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Do Residential Customers Respond to Hourly Prices? Evidence from a Dynamic Pricing Experiment

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Widespread participation of retail electricity consumers in short-term wholesale electricity markets throughout the United States is rapidly becoming technologically feasible. A number of jurisdictions are installing or have installed interval meters for a large fraction or all of their retail customers. With this technology in place, the only remaining barrier is whether state regulators will require customers to pay for their electricity according to retail prices that vary with hourly system conditions.

A common complaint about retail tariffs that pass through the hourly wholesale price in the retail price is that these dynamic pricing tariffs require customers to monitor hourly prices in order to decide whether to reduce demand during a given hour of the day. The customer must assess whether the pattern of hourly prices is sufficient to justify taking action to reduce demand. For example, if the customer has a fixed cost to take action to reduce demand and the wholesale price increase lasts only one hour, then a very large price spike is necessary to cause the customer to take action.

Taking the example of a residential customer with a 2.5 kilowatt-hour (KWh) demand in that hour and $5 fixed cost of taking action to reduce demand by 20 percent implies that an hourly price spike of at least $10,000 per megawatt-hour (MWh), or 1,000 cents/KWh, is needed to produce sufficient cost savings from reducing demand by 0.5 KWh (20 percent of 2.5 KWh) to overcome the $5 cost of taking action. This logic implies that if customers face a fixed cost of taking action to reduce their demand, there may be hours with high prices that the customer decides not to respond to because the expected cost savings from the expected demand reduction is insufficient to pay this $5 cost of taking action.

A dynamic pricing tariff that commits to several consecutive hours of high prices implies that a lower average hourly price is needed to overcome the fixed cost of taking action. For example, if the duration of the price spike is two hours, then the average price for the two hours must exceed $5,000/MWh for a 0.5 KWh demand reduction during each hour to compensate for the $5 cost of taking action. A three-hour duration price spike requires only an average price greater than $3,333/MWh to compensate for the fixed cost of taking action to reduce demand by 0.5 KWh in each of the three hours.

This paper uses the results of a dynamic pricing experiment to compare the magnitude of the demand reduction obtained from hourly pricing to the demand reduction obtained from an alternative dynamic pricing tariff that precommits to a longer duration of high prices to determine whether this "cost of taking action" exists. I find that the magnitude of the average hourly percentage demand reduction from hourly pricing is roughly equal to the estimated percentage demand reduction over a longer duration of high prices, once the demand reduction under hourly pricing is adjusted for the ratio of the percentage price increases under the two dynamic pricing programs. This result argues against the existence of a “cost of taking action” associated with charging customers retail prices that vary with hourly system conditions. The paper closes with a short explanation of this result.

I. Dynamic Pricing Programs

All dynamic pricing programs attempt to pass through real-time wholesale price signals in the retail prices that a consumer faces. An essential precondition for dynamic pricing is that the customer has an advanced meter that can record his consumption in real time. For example, if

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the customer's retail price changes every hour of the month, then the meter must be able to record the customer's consumption every hour of the month in order to determine the monthly wholesale electricity costs to serve the customer and how much to charge for his consumption each hour of the month.

The most straightforward form of dynamic pricing passes through the hourly price in the retail price that a customer pays. For example, if the wholesale price for an hour is 5 cents per kilowatt-hour (KWh), the regulated price of using the transmission and distribution networks to serve the customer is 4 cents/KWh, and the retailer's cost (including a normal return on capital) is 1 cent/KWh, under hourly pricing (HP) the retail price for that hour would be 10 cents/KWh. The usual objection from regulators and customer advocates to this form of dynamic pricing is that the customer faces up to 744 different hourly prices each month and must decide what action to take in response to each of these prices.

For this reason, a dynamic pricing plan that commits to a sustained period of high retail prices may obtain a larger percentage demand reduction for the same percentage price increase. The critical peak pricing (CPP) tariff commits to the same high price for four to six hours. Comparing the household-level hourly average demand reduction under hourly pricing to the average demand reduction achieved under a CPP tariff with the same percentage price change can be used to determine whether there is a significant "cost of taking action" associated with hourly pricing.

The experiment also includes a CPP with a rebate (CPR) tariff that is popular with customers because it pays a rebate that depends on the amount a customer's hourly consumption is below a prespecified reference level during a CPP event. However, different from a CPP tariff, if the customer's hourly consumption is not below its reference level, the customer pays for his consumption during a CPP event at the standard fixed retail price. In contrast, a customer on the CPP tariff pays for all of his consumption at the high CPP price during a CPP event. However, if the customer is receiving a rebate during a CPP event because his consumption is below the reference level, then the marginal price paid for electricity under the CPP tariff and CPR tariff are approximately equal.

II. The PowerCentsDC Experiment

The Smart Meter Pilot Project, Inc. (SMPPI), which was formed as a nonprofit organization through a merger settlement approved by the Public Service Commission of the District of Columbia in 2002, initiated the PowerCentsDC program to investigate the impact of a variety of dynamic pricing programs and smart meter and smart thermostat technologies on the household-level consumption of electricity. Starting in July 2008, 1,245 customers—857 treatment and 388 control customers—participated in an experiment designed to measure the demand reductions of households on three types of dynamic pricing tariffs: HP, CPP, and CPR. The complete PowerCentsDC experiment is described in Frank A. Wolak (2010).

As part of this experiment, random samples of treatment participants were chosen from all eight wards of the District of Columbia. Two types of customers, (i) R—regular residential customers, and (ii) AE—all electric residential customers (households with electric heating), were randomly assigned to the three types of pricing programs—CPP, CPR, and HP. Treatment customers were assigned to each pricing plan and were not told about the existence of the other two pricing plans.

The control group was also randomly selected from the eight wards of the District of Columbia. Control participants were not made aware of the PowerCentsDC program and did not receive any information about the program, CPP events, or hourly prices. Interval meters were installed on the premises of all customers in the treatment and control groups. The meters record electricity use hourly and transmit it every day to the data center using a wireless communications link. Both treatment and control customers received their standard monthly billing statements. All treatment customers also received a detailed Electric Usage Report in their monthly bill detailing their rate code and the breakdown of CPP period payments for CPP customers, and CPP period rebates for CPR customers and average hourly prices during the month on weekdays and weekends for HP customers.

For both the CPP and CPR pricing programs, customers were subject to at most 12 CPP events during the summer months (June 1 to September 30) and three CPP events during the winter months (November 1 to February 28). The critical peak hours occur between 2 p.m. and 6 p.m. in the summer and between 6 a.m. and 8 a.m. and 6 p.m. and 8 p.m. during the winter months. Critical peak events were called based on a day-ahead temperature forecast above a prespecified threshold during the summer months and below a minimum temperature threshold during the winter months. The summer 2008 threshold was 90 degrees and the winter 2008–2009 threshold was 18 degrees. Treatment group customers on the CPP and CPR tariffs were notified by their choice of phone, e-mail, or text message on a day-ahead basis whether the following day was a CPP day.

All control customers paid for their electricity according to increasing block price schedules with two blocks or tiers. Table 2 of Wolak (2010) lists the price schedules faced by the R and AE control customers. The CPP treatment customers paid according to increasing-block schedules with two tiers that had slightly lower tier prices than the corresponding control tier prices, and they paid 78 cents/KWh for their consumption during critical peak events. Table 3 of Wolak (2010) lists the increasing block schedules for these customers and the CPP event prices for these customers.

The CPR customers pay according to the same increasing block prices as control customers, but they receive rebates for the amount their actual consumption, $Q(\text{act})$, is less than their reference level, $Q(\text{ref})$, during critical peak periods. Otherwise, CPR customers receive no rebate. The rebate is computed as $\max(0, Q(\text{ref}) - Q(\text{act})) \times P(\text{rebate})$, where $\max(0, x)$ is the function that gives the maximum of zero and x. If there are no CPP periods within a month or the customer is unable to reduce its consumption below $Q(\text{ref})$ during any of the CPP periods that occur in that month, the customer's bill is computed the same way as the bill of a control customer. Because of concerns that a CPR household might be able to manipulate its reference level in the manner discussed in Wolak (2006) for the Anaheim CPR experiment, customers were not told how their reference level, $Q(\text{ref})$, was computed each month. Each customer's monthly reference level was computed as the average of the three highest nonevent consumption amounts on nonholiday weekdays during CPP periods of that billing month.

Table 4 of Wolak (2010) lists the CPR rebate prices, $P(\text{rebate})$, for each of the four customer types. The rebate prices for the R and AE customers were selected to yield very similar marginal prices during a CPP event for CPP customers and CPR customers. For example, the Summer Tier 1 CPR rebate price from Table 4 is 63.9 cents/KWh and the Tier 1 block price for the CPR customer from Table 2 is 12.9 cents/KWh, which implies a marginal price for a CPR customer receiving a rebate during a summer CPP event of 76.8 cents/KWh. The Summer Tier 1 CPP price from Table 3 is 77.1 cents/KWh. For both R and AE customers and all pricing tiers, rebate prices were chosen to come as close as possible to satisfying the equation $P(\text{CPP}) = P(\text{rebate}) + P(\text{tier})$, where $P(\text{CPP})$ is the CPP event price for CPP customers and $P(\text{tier})$ is the tier fixed price for CPR customers. During the summer months of 2008, only six CPP events were declared. During the winter months of 2008–2009, three CPP events were declared.

Hourly pricing customers paid according to the day-ahead prices that tracked prices set in the PJM day-ahead wholesale electricity market for the District of Columbia. These prices were weighted across hours of the day so that the wholesale price implicit in the hourly retail price was higher in the high-priced hours of the day and lower in the low-priced hours of the day than the PJM day-ahead prices. This was done to increase the attractiveness to HP customers of reducing their hourly demand in response to these prices. The hourly prices were posted on the PowerCentsDC project website for HP participants to access and are also available by calling a toll-free number.

HP participants were also notified on a day-ahead basis by phone, e-mail, or text message when hourly prices were "high" as determined by a preset threshold. The threshold for high hourly prices was set to be 23 cents/KWh during the summer months. Because of the massive slowdown in economic activity after September 2008, the threshold was revised downward to 15 cents/KWh for the winter months. These "high price" hour notifications were sent to customers before 5 PM of the day before these prices were in effect. Different from the CPP event notification, customers were told which hours of the following day the hourly price exceeded the threshold. Notifications were given for 38 hours during the sample period. Figure 4 of Wolak (2010) displays the time path of hourly prices from July 2008 to February of 2009.

III. Estimation Results for HP versus CPP Comparison

This section presents the analysis of household-level behavior under the three dynamic pricing plans for the entire sample period and the summer and winter months separately for the R and AE customers. For these customers, I recover hourly average treatment effects for a CPP event for CPP customers and CPR customers combined and an hourly average treatment effect for an HP warning for HP tariff customers.

Define the following notation: $y(i, h) =$ the natural logarithm of the consumption in KWh of customer i during hour h, $\text{Hour}(h) =$ indicator variable for hour-of-sample $h = 1, \ldots, 24{*}D$, where D is the number of days in the sample period, $\text{Treat}(i, j) =$ indicator variable for whether customer i is in treatment group j ($j =$ CPP, CPR, or HP), $\text{CPP}(h) =$ indicator variable for whether hour-of-sample h is a critical peak event hour. From these variables construct the following interactions: $\text{CPP\_PER}(i, h) = \text{CPP}(h) \times \text{Treat}(i, j) = \text{CPP or CPR}) =$ indicator variable for whether customer i is in the treatment group and is either a CPP or CPR customer and hour h is during a CPP event, $\text{HP\_PER}(i, h) = \text{HP}(h) \times \text{Treat}(i, j = \text{HP}) =$ indicator variable for whether customer i is in the treatment group and is an HP customer and hour h is during a HP warning hour.

The basic average treatment effects model takes the following form:

$$(1) \quad y(i, h) = \alpha(\text{CPP\_PER}(i, h)) + \beta(\text{HP\_PER}(i, h)) + \lambda_h + \delta_i + \varepsilon_{ih},$$

where δ_i is a customer-specific fixed effect that controls for persistent differences across customers in their hourly consumption, λ_h is an hour-of-sample fixed effect for hour-of-sample h which accounts for differences in $y(i, h)$ across hours in the sample period for a given household, and ε_{ih} is an unobserved mean zero stochastic disturbance that is uncorrelated with any of the regressors in this model, including the two sets of fixed effects. This model assumes the same hourly average treatment effect associated with the CPP event for CPP customer and a CPR customer and a separate hourly average treatment effect for an HP warning.

Table 1—Estimation Results for R Customers

Parameter	Estimate	SE
Full sample results		
HP_PER	−0.030	0.011
CPP_PER	−0.090	0.007
Summer sample results		
HP_PER	−0.026	0.013
CPP_PER	−0.089	0.008
Winter sample results		
HP_PER	−0.008	0.018
CPP_PER	−0.055	0.014

Table 2—Estimation Results for AE Customers

Parameter	Estimate	SE
Full sample results		
HP_PER	−0.175	0.024
CPP_PER	−0.162	0.014
Summer sample results		
HP_PER	−0.058	0.027
CPP_PER	−0.126	0.014
Winter sample results		
HP_PER	−0.322	0.036
CPP_PER	−0.043	0.030

Table 1 presents the estimates for R customers and Table 2 the estimates for AE customers of (1) for the full sample period of July 21, 2008 to March 17, 2009, the summer months of 2008, and winter months of 2008–2009. To guard against arbitrary forms of both heteroskedasticity and autocorrelation in the ε_{ih}, all of the standard errors presented in the remainder of the paper are computed using the heteroskedasticity and autocorrelation-consistent covariance matrix for two-way panel data models presented in M. Arrellano (1987).

The R customer results demonstrate sizable and precisely estimated average treatment effects associated with both HP warnings and CPP events for both CPP and CPR customers. For the full sample, the hourly average treatment effect of a CPP event for both CPP and CPR customers is 9 percent, and hourly average treatment effect for an HP warning is 3 percent.

For the summer sample the treatment effect of an HP event is 2.6 percent, and the treatment effect for a CPP event is 8.9 percent. The winter period results are far less precisely estimated, particularly the treatment effect for an HP event.

The AE customer results demonstrate larger and generally more precisely estimated average treatment effects associated with both HP warnings and CPP events for both CPP and CPR customers. For the full sample, the hourly average treatment effect of a CPP event for both CPP and CPR customers is 16.2 percent, and hourly average treatment effect for an HP warning is 17.5 percent. For the summer sample the treatment effect of an HP event is 5.8 percent, and the treatment effect for a CPP event is 12.6 percent. The winter period results are far less precisely estimated for a CPP event, although the treatment effect of an HP event is extremely large in absolute value. Because of the small number of CPP events and HP warnings during the winter months, the estimation results for the R and AE customers for the winter months should probably be viewed with some skepticism.

The results in Tables 1 and 2 provide strong evidence against a cost of taking action effect associated with hourly pricing, particularly for the AE customers. The treatment effect associated with an HP warning is roughly one-third to one-fourth of the absolute value of the hourly average treatment effect of a CPP event for a CPP customer, which is consistent with no cost of taking action because the price during a CPP event is roughly 70 to 75 cents per KWh and the lowest hourly price at which an HP warning is issued is 23 cents/KWh in the summer and 15 cents/KWh in the winter, which are both roughly one-third to one-fourth of 70 to 75 cents/KWh. Therefore, the ratio of the hourly average percent demand reduction due to a CPP event (that lasts for four hours) divided by the hourly average percent demand reduction due to an HP warning for an HP customer appears to be roughly consistent with the ratio of the hourly price faced by a CPP customer during a CPP event (and a CPR customer receiving a rebate during a CPP event) versus an HP customer during an HP warning.

IV. Implications of Experimental Results for the Design of Dynamic Pricing Programs

The results of the PowerCentsDC Program experiment demonstrates that all three dynamic pricing programs provide stable, predictable, and sizable demand reductions in response to CPP events and HP warnings for both R and AE customers. These experimental results are consistent with no economically significant cost of taking action to reduce demand associated with hourly pricing. This result is likely due to the fact that day-ahead hourly wholesale prices in all US wholesale electricity markets tend to be very positively correlated, so that if prices are high in during one hour of the day, they are also high in the neighboring hours of that day. This pattern of prices implies that responding to single HP warning by reducing demand in that hour and surrounding hours of the days is likely to deliver economic benefits because wholesale prices in those hours are also likely to be high.

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