 - Jun 30, 2013	1050 kWh	$128	$138	$10
Jul 1, 2013 - Jul 31, 2013	1088 kWh	$114	$128	$14
Total	4173 kWh	$413	$453	$239.0

Figure 1: Example of Web Portal Display of Pricing Information.

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rate × (consumption during all hours on event days other than 4 p.m. to 7 p.m.)]

At the end of the pricing trial, participants with positive credit adjustment balances received payments equal to the amount of the final credit adjustment balance in their accounts, up to a maximum of $700 per customer. Participants with negative credit adjustment balances did not owe anything.

The day-ahead CPP call was made to simulate a call by a utility or a retail electric provider anticipating an extremely high next-day system load. The CPP events were called when temperatures exceeded various thresholds, which were adjusted once actual weather conditions became better known each summer. Figure 2 presents the process that was employed to determine how and when to call a CPP event and notify the participants.

Recruitment of pricing trial participants began in February 2013 targeting residents living in the Mueller community. Owners of single-family residential homes were contacted via e-mail.

While recruitment via voluntary enrollment may have introduced some self-selection bias, this was not deemed to be of critical concern for a variety of reasons. Both pricing trial participants and control group members had previously agreed to be part of the broader Pecan Street project involving the installation of energy usage monitoring, PEV promotions, and promotions of other energy-related technologies (e.g., remotely programmable thermostats). Further, the extrapolation of the results to a larger general population was not among the objectives of the experiment.

Before the start of the experiment in March 2013, the pricing group received e-mail communications outlining the experiment design and suggestions for shifting or reducing their energy consumption, such as deferring laundry use until after 10 p.m. during the five wind enhancement months or reducing air conditioner use during CPP events over the four summer months. One in-person workshop was conducted for the pricing group to further detail the pricing trial's design, goals, and research benefits. Each member of the pricing group was given secure access to a personal online Web portal to check the monthly status

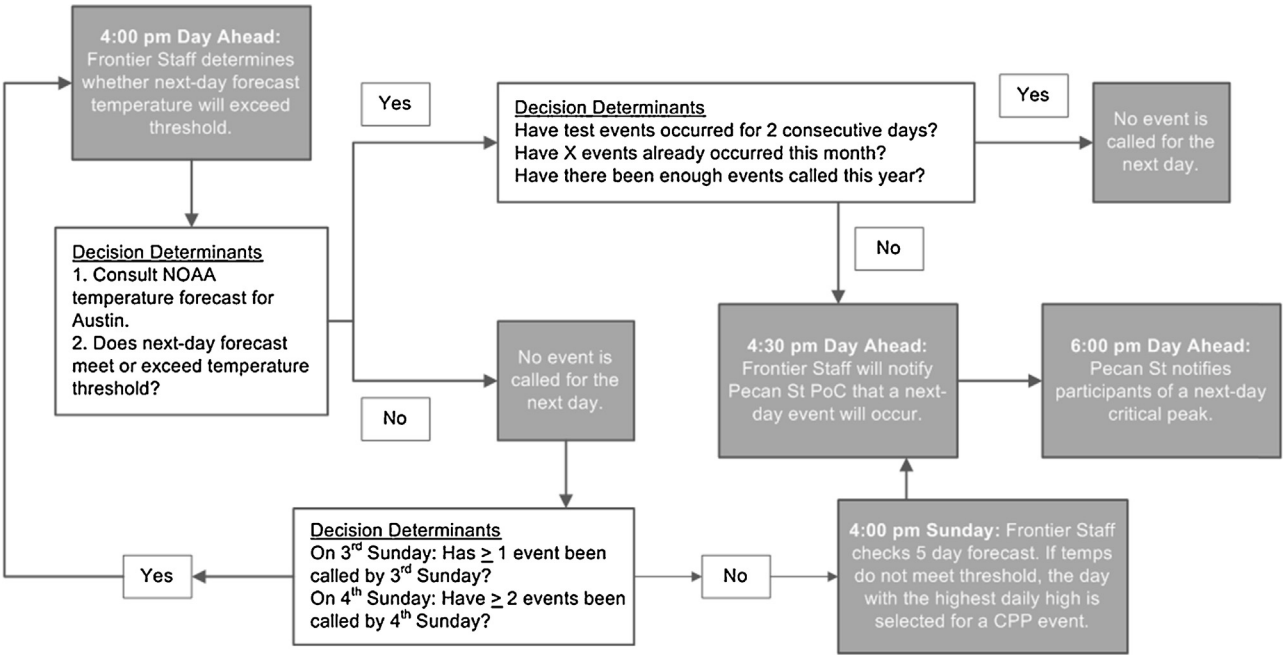

Figure 2: Flowchart for Calling Next-Day CPP Events.

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of their energy usage, pricing trial bill, an estimate of their Austin Energy bill, and adjustment credit balance. On the Web portal, in addition to information pertaining to the pricing trial, pricing group participants had access to the following information:

- Monthly whole home energy use in kWh,
- Monthly energy cost in U.S. dollars per appliance,
- Real-time energy consumption in kWh,
- Monthly energy cost comparison to other participants within the same zip code, and
- Monthly energy usage trends.

During the summer months, pricing group participants also received CPP notifications via cell-phone text messages and e-mail by 6:00 p.m. the day before a CPP event.

III. Data Collection

Each HEM system is comprised of a home energy management device, a HomePlug adapter (power line communication device) allowing communications from the HEM system to the participant's Internet gateway, and up to 24 current transformers (CTs) for measuring consumption on individual circuits within the home.

The HEM system directly measures electricity use for the whole home and a number of circuits at one-minute intervals. Individual circuits typically monitored include:

- Refrigerator
- Furnace and air handler
- AC/heat pump condensing unit
- Clothes dryer
- Clothes washer
- Oven and cook-top range
- Microwave
- Electric vehicle level II

charger

- Lighting – whole home
- Lighting – individual room
- Plug loads
- Solar generation (if installed)

The data from the HEM system was streamed through the participants' Internet gateway to Pecan Street's server cluster where it was stored in a secure database environment.

IV. Evaluation Approaches

The pricing group's hourly electricity consumption pattern during months in which TOU pricing was in effect was compared to the control group's consumption pattern. Consumption patterns for certain sub-metered end uses (e.g., PEV charging, kitchen appliances, and laundry) were also examined to explain any observed shifts. Additionally, the pricing group's consumption patterns were compared to their own pre-trial consumption patterns. The end-use comparison is important due to the different levels of PEV ownership between the pricing and control groups (54 percent of the pricing group had PEVs, in contrast to 10 percent in the control group).

Peak demand reduction on critical peak days during the high-priced afternoon hours was analyzed using three different statistical methods. Fixed effects panel data analysis was adopted as the primary method, following Cappers et al. (2013). An historical baseline method and a difference-in-difference (DID) model were additionally used to verify the results from the fixed effects regression models and provide further insights.

In the panel data analysis, time-of-day, day-of-week, and weather were taken into consideration. Separate regression models were estimated for each of the two summers. All summer afternoon hours were analyzed. The dataset included both the pricing and control groups. Different intercept terms were estimated for each household.

Under the historical baseline method, estimated kW savings

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were based on a comparison of actual load during CPP events to the average load experienced during the four non-event weekdays immediately preceding a CPP day.

The DID approach also followed Cappers et al. (2013). Data for the event days from 4:00 p.m. to 7:00 p.m. were used as the treatment period and the same hours of the previous non-event weekday were used as the control period.

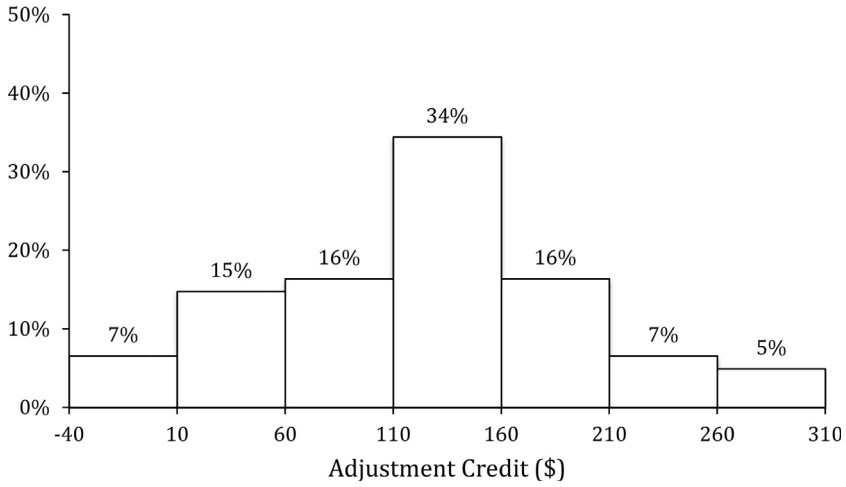

Figure 3: Adjustment Credit Earnings Distribution.

V. Results

The impacts of the pricing experiment can be illuminated by a review of the final adjustment credit balances, the changes in load patterns at the whole-house and end-use levels resulting from the TOU pricing, the peak demand reduction resulting from CPP events at the aggregate and end-use levels, and feedback received from the participants. Each of these metrics is reviewed here.

A. Payments to participants

Overall, there was a positive response to price signals as indicated by the levels to which the initial credit of $200 was adjusted based on the pricing group participants' response to the prices. Some 97 percent of participants had positive credits while 3 percent (two participants) incurred deductions on their incentive account. Some 84 percent of participants had earnings greater than $40 (in addition to the $200 beginning credit) and the maximum adjustment credit earned was $280.57, in addition to the beginning credit. The predominant amount of additional credit earned over the course of the project was in the range of $110 to $160. Even though the largest incentive amount earned was significantly below the maximum allowable amount of $700, overall there was a positive response to these pricing programs. Figure 3 displays the distribution of incentive credits earned by the participants over the course of the pricing trial.

B. Response to TOU pricing: overall consumption

Figure 4 compares pricing and control group daily consumption patterns during the 2013 and 2014 wind pricing months, plotted in hourly percentage of daily total usage. The seasonal average hourly Texas wind generation is represented by the dotted line in the background.[2] Note that shifting electricity consumption from daytime to overnight supports better matching of load to wind energy generation. Patterns observed during the other two time frames in which TOU pricing was in effect followed similar patterns.

In contrast to the shifts evident in wind-pricing months, there is no clear shift in non-wind months. Energy consumption patterns for the pricing and control groups were similar in non-wind months. Figure 5 shows average patterns for June 2014 for illustration.

A 4 percent shift from daytime to overnight consumption for the months in which TOU pricing was in effect is suggested by a comparison of the load patterns of the pricing and control groups. Since these two groups had different levels of

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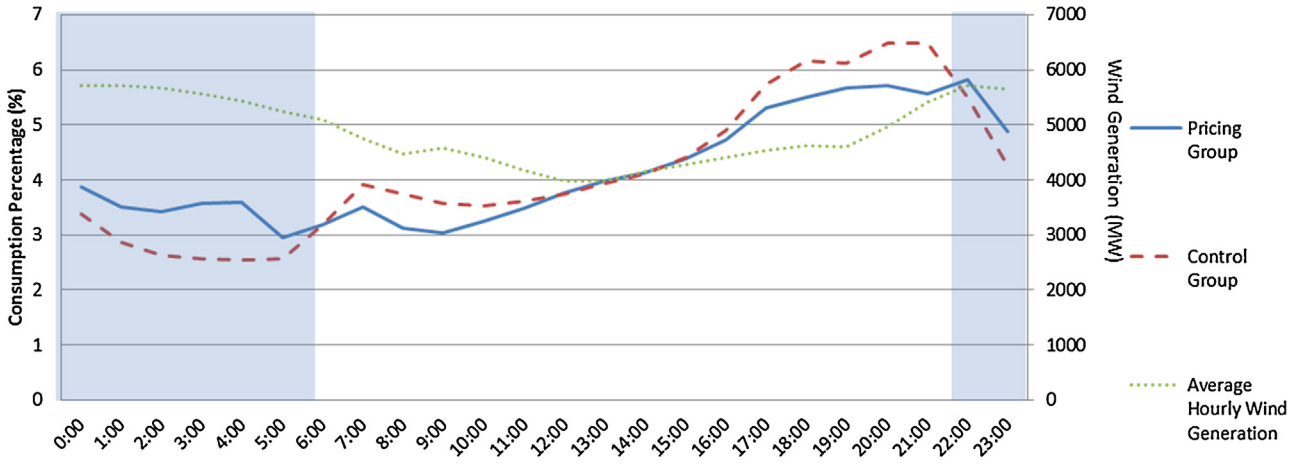

Figure 4: Pricing Group vs. Control Group March to May 2013 Wind Pricing Period.

PEV ownership, a more-appropriate baseline might be the pricing group's load pattern prior to the pricing trials. Using this baseline, a 5 percent shift in usage from peak to non-peak pricing hours is suggested. This response is similar to the findings from other TOU studies involving more-typical homes and pricing plans involving similar diurnal rate differentials.

The percentage of PEV ownership in the pricing group affects the amount of daytime load available to shift to nighttime. The following discussion examines PEV charging behavior, as affected by TOU pricing.

C. PEV charging responds to TOU pricing

The percentage of PEV charging shifted to nighttime in response to the TOU pricing for both plug-in hybrids and full electric vehicles was impressive. For the group exposed to the TOU pricing, the energy consumed by PEV charging during the nighttime increased from 32 percent prior to the pricing experiment to 55 percent during the months with TOU pricing.

Figure 6 displays the average PEV charging consumption daily load shape for owners of plug-in hybrids for three different periods – before the trial started, during all wind months, and during the summer. There was a marked reduction in daytime charging by hybrid owners when the TOU wind pricing was in effect, taking advantage of very inexpensive overnight charging. Also note the partial rebound in daytime charging during the summer months when wind pricing is not in effect. This summer rebound may be partially caused by the longer daylight hours and increase in evening activities in the summertime, calling for increased seasonal afternoon charging due to the short range of hybrids. Some participants stated in their final survey response that they

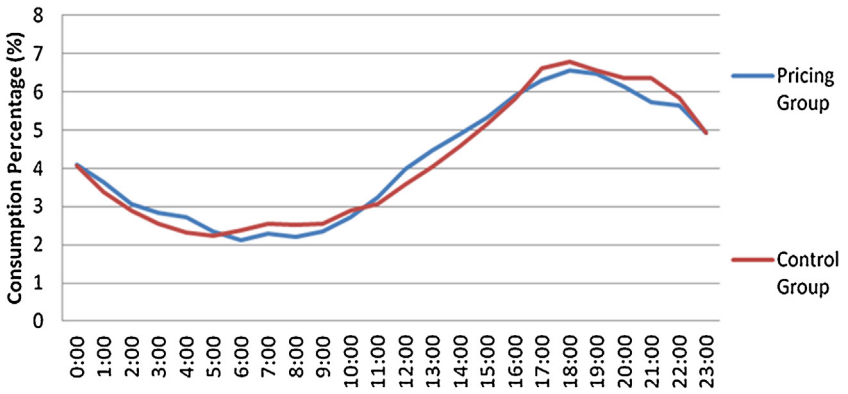

Figure 5: Pricing Group vs. Control Group June 2014.

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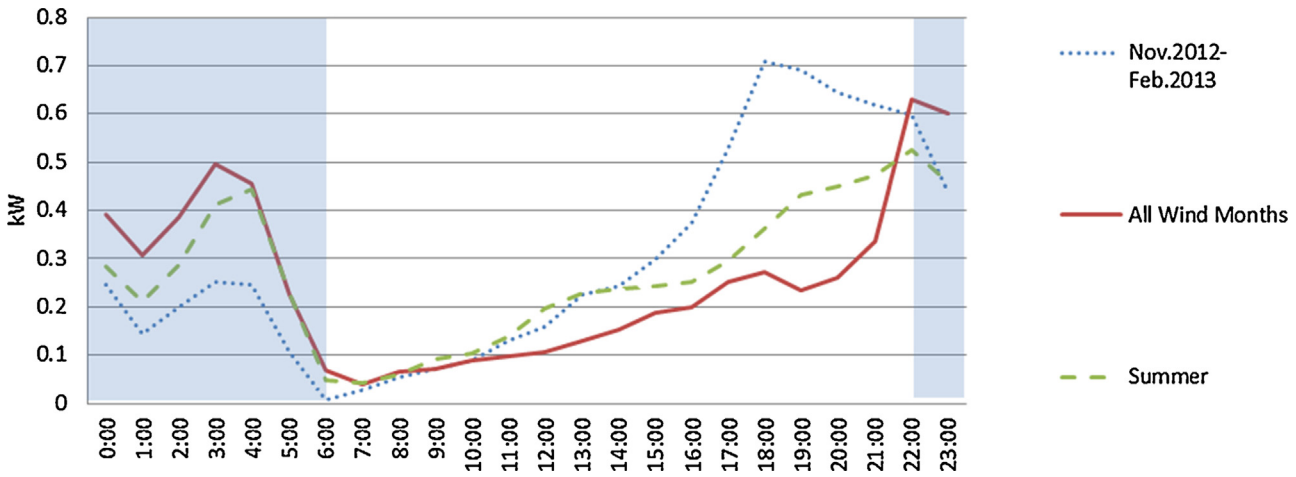

Figure 6: Pricing Group Hybrid PEV Owners Average Charging Behavior.

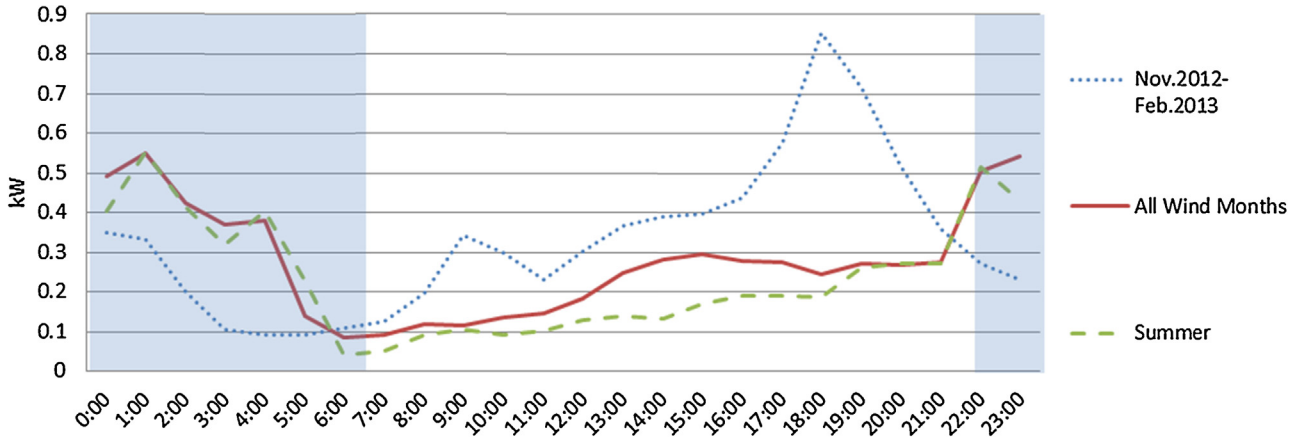

Figure 7: Pricing Group Full Electric PEV Owners Average Charging Behavior.

went back to charging as convenient (including during daytime hours) when the TOU pricing was not in effect.

Figure 7 provides a similar graph for the full electric PEV owners. For the full electric PEV owners, as was also evident for the hybrid PEV owners, there is a marked reduction (dotted line to solid line) in daytime charging when the TOU wind pricing is in effect. The summer rebound is not seen in this case, likely because full electric PEVs often have the range needed to handle the evening tasks, allowing charging to be scheduled for overnight.

Because summer on-peak charging is of interest for system planning, and since charging is not highly correlated to weather, Table 2 compares

Table 2: PEV Charging Response to Pricing.

Period of Interest	Avg kW Weekday non-Holiday 4 p.m. to 7 p.m. Plug-in Hybrid PEV Owners	Avg kW Weekday non-Holiday 4 p.m. to 7 p.m. Full Electric PEV Owners
Pre-trial (default behavior)	0.5376 kW	0.6226 kW
TOU wind pricing months	0.2414 kW	0.2655 kW
Summer (no TOU pricing)	0.3032 kW	0.1888 kW

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charging behavior of plug-in hybrid and full electric PEV owners in the 4 p.m. to 7 p.m. window, with and without TOU wind pricing.

It is likely that the average pre-trial charging load (0.6226 kW) for full electric PEVs was boosted by the higher level 2 charging requirements for these vehicles versus some of the hybrids.

The pre-trial default behavior for both hybrid and full electric PEV owners involved charging for convenience during the daytime hours, peaking at around 6 p.m. as reported elsewhere, upon arriving back home from work (see also, Faruqui et al., 2011, p. 7).

Response to the TOU pricing was very pronounced for PEV owners as a group, resulting in greater than a 50 percent reduction in daytime charging and 4 p.m. to 7 p.m. charging. Nighttime charging nearly doubled.

Feedback from participant PEV owners indicated that the pricing incentives and educational outreach offered with these trials prompted them to learn how to program their vehicle for overnight charging, rather than charging at will during the day or simply manually starting to charge at 10 p.m. Changes in charging behavior were found to be persistent over the period of this study for most participants as they became part of the daily routine.

D. Response to TOU pricing: other end uses

Kitchen appliance use, water heating, and laundry-related consumption could be other sources of significant load shifting impact. In fact, participant surveys reported that dishwashing and laundry activities were often shifted to after 10 p.m. However, these changes did not produce dramatic shifts, largely because the Mueller community is served by natural gas, so the majority of cooking and water heating (and some clothes drying) is fueled by natural gas.

Daytime HVAC use is not a candidate for shifting to overnight; also, the wind months are shoulder months (low heating and cooling energy required). So, aside from the shifting of PEV charging, water heating and laundry-related loads to nighttime, the balance of load shifting was observed to be split unremarkably among various end-uses of electricity in these homes.

E. Overall CPP trial results

The average per-household CPP demand reductions per event appearing in Tables 3 and 4 were estimated using fixed effects panel data analysis.

Based on this analytic approach, the impacts during the summer of 2013 of 0.44 kW, or 15 percent reduction in demand, were much higher than the summer of 2014 average impact of 0.17 kW, or 6 percent reduction in demand. The historical baseline

Table 3: 2013 Panel Data Analysis Results.

Critical Peak Day	Daily High (F)	Estimated kW Savings
June 20th	98	0.5475
June 26th	101	0.7455
June 28th	104	0.7002
July 24th	97	0.4194
July 26th	99	0.3590
August 1st	103	0.2100
August 7th	103	0.7047
August 8th	104	0.6429
August 29th	99	0.2768
August 30th	102	0.2897
September 5th	96	0.1259
September 13th	97	0.3272
Average savings per event:		0.44 kW

Table 4: 2014 Panel Data Analysis Results.

Critical Peak Day	Daily High (F)	Estimated kW Savings
June 24th	93	-0.2484
June 30th	96	0.2840
July 2nd	97	0.0068
July 14th	97	0.2064
July 24th	101	0.0052
July 28th	99	0.1574
August 7th	102	0.2292
August 15th	101	0.1420
August 19th	96	0.5093
August 21st	103	0.5163
August 26th	101	0.2264
September 3rd	100	0.1601
September9th	97	0.2082
September 11th	99	−0.0185
September15th	88	0.2618
Average savings per event:		0.17 kW

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Table 5: CPP Peak Reduction Results.

	Estimated 2013 Peak Reduction	Estimated 2014 Peak Reduction
Historical baseline method	0.29 kW	0.085 kW
Panel data analysis	0.44 kW	0.17 kW
Difference in difference method	0.498 kW	0.245 kW

and DID approaches yielded different estimates of CPP event demand reduction, as noted in Table 5. The results from the panel data regression model were between the estimates provided by these alternative estimation methods.

Based on responses to the final survey of program participants, the greatest cause of lesser savings the second summer was lifestyle changes at the beginning of or early in the trials that were persistent throughout the trial period, thus reducing the apparent 2014 savings yielded by panel data analysis and historical baseline methods. Examples include moving their PEV charging, laundry and kitchen appliance use to outside the peak hours. A second behavioral impact on 2014 savings was customer fatigue. In consideration of these factors, the 2013 results are considered more representative of the group's CPP response. To some degree, the CPP peak reductions reported here can be considered incremental to the benefits realized from a TOU pricing program that was implemented for three months prior to the start of the first CPP season.

Antecedent studies of different CPP pricing trials found that CPP tariffs typically induce a drop in peak demand between 13 and 20 percent and, with enabling technologies, the reduction grows to between 27 and 44 percent (Faruqui and Sergici, 2010). Several pilot studies in North America suggest that the most effective of the common strategies for peak demand reduction is a CPP program with enabling technology to automatically curtail loads on event days (Newsham and Bowker, 2010).

Thus, the results of this study are on the low side of the range of findings from earlier pilots targeting more-typical residential energy consumers. This is presumably due to the unique attributes of the participants in this experiment, including a higher penetration of electric vehicles (54 percent), energy efficient building shells, and greater home occupancy during weekdays (46 percent) than the general population. Also, the first CPP season was followed by the first three months of TOU pricing, so the CPP results were to some degree reduced by the behavioral change induced by the TOU rates.

F. CPP results by end use

Changes in HVAC use and PEV charging were found to contribute the most to the energy reduction. Separate analyses were conducted on participants with and without PEVs. Since HVAC usage is weather-sensitive, sub-metered HVAC consumption was used with panel data analysis to estimate average HVAC kW reductions for each CPP event. For those who own PEVs, the day-matching historical baseline method described previously was used to calculate PEV kW savings for each CPP event. For the subgroup owning PEVs, kW savings breakdown analysis results are given in Table 6, while Table 7 presents a breakdown for participants who did not own PEVs.

For pricing group members with PEVs, around 62 percent of the CPP kW reductions were attributed to HVAC- and PEV-related behavior change. For pricing group members without PEVs, around 57 percent of the CPP kW reduction was attributed to HVAC-related behavior change. Apart from HVAC and PEV kW reductions, the other 40 percent or so of total CPP kW reductions came from other end uses, with additional reductions distributed unremarkably throughout multiple end uses.

Pricing group members with PEVs saved more energy during CPP events (0.46 kW versus 0.28 kW) than non-PEV owners, as depicted in Figure 8 for the

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Table 6: 2013 Breakdown Analysis of kW Savings – Participants with PEVs.

	Estimated Total kW Savings	HVAC kW Savings	Estimated PEV kW Charging Savings	The Rest
June 20th	0.5390	0.1714	0.1123	0.2553
June 26th	0.8075	0.3481	0.3234	0.1360
June 28th	0.8816	0.4032	0.2225	0.2559
July 24th	0.3298	0.1325	0.0446	0.1527
July 26th	0.4097	0.1774	0.0928	0.1395
August 1st	0.2023	0.1253	−0.2143	0.2913
August 7th	0.6167	0.252	0.1462	0.2185
August 8th	0.8449	0.3014	0.2019	0.3416
August 29th	0.1939	0.0633	0.1057	0.0249
August 30th	0.1377	0.0064	0.2312	−0.0999
September 5th	0.2317	0.0923	0.0100	0.1294
September 13th	0.3102	0.1358	−0.0465	0.2209
Average	0.45875	0.184092	0.102483	0.172175
Percent of total	N/A	40.13%	22.34%	37.53%

2013 events. Tables 8 and 9 present average impacts for PEV owners and participants without PEVs.

The pricing group participants who own PEVs exhibited more variability in responding to CPP events. If charging normally begins when they arrive home, but they delay that charging until after 7:00 p.m. during CPP events, then their savings will be much higher than for those without PEVs. PEV charging is a high kW load that can often be delayed until later in response to pricing.

Table 7: 2013 Breakdown Analysis of kW Savings – Participants without PEVs.

	Estimated Total kW Savings	HVAC kW Savings	The Rest
June 20th	0.4181	0.2499	0.1682
June 26th	0.5674	0.3725	0.1949
June 28th	0.458	0.2570	0.2010
July 24th	0.3504	0.2262	0.1242
July 26th	0.1574	0.0864	0.0710
August 1st	0.1506	0.1315	0.0191
August 7th	0.3623	0.2702	0.0921
August 8th	0.2627	0.0991	0.1636
August 29th	0.2259	0.0343	0.1916
August 30th	0.1276	0.0384	0.0892
September 5th	0.0618	0.1368	−0.0750
September 13th	0.2465	0.0445	0.2020
Average	0.282392	0.162233	0.120158
Percent of total	N/A	57.45%	42.55%

G. Feedback from participants, at the half-way point

On Dec. 10, 2013 – about half-way through the pricing experiment – a subset of residents participating in the pricing trial met with the project team to provide feedback. Participants were asked questions in an informal setting to gain more understanding about reactions to the pricing options and the text message alerts. Each resident present at the meeting reported having made changes to their electricity use at the onset of the project due to gaining more knowledge about the program itself and not necessarily due to the pricing triggers. Energy use that could be switched to overnight or off-peak hours was generally moved early on in the trial period, if convenient, with electric vehicle charging being the biggest contributor to this shift. When convenient, other electric loads were also moved, such as dishwasher use or laundry activities.

The residents generally reacted to the critical peak alerts, if possible and convenient. Access to a remote-controlled thermostat, which all the participants had, was key in reacting to these alerts by being able to change the set point temperature in their homes.

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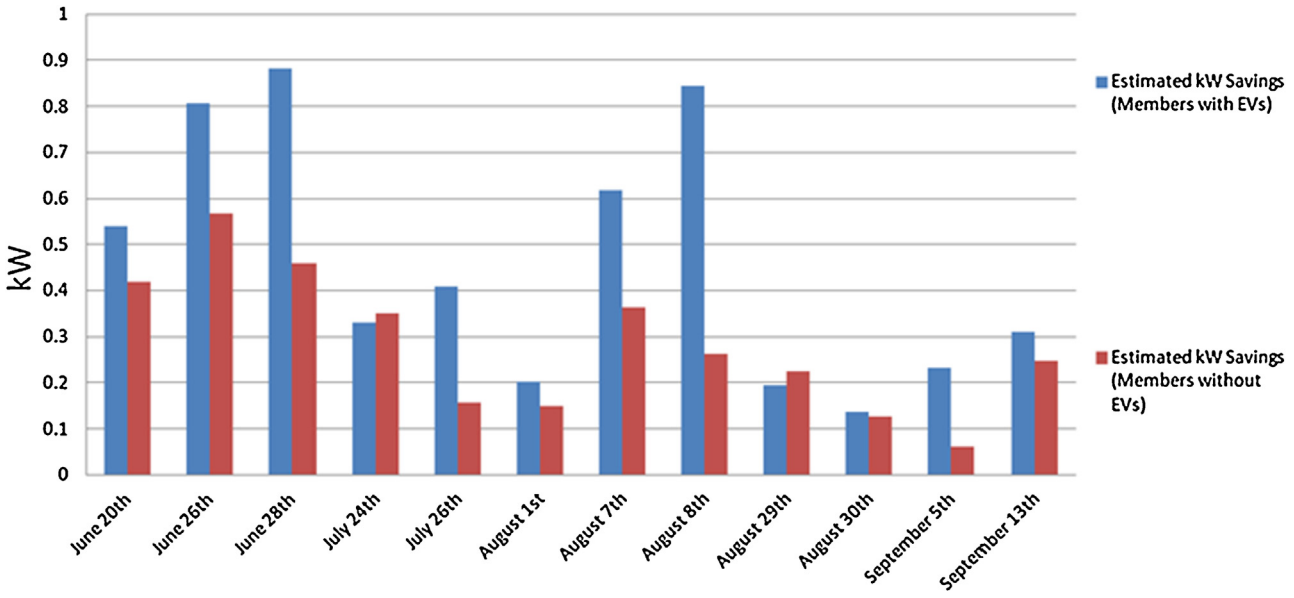

Figure 8: Overall 2013 kW Savings Comparison of CPP Participants With and Without PEVs.

Table 8: (2013) CPP Peak Demand Reduction per Event (PEV Owners).

	Estimated Total kW Reduction	HVAC kW Reduction	Estimated PEV kW Charging Reduction	The Rest
Average	0.45875	0.184092	0.102483	0.172175
Percent of total	N/A	40.13%	22.34%	37.53%

Table 9: (2013) CPP Peak Demand Reductions per Event (Non-PEV Owners).

	Estimated Total kW Reduction	HVAC kW Reduction	The Rest
Average	0.282392	0.162233	0.120158
Percent of total	N/A	57.45%	42.55%

If a participant worked from home, pre-cooling was often done and the thermostat was set higher during the 4 p.m. to 7 p.m. window. Otherwise, comfort was chosen over conservation.

One resident who worked from home scheduled his daily energy use around the pricing trial and potential alerts, including pre-cooling the house before 4 p.m. every day, so that even if a critical peak day alert was called, no changes were needed.

None of the residents interviewed stated that the program was too difficult to manage, or a nuisance. Again, convenience, comfort, and conservation commitment were the deciding factors on program participation. The monetary incentive was more of a bonus for participating in the trial. Interviewees even mentioned that the 64 cent/kWh CPP rate might need to be increased to become a more effective incentive.

H. Final feedback from participants

In November 2014, after the study period ended, additional input was sought from pricing group participants via a final e-mail survey with a few targeted questions. Some 31 percent responded, providing the following insights:

- Over half of survey respondents indicated that they altered their energy use to take advantage of cheaper overnight power during the TOU trial.
- Most participants made lifestyle changes at the beginning of the trial in response to TOU pricing, shifting load

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away from afternoon peak hours, to after 10 p.m. where feasible – e.g. charging PEV, doing laundry and running the dishwasher.

- 80 percent of those who actively participated said that the trial resulted in persistent changes to their energy consumption patterns. This indicates that they practiced this ''learned'' behavior during the CPP trial months as well, thereby reducing the measured average kW reduction of the pricing group in the CPP trial.
- Virtually all PEV owners in these programs stated that they shifted their car charging to alternate times.
- One-third of the respondents shifted their laundry and dishwasher activities to after 10 p.m.

Regarding the CPP feature of the experiment, virtually all reported they had reduced their HVAC use, almost half by pre-cooling before the event period started (4 p.m.) on CPP event days. About half adopted some of their CPP response actions into their summertime routine every day, not just on event days. Some 20 percent of respondents who are at home during a typical weekday afternoon reported that they intentionally left the house during a called event period. Many respondents reported ''fatigue'' from participating in the program. Two respondents mentioned the difficulty of maintaining participation with small children.

VI. Conclusions

If trends continue and energy policies succeed, tomorrow's residential energy consumers will have the ability to monitor their appliance-specific energy usage, the ability to remotely program and control their HVAC system and other energy

appliances, live in more energy-efficient dwellings, obtain much of their electricity needs through rooftop solar photovoltaic systems, drive plug-in electric vehicles, and have a generally-higher level of knowledge about household energy usage. How will these consumers respond to electricity price signals? We explored this question through pricing experiments at a neighborhood in Austin where, to some degree, ''the future is now.''

The amount of electricity consumption shifted from a higher-price daytime period to a lower-price nighttime period in response to TOU pricing in this experiment was similar to what has been found in pilot programs targeting more-typical households. The shift of 4 percent to 5 percent quantified here is in alignment with the 3 percent to 6 percent impacts found in other studies involving similar differentials between on-peak and off-peak period prices.

Compared with other CPP tariff trials, the 0.44 kW or 15 percent per home demand reduction measured in this trial for the first summer during CPP events is fairly low, but reasonable considering the energy efficiency of the dwellings and some behavioral changes that had already occurred once participants had been exposed to three months of TOU pricing. Impacts from CPP events during the second summer were considerably lower, as customer fatigue set in and baseline behaviors had changed.

The impact of PEV charging is the big story here. Electric vehicle charging, typically at 3.3 kW or 6 kW, is likely to be the largest single end-use load that can be shifted to nighttime in homes with such vehicles. But in the absence of pricing incentives, education and outreach, new PEV owners are not likely to set a programmed charging schedule, let alone set charging for overnight hours. Default behavior of the PEV owners in this study, as found in other studies, is to charge the

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vehicle for convenience during the day, year-round, charging heavily during peak hours of 4 p.m. to 7 p.m., i.e. upon returning home from work. Daytime charging is just as prevalent among full electric PEV owners as among hybrid PEV owners. With pricing incentives and prompting, PEV owners will shift most of their daily electric vehicle charging to overnight. Such a shift in a future world with high concentrations of electric vehicles could be powerful tools for grid operators who need to use a number of tools to accommodate a growing concentration of renewable generation such as wind on the grid. If the pricing incentives go away, some of the PEV owners, especially hybrid owners, will revert to daytime charging. Others will retain the charging schedule they had adopted under TOU pricing. Educating PEV owners about charging controls and how to use them, and providing an appropriate financial incentive to charge off-peak are steps toward shifting these loads. In these trials, for homes with a PEV, charging load accounted for nearly 25 percent of the peak load shift on critical peak days and was a key element in shifting load to overnight hours during months when TOU pricing was in effect. As PEV sales continue to grow,[3] providing appropriate price signals to manage charging patterns will be a challenge for electric utilities.■

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Endnotes:

1. This pricing experiment was part of a larger *Discovery Across Texas* project jointly funded by the Center for the Commercialization of Electric Technologies (CCET) and the U.S. Department of Energy (DOE) focused on technologies for wind integration in the Electric Reliability Council of Texas (ERCOT) market. The pricing experiment was led by CCET and carried out at the Pecan Street Project. Frontier Associates LLC designed the pricing experiments and analyzed the results. Detailed results are provided in CCET (2015).

2. Wind generation data was obtained from: http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13424&reportTitle=Hourly%20Aggregated%20Wind%20Output&showHTMLView=&mimicKey.Note: The curves shown include inland and coastal wind generation.

3. Source: http://evtc.fsec.ucf.edu/research/project5.html.

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