

The Effect of Customer Participation in Electricity Markets: An Experimental Analysis of Alternative Market Structures

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Abstract

An experimental structure is demonstrated that represents end-use customers in electricity markets who can substitute part of their usage between day and night. Individuals' demand relationships are represented by a two-step value function for each period that are disaggregated from observed market demand relationships. Demand varies between day and night and during heat waves. Three alternative demand-side market structures are evaluated: 1) customers pay the same fixed price (FP) in all periods – the base case, 2) a demand response feature (DRP) is added in periods of supply shortages, wherein buyers receive a pre-specified credit for reduced purchases, and 3) a real time pricing (RTP) case where prices are forecast for the upcoming day/night pair, then buyers select their quantity purchases sequentially and are charged the actual market-clearing prices.

Initial experiments were conducted with active demand-participants, but with a predetermined typical “hockey-stick” supply structure that was varied randomly, over eleven day-night pairs that included heat wave and supply shortages. The RTP structure resulted in the greatest market efficiency, despite the more difficult cognitive problem it poses for buyers. Furthermore, a preference poll comparing DRP and RTP was conducted after each trial; and while 64% of the participants said they preferred DRP before RTP experiments, 76% selected the RTP structure afterwards, a statistically significant reversal of preferences.

1. Introduction

A significant problem for most electricity markets in the United States has been the lack of

substantial, timely demand-side participation. While some jurisdictions have provided customers with a choice of suppliers, since most suppliers continue to offer fixed-price contracts and assume the risk of variations in wholesale costs, that choice is a very blunt instrument. It is the load-serving utilities and/or Independent System Operators (ISOs) who make most of the purchases in wholesale markets on behalf of retail customers by forecasting and committing to period-ahead demand quantities. As a result, the suppliers are in effect selling into a single-sided market with pre-determined demand quantities. Although the level of the fixed prices paid by customers will adjust gradually to actual wholesale market conditions, those effects are averaged and occur well after the electricity is used and production costs are incurred. Thus there is a two-part disconnect between a customer's decision to buy electricity and their facing the cost consequences of that choice – a substantial moral hazard. Furthermore, many of those customer choices are not conscious, but rather are a consequence of automated controls triggered by temperature, time or motion. With the proper real-time price incentives many of those controls could be programmed with an automated demand response. What is lacking at present is the means of communicating in real time the likely price of electricity, and with the exception of a few large business customers in some locations, the availability of a billing mechanism that reflects those real-time prices.

With the absence of effective real time demand-response to prices, and because of the limited number of suppliers that can reach particular markets at peak-usage periods in many regions because of transmission line capacity constraints, the repeated nature of these markets for a homogeneous commodity provides ample opportunity for suppliers to learn from past

experience and to behave strategically. Absent price caps or other mitigating regulation in these markets, the exercise of market power by suppliers has been predicted in theory (see Hobbs and Schuler [4], and Schuler [8]), demonstrated in laboratory experiments (Bernard, et. al. [2]), and sadly, widely observed in practice in extremely costly experiments of the whole – particularly in California. But by letting customers express their desires in the real-time, couldn't these markets be self-regulating? That's the theory; this experimental analysis illustrates the practical promise. Additional reasons for affording greater customer participation in the market are to improve the efficient use of resources and because it's fair. In an earlier theoretical analysis, Mount, Schuler and Schulze [6] have demonstrated that the efficient operation of reliable electricity markets requires that customers face both real-time energy prices, and the opportunity to reduce their loads (effectively providing generation reserves to the system) in exchange for receiving the opportunity cost of providing that additional generating capacity.

The two most debated structures for retail participation are Demand Response Programs (DRP), that frequently have the word "Emergency" as a prefix, and Real Time Pricing (RTP) programs. Limited trials in actual electricity markets suggest that **DRP** programs can elicit reasonable customer response in periods of supply shortages (See NYISO, as an example). In these **DRP** applications where the period in which payments for usage reduction are announced ahead of time to customers who have agreed to participate, those payments are usually linked to estimated peak energy price savings. Our theoretical analysis [6] emphasizes that in order to obtain economically efficient demand-side participation, *both a **DRP** program*, which however pays participants for the foregone requirements for additional generation reserves, not energy price savings, *and a **RTP** scheme*, wherein customers realize the energy cost savings (and bear the brunt of their purchases if aggregate consumption is not reduced) *are required*. Thus it is of interest to investigate the response of buyers to both of these structures for demand-side participation in the market.

Questions to be asked include: how do buyers actually perform under these different demand-side structures, given a choice, which structure might they select voluntarily, and to what extent do these different demand-side structures succeed in muting the exercise of market power by suppliers and lead to self-regulating markets?

These are practical questions that are amenable to experimental analysis (these repeated markets where sellers have multiple units that they can choose to supply are too complex to develop definitive game-theoretic analyses of the market outcomes). And while numerous promising tests of alternative demand-side structures have been conducted by utilities around the country with their actual customers, the results are frequently subject to question because of the diversity of customers and the time duration of the tests, over which other things can change.

2. Laboratory Experimental Analysis

As an alternative, a representative demand-side structure is developed here for use in controlled laboratory experiments. Rassanti, Smith and Wilson [7] have conducted illustrative two-sided market experiments to represent what might occur in electricity markets where customers let into the game, using simultaneous price and quantity bids and offers into a real-time energy market with four buyers, five sellers and one computer-simulated buyer, facing three different demand periods in a day (peak, shoulder and off-peak periods). As in all laboratory experiments for buyers, the actual valuation of purchases must be pre-assigned (induced valuations) and the participant must be paid in proportion to the difference between the assigned valuation for the electricity purchased and the price paid. In their experiments both buyers and sellers were assigned representative values and production costs, and buyers were given a multi-step demand relationship to reflect their values. In their experiments where the buyers' valuations were calibrated so that the maximum possible combined reduction in the quantity demanded was 16 percent, Rassanti, Smith and Wilson [7] demonstrate the potential for an active demand-side to completely eliminate the exercise of market power by suppliers.

Using the alternative methodology of autonomous agents in a numerical simulation of a two-sided market, Talukdar, et. al. [9] have shown how buyers' and sellers' propensity to "learn" how to maximize their gains can offset each other. This agent-based simulation methodology has the advantage of being able to replicate hundreds of market periods with a large number of participants much more rapidly and at a lower cost than in laboratory experiments with human subjects (human subjects must receive appreciable compensation in proportion to their

performance in order for the experimental outcomes to be valid). The suspicion about numerical simulations, particularly when not preceded by controlled experiments with humans that reveal their cognitive processes, is that the outcomes are biased by the agent's "learning" mechanisms that are pre-programmed, and that these simulations can never accurately reflect the cognitive insights and/or limitations that are inherently human.

In this analysis, therefore, a demand-side platform was constructed and tested that is representative of the decisions that electricity customers would have to make in real-time markets, and whose valuations are calibrated to reflect previous statistical analyses of aggregate buyer behavior. In particular, since much of the response by customers to **DRP** and **RTP** programs has been to shift a portion of their usage to adjacent time periods, it was essential to incorporate this inter-temporal decision-making into the demand side platform. As a consequence, the demand-side representations that are tested here can be used to address many other important issues in the future, including tests on markets for reserves, forward markets, etc. However, the current experiments are designed to demonstrate that a representative mechanism is available for future analyses of three alternative (and/or in various combinations) forms of demand-side participation in electricity markets: a pre-announced Demand Response Program (DRP), a Real Time Pricing (RTP) program, and as a base case for comparison, the pre-specified identical Fixed Price (FP) charged by most utilities today in every usage period. This analysis also tests the relative efficiencies of the three alternative demand-side treatments, as well as the participants' subjective preferences in a sequence of polls.

3. Experimental Structure

3.1 Supply-Side Representation

In these tests that are intended primarily to demonstrate the development of a realistic demand-side platform for experimental purposes, the supply-side of the market was predetermined, based upon previous supply-side experiments conducted at Cornell, (Mount, et. al. [5]) and of actual offer structures observed in wholesale electricity markets. Thus the typical "hockey-stick" shaped offer function shown in Figure 1 was applied in all cases, except that randomly-selected outages of particular generators caused

this offer curve to slide back and forth horizontally in some market periods. Furthermore, to insure that the market always clears, regardless of buyer behavior, sufficient external supplies are always available to meet demand at the highest offer price (here \$1.00/kWh).

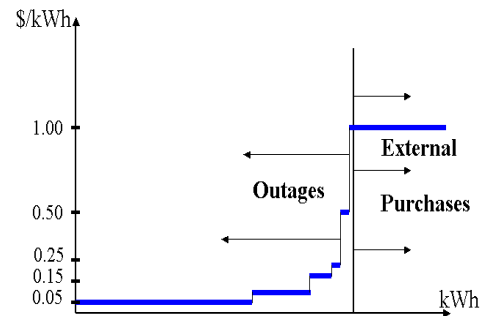


Figure 1. "Hockey-Stick" Supply Curve

3.2 Demand-Side Representation

To keep the demand-side decisions simple for the participants, each buyer is assigned a simple two-step discrete demand function with separate valuations for day and for night usage, as shown in Figure 2. In fact, these individual demand relationships are decomposed from an aggregate demand function, shown in Fig. 3 that has a retail price elasticity of demand at the mean price of -0.3 , Faruqi and George [3]. Furthermore, the overall demand function ranging from very low prices to the reservation price was given the inverted S-shape suggested by Schulze's work (reported by Woo, et. al. [10]) on consumer value loss for interruptible service. Note that each customer's day valuation is somewhat higher than their night valuation. Furthermore, there is an additional "substitutable" block of energy that customers can choose to buy either during the day or the subsequent night period (unused substitutable energy cannot, however, be carried over to the next day/night pair of periods). Typically, substitutable electricity purchases are valued less than the regular purchases in each of these periods, and substitutable night energy is valued less than if it is used during the day. These substitutable blocks were also decomposed from the aggregate demand curve that has an elasticity of substitution between day and night usage of 0.3 , Faruqi and George [3]. Thus, the buyer is confronted with an inter-temporal optimization problem. In addition, these induced valuations are increased substantially in pre-specified

periods called “Heat-Waves” to reflect the added value of electricity in extreme climatic conditions. The buyer’s problem then is to maximize the spread between their assigned valuation for each quantity of electricity they buy, and the price they have to pay for it.

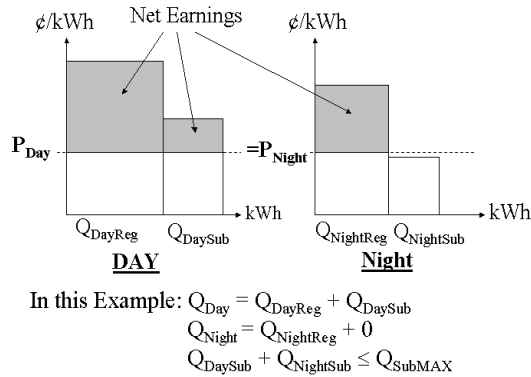


Fig. 2. Buyer’s Problem under a Fixed Price System

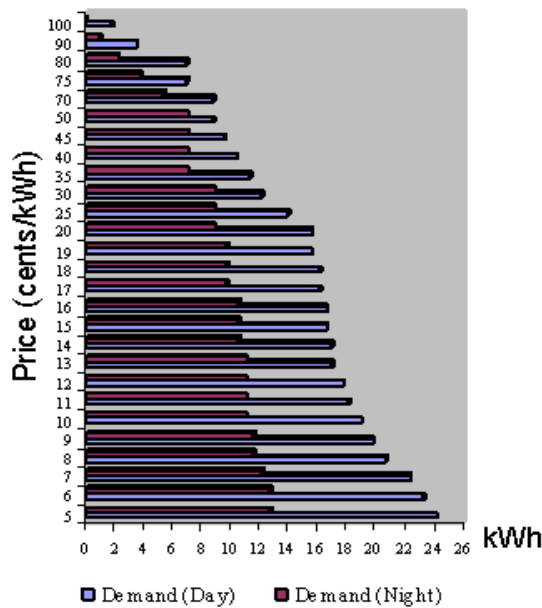


Figure 3. Average Demand Curve

3.3 Alternative Market Structures Considered

The experiments are designed to test the efficiency of two alternative forms of active demand-side participation in electricity markets. As a base case for comparison, the first set of experiments reflect typical utility pricing where buyers pay a pre-determined fixed price (FP) in

all periods and merely determine how much electricity they wish to purchase in each period. In the second treatment, buyers are alerted prior to consumption periods when supply shortages are anticipated. In those periods, customers are given the opportunity of reducing their consumption below their normal benchmark purchases in similar periods, and by doing so they can earn a pre-specified credit per kWh for each unit of electricity less than their benchmark that they choose to buy. This treatment is analogous to the NYISO's Emergency Demand Response (DRP) program. All electricity actually purchased under this **DRP** scheme is priced at the same fixed price used in the base case, but total customer payments are reduced by any **DRP** credits earned. The third treatment is a simple real time pricing (RTP) scheme; wherein, price forecasts are announced for the next day and night periods, and based upon these forecasts, buyers decide how much electricity to purchase. However, *buyers must pay the actual market-clearing price in each period* for their actual purchases, and that price may differ from the forecasted price.

In pilot experiments that were conducted before the production runs that are reported here, a second type of **RTP** market structure was also tested. In that alternative, participants were asked to submit prices that reflected their maximum-willingness-to-pay together with each block of quantity bids. In these pilots, each participant’s performance was compared for the same three day-night pairs that included heat-waves and supply outages under the **FP**, **DRP**, **RTP** and **RTP** with limit price bids market structures, in that order. Using experienced undergraduate students, they nevertheless did not perform as well in the **RTP** runs where they specified limit price as they did in the previous **RTP** runs where their only bids were for the quantity they wished to buy (their earnings were 94.9% of optimal, as compared with 98.7% under the simpler, quantity-only bid structure). Because the designed experimental runs were to be much longer, and participant fatigue was a concern, only the more simple form of the **RTP** market structure was explored in these experiments. This is the structure that approximates a scheme used in France where customers are notified a day ahead by color code whether electricity prices are anticipated to be high, moderate or low, and then based upon that information the customers make their quantity purchases, but are charged the actual clearing price (Aubin, et. al. [1]).

3.4 Description of Trials and Composition of Participants

After an exhaustive review of instructions, the nature of the market and of how it would be cleared, and how participant earnings would be determined, each participant was engaged in experiments with the three different demand-bidding/ payment-determination mechanisms that were described above. Each of these three treatments were repeated over the same eleven day-night pairs (up from three in the pilots) for a total of 22 trials per treatment, or 66 bidding and market-clearing trials in total. The same sequence of events was used for each treatment in the following order for the day-night pairs: 1(N=normal); 2(S= supply shortage); 3(H= heat wave); 4(N); 5(N); 6(N); 7(H+S); 8(H+S); 9(N); 10(S); 11(H). The periods noted only with an S were normal periods in terms of customers' valuation of energy, but supply shortages existed.

In all treatments, the market is conducted for wholesale supplies of electricity only, but the price paid by customers has a \$.04/ kWh wires charge added to it (demand valuations were calibrated at retail prices). In the Fixed Price treatment, the retail price was set at \$.11/ kWh (\$.07/kWh for the average wholesale price for electricity), based on the stochastic offer structure that was predetermined, and the assumption of optimal bidding strategies by the buyers where their valuations are also known by the designers of the experiments.

For the Demand Response Program, the price for retail purchases of electricity remained at \$.11/ kWh, but whenever a randomly predetermined supply shortage occurred, a **DRP** period was announced and buyers received a credit of \$.25/ kWh for the difference between their benchmark consumption (what they would have bought in that period had they behaved optimally without the **DRP** credit and fixed-price purchases) and the amounts they actually bought. The **DRP** credit was computed to include both the estimated savings in the actual wholesale price of electricity for their reduced consumption, plus the pro-rated savings experienced by the market. Note, that under both the **FP** and **DRP** treatments, the actual payment by buyers may not equal the cost of purchases from suppliers, unless the actual participants behave optimally, since that was the basis for setting the fixed prices and **DRP** credit. Under the **RTP** treatment, the buyers were given an accurate estimate of what the wholesale price

plus the \$.04/ kWh wires charge would be, were they to make optimal quantity bids. The buyers were also told, given experience with earlier experiments, that they could expect the actual clearing prices to vary by 20%, but they were also told that they would pay the actual market-clearing price. Thus for the **RTP** treatment, the prices paid and costs of purchases should be identical.

The buyers in these experiments were the same 21 professional graduate students who were in MBA, MPA or M. Engineering degree programs at Cornell. They were divided into two groups, and each member participated as a buyer with the same other players – the one group meeting on successive Monday nights, the other over successive Thursday evenings, for two consecutive weeks – because of the length of the total experiment. During the first week, the instructions were reviewed in detail and the **FP** treatment was conducted. In the second week, the **DRP** and **RTP** treatments were conducted and each session lasted approximately 90 minutes. Each player pledged secrecy since their earnings were related to the behavior of others. Since different participants were assigned different valuations for their energy purchases, a different exchange rate was assigned to each player so that if they performed optimally, each might expect the same actual payment for their performance. The actual average earnings per player ranged from \$38 to \$48.

3.5 Market Sequence and Clearing Process

Each market period begins with buyers being provided with information about the upcoming day or night period, including whether or not there is a heat wave, the value they will earn for their energy purchases (that may vary from day to night if it is substitutable electricity, or between days if there is a heat wave), and the maximum quantity for which they may receive value under each condition. Buyers then submit their quantity bids for that period. For the **FP** treatments, the buyers are also told the predetermined price that remains constant throughout the treatment. If the market being tested encompasses **DRP**, the buyers are also told when **DRP** is in effect and the amount of the credit for reduced purchases in that period, as well as the fixed price that is charged for all of their purchases. Under **RTP**, the buyers will be provided with a fair price forecast for the

following day/night pair prior to their submission of quantity bids.

In all cases, the market is cleared by a uniform price auction where all suppliers are paid the same price for all energy purchased, and that price is equal to the highest offer required to meet demand. In all cases the actual demand, which equals the sum of the quantity bids by all customers, represents the energy that must be purchased from suppliers in order to clear the market. The market is always cleared since the ISO has available to it an appreciable amount of electricity from external sources, that however is very expensive.

Since the buyers' valuation is calibrated for representative retail prices, a \$.04/Kwh wires charge is subtracted from the price customers pay in order to determine the wholesale price received by suppliers. Furthermore, under the **FP** experiments in which that price is based upon the average outcome of a competitive market, the actual price paid to suppliers may vary appreciably from the price projected in setting the retail price. In that case, suppliers still receive the actual market-clearing price, and buyers continue to pay the preset price, but eventually, the authorities may have to change the fixed price. That rate decrease or increase, however, does not occur during these experiments. Similarly, under **DRP**, since the prices paid for electricity and the **DRP** credit received is pre-determined, there is no guarantee that the outcome will be revenue neutral since suppliers receive actual market-clearing prices. Again, however, the subsequent rate changes that may be necessary are not a concern for the purpose of participating in this experiment, since those adjustments would be made after the experiment is concluded. Considerations of subsequent needed retail price adjustments should also not be of concern to participants in the **RTP** experiments, since in this case the buyers are paying the actual market-clearing prices to suppliers in each period.

3.6 Preference Polls

Since it is frequently alleged that one reason there are so few real-time pricing programs that are widely available to customers in practice is because of the difficulty customers have in understanding and participating effectively, a preference poll was conducted after each of the three demand-side treatments to test the

participants' attitudes. At the beginning of the trials, all three treatments were summarized, but added emphasis was placed upon the upcoming treatment before each. Following the completion of the **FP** treatment, the remaining two options were reviewed, and a poll was conducted asking: based upon available information, which system would they prefer, **DRP** or **RTP**? The same poll was conducted after the participants had completed the **DRP** treatment, and then again after the **RTP** experiment. The only difference in the nature of the polls was that following the **RTP** experiments, when the participants had gained experience with both forms of demand-side experience, the participants were told that based upon the majority's preferences revealed by that final poll, two additional day-night period pairs of experiments would be conducted with a much higher exchange rate applied to their earnings (5.5 times of their previous earnings, so that the total expected earnings were similar to previous treatments). Of interest is to see whether or not preferences change with experience.

4. Experimental Results

Figure 4 summarizes the experimental results succinctly as an average across all buyers in both the Monday and Thursday groups. By day-night pair, it shows that **RTP** always leads to higher levels of economic surplus (the sum over all usage in each period of the difference between the buyers' assigned valuation of their energy purchases and its cost of supply as specified by the offer curve in effect for that period). Economists describe this as the sum of consumers' surplus (**CS**), the sum of the spread between the consumers' valuation and the price they paid, plus producers' surplus (**PS**), the sum of the spread between what suppliers are paid and their costs of supply. Under **FP** and **DRP** where there may be a difference between the net amount collected from buyers and paid to the suppliers in addition to the \$.04/ kWh wires charge, any excess would be added to the total surplus, and any deficit, representing a required rate increase in some subsequent periods, would be subtracted. Not only is the overall dominance of **RTP** in efficiency terms emphasized in Figure 4, in most periods with this active demand-side only, **FP** leads to higher average efficiency than does **DRP**.

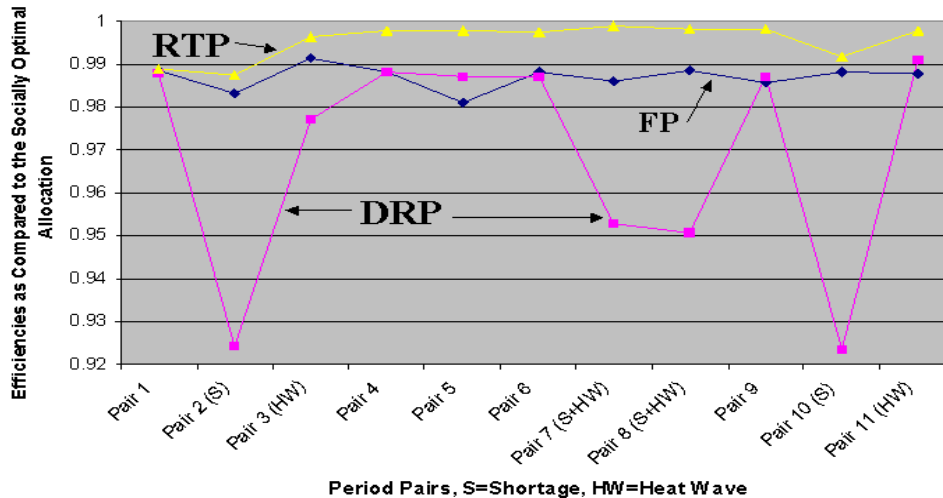


Figure 4. Efficiencies by Treatment and Period Pairs

Table 1. Paired t-tests Based on Individual Buyer Quantity Differences

| Periods | FP - DRP | FP - RTP | FP - OPT | DRP - RTP | DRP - OPT | RTP - OPT | Contingency |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-------------|
| 1 | (+) | (-) | (-) | (-) | 95 %, (-) | (-) | N |
| 2 | (-) | 95 %, (-) | 95 %, (-) | 90 %, (-) | 95 %, (-) | 90 %, (-) | N |
| 3 | 95 %, (+) | (+) | (+) | -2.3578 | 95 %, (-) | (-) | S, DRP |
| 4 | (+) | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | 90 %, (-) | S |
| 5 | (+) | (-) | (-) | (-) | (-) | (-) | H |
| 6 | 0 | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | (-) | H |
| 7 | 0 | 95 %, (-) | 95 %, (-) | 95 %, (-) | 95 %, (-) | (+) | N |
| 8 | 0 | 95 %, (-) | 95 %, (-) | 95 %, (-) | 95 %, (-) | (-) | N |
| 9 | 0 | 95 %, (-) | 95 %, (-) | 95 %, (-) | 95 %, (-) | (+) | N |
| 10 | 0 | 99 %, (-) | 95 %, (-) | 99 %, (-) | 95 %, (-) | (-) | N |
| 11 | (+) | 95 %, (-) | 95 %, (-) | 95 %, (-) | 95 %, (-) | (-) | N |
| 12 | 0 | 99 %, (-) | 95 %, (-) | 99 %, (-) | 95 %, (-) | (-) | N |
| 13 | 99 %, (+) | 95 %, (+) | 95 %, (+) | 95 %, (-) | 95 %, (-) | (+) | H+S, DRP |
| 14 | 0 | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | 95 %, (-) | H+S |
| 15 | 99 %, (+) | 95 %, (+) | 95 %, (+) | 95 %, (-) | 95 %, (-) | (-) | H+S, DRP |
| 16 | 0 | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | (-) | H+S |
| 17 | (-) | 99 %, (-) | 95 %, (-) | 99 %, (-) | 95 %, (-) | (-) | N |
| 18 | 0 | 99 %, (-) | 95 %, (-) | 99 %, (-) | 95 %, (-) | (-) | N |
| 19 | 99 %, (+) | (+) | (+) | 95 %, (-) | 95 %, (-) | (+) | S, DRP |
| 20 | 0 | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | 90 %, (-) | S |
| 21 | (-) | (-) | 90 %, (-) | (-) | (-) | (+) | H |
| 22 | (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | 99 %, (-) | (-) | H |

99%, (+): significant positive difference at 99%
 99%, (-): significant negative difference at 99%
 95%, (+): significant positive difference at 95%
 95%, (-): significant negative difference at 95%
 90%, (+): significant positive difference at 90%
 90%, (-): significant negative difference at 90%
 (+): insignificant positive difference at 90 %
 (-): insignificant negative difference at 90%
 0: two treatments are exactly equal

Table 2. Paired t-tests Based on Individual Consumer Surplus Differences

| Period Pairs | FP - DRP | FP - RTP | FP - OPT | DRP - RTP | DRP - OPT | RTP - OPT | Contingency |
|--------------|----------|----------|----------|-----------|-----------|-----------|-------------|
| Pair 1 | (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 95%, (+) | N |
| Pair 2 | 95%, (-) | 95%, (-) | (-) | (+) | 90%, (+) | 99%, (+) | S, DRP |
| Pair 3 | (+) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | H |
| Pair 4 | 0 | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | N |
| Pair 5 | (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | N |
| Pair 6 | (+) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | N |
| Pair 7 | 99%, (-) | 99%, (+) | 99%, (+) | 99%, (+) | 99%, (+) | 99%, (+) | H+S, DRP |
| Pair 8 | 95%, (-) | 99%, (+) | 99%, (+) | 99%, (+) | 99%, (+) | 99%, (+) | H+S, DRP |
| Pair 9 | (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | N |
| Pair 10 | 90%, (-) | (-) | (+) | (+) | 90%, (+) | 99%, (+) | S, DRP |
| Pair 11 | (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (-) | 99%, (+) | H |

Tables 1 and 2 summarize the only hypotheses that are testable statistically with this single set of experiments. Both demonstrate the t-statistic constructed to estimate whether differences in performance, by participant, are significantly different across pair-wise comparisons of the different market-clearing treatments. The results that are easy to interpret are those that compare the participants' performance on each treatment against the theoretically ideal, socially optimal performance. Comparing actual versus ideal quantity purchases, Table 1 shows that in the **FP** treatment, those quantities deviate significantly (at the .95 level) from the optimal purchases in 17 of the 22 periods, under **DRP** those quantities deviate significantly from the optimum in 21 of the 22 total periods, whereas under **RTP**, the quantities are significantly different than the optimal purchases in only one of the 22 periods!

The results on the pair-wise comparison of consumers' surplus are somewhat surprising, but they reveal the underlying behavior of single-sided markets. Because some energy can be substituted between day and night periods, in this case the test statistic is computed as the difference in total **CS** across each day-night pair combined. Here for both the **FP** and **DRP** treatments, there is significant deviation from the optimal consumer surplus in 9 of the 11 pairs, and in only two of those pairs is the surplus greater than the optimum amount; in seven of the eleven periods the surplus is lower than optimal. *By comparison, under the RTP treatment the CS is greater than optimal in every period.*

It is not surprising, therefore, that in the preference polls conducted after the final treatment, the participants acted in their own self interest and voted by a 75% majority to select **RTP** for their final experiments (for which they would be paid in proportion to their earnings). As summarized in Table 3, however, that was

not the participants' perception in earlier stages of the trials. Here two-thirds thought they would prefer **DRP** over **RTP**, after having tried the **FP** treatment, both before and after having experienced **DRP**, but before having tried **RTP**. As reported in Table 3, this switch in preferences is statistically significant according to the binomial proportions test.

Figures 5 and 6 demonstrate the effects these alternative demand-side and market-clearing schemes have on wholesale prices. The pricing patterns are remarkably similar for the two different groups of participants, and in periods where there are significantly higher prices (optimally so according to the theoretical calculations shown in the figures), they are highest under the fixed price treatment and lowest under **DRP**. Under **RTP**, those market-clearing prices are closest to the theoretical optimum (note that **RTP** prices are generally lower than for **FP** and **DRP** in low load periods).

These experimental results are therefore consistent with customers' intuition: **DRP** is shown to be an effective way of curbing price spikes. The problem is it does it in an inefficient way, and once the participants in these experiments experienced **RTP** and reaped its benefits, they voluntarily switched their preferences and selected **RTP** as their preferred buying mechanism going forward.

Table 3. Binomial Proportions Tests on Buyer Votes

| | Number of Buyers Voted | | |
|---------------------------------|------------------------|-----|-------|
| | DRP | RTP | Total |
| Vote 1 (after FP, before DRP): | 14 | 7 | 21 |
| Vote 2 (after DRP, before RTP): | 13 | 8 | 21 |
| Vote 3 (after RTP): | 5 | 16 | 21 |

$\text{Prob}(\text{Vote 1} = \text{Vote 2}) \leq 0.7470$
 $\text{Prob}(\text{Vote 2} = \text{Vote 3}) \leq 0.0053$
 $\text{Prob}(\text{Vote 2} = \text{Vote 3}) \leq 0.0116$

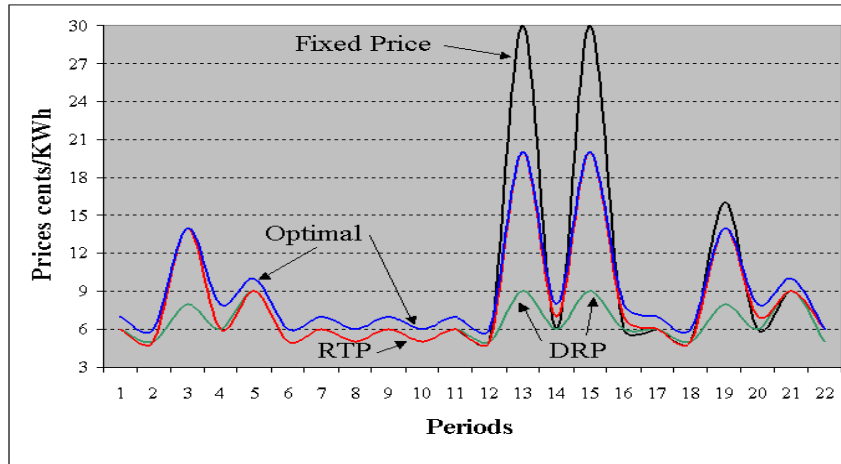


Figure 5. Market Clearing Prices (Monday Group)

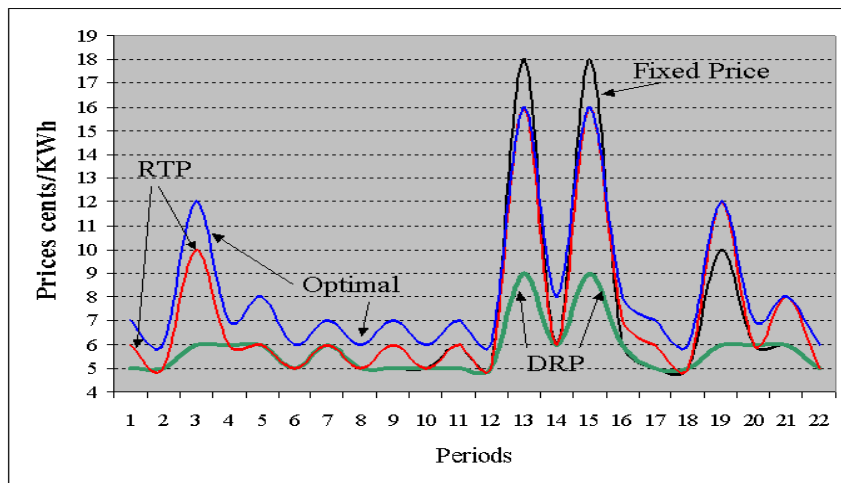


Figure 6. Market Clearing Prices (Thursday Group)

5. Conclusions

An active demand-side platform that is representative of customer behavior in U.S. electricity markets is developed, reported and tested in an experimental framework. This demand-side platform is capable of accommodating markets for reserves as well as real-time clearing, and it permits buyers to substitute a portion of their purchases between day and night periods. The platform is calibrated to aggregate elasticities that have been estimated statistically in previous analyses of U.S. electricity demand.

In single-sided market tests where representative offer structures were pre-selected and varied randomly, participants quickly demonstrated their ability as buyers to solve a non-trivial inter-temporal optimization problem in the RTP experiments. Under RTP participants were required to make their quantity purchases based upon a prior set of day-night price forecasts. Both groups of participants performed this task exceptionally well, demonstrating statistically significant smaller deviations from the socially optimal level of consumption than in either fixed price (FP) or DRP experimental trials.

In fact, symptomatic of the problem of single-sided markets, the buyers did so well under RTP that they captured a portion of the optimal producers' surplus, yielding higher than optimal levels of consumers' surplus. This is precisely the opposite result from that obtained when active suppliers offer into a single-sided market where demand is predetermined, in which case the sellers capture more than the efficient share of surplus.

What remains to be done, therefore, is to conduct full two-sided markets with this experimental platform in order to determine whether or not these markets can be self-regulating, and under which demand-side platform that self-regulation is most effectively achieved.

These experiments do emphasize the effectiveness of DRP programs in reducing price spikes greatly – but too greatly! Both DRP and FP clearing mechanisms are less efficient than RTP, which results in lower prices in all but the peak periods, and once the participants in these experiments experienced RTP, they reversed their preferences and opted to continue with this market-clearing mechanism.

6. References

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