Discriminatory Price Auctions in Electricity Markets: Low Volatility at the Expense of High Price Levels[*]

by

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Abstract: A 'pay-as-offered' or discriminatory price auction (DPA) has been proposed to solve the problem of inflated and volatile wholesale electricity prices. Using the experimental method we compare the DPA with a uniform price auction (UPA), strictly controlling for unilateral market power. We find that a DPA indeed substantially reduces price volatility. However, in a *no* market power design, prices in a DPA converge to the high prices of a uniform price auction *with* structural market power. That is, the DPA in a no market power environment is as anti-competitive as a UPA with structurally introduced market power.

JEL Classifications: L13, L94, C92

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1. Introduction

In the electricity industry, where a few points of exchange efficiency are worth tens of millions of dollars, the danger persists that policy makers design new institutional rules for a complex trading arena on the basis of testimonial conjecture. For example, in November of 2000 just prior to the demise of the California Power Exchange (CPX), CEO George Sladoje wrote an open letter announcing that, because of public pressure, a Blue Ribbon Panel had been formed to examine the PX's policy of running a uniform-price rather than pay-as-offered auction for electricity. Apparently, during the ongoing investigations into the upheaval in California prices, several parties had suggested that switching the PX to use of a 'pay-as-offered' auction would go a long way toward curtailing inflated and volatile wholesale electricity prices. Some had gone as far as suggesting that providers of electricity should retroactively be required to refund any 'profit' above their offer prices that had been accumulated because of the uniform-price rule. Meanwhile in England, one of the pioneering nations in the adoption of free-market electricity pricing, the New Electricity Trading Agreement (NETA) reflected the same dissatisfaction with a centrally managed uniform-price day ahead sealed bid market. In April 2001, the British implemented a new institutional regime: bilateral forward trading between wholesale providers and distributors,[1] combined with a voluntary 'pay-as-offered' last minute balancing market which would deal with system constraints (essentially, the new spot market). In this paper we test the chief publicized justification for implementing a 'pay-as-offered' discriminatory price auction in these electricity network markets—reducing price volatility and average price paid in trading environments with minimal demand elasticity, cyclical demand uncertainties and an absence of significant excess generation capacity.

2. Market Institution, Structure, and Design

In this paper we use the electricity network-trading environment that we developed in Rassenti, Smith, and Wilson (2001), hereafter, RSW, to examine how a discriminatory price (sealed offer) auction (DPA) affects seller behavior and market performance. We measure the DPA against the uniform price (sealed offer) auction (UPA) that we previously studied with three experimental treatment variables (unilateral generator market power, transmission line constraints, and demand-side bidding) in RSW. Comparisons of buyer-bid UPA and DPA institutions exist for simpler

[1] Olson et al. (2001) compare bilateral trading with a uniform price sealed offer spot market to find less efficiency in the former.

environmental contexts. In a single unit (per buyer) demand environment, Cox et al. (1985) could not distinguish a significant revenue effect with the institutional treatment. In a multi-unit stationary demand and fixed supply environment, where truthful revelation constituted a Nash equilibrium, Miller and Plott (1985) found that the DPA/UPA generated higher revenues when demand was inelastic/elastic. The RSW environment that we use has a stationary supply but cyclic demand where truthful revelation does not constitute a Nash equilibrium. Alsemgeest et al. (1999) show that in non-stationary two-unit demand fixed supply environments, a UPA produces bids above the Bayes-Nash prediction—better revelation than expected. They do not test a DPA in their environment.

2.1 Auction Institution

The primary objective of this paper is to compare the impact on spot prices of electricity market pricing rules (*Uniform vs Discriminatory*), while holding constant all other features of the system—the costs and structure of supply, and the resale values and structure of demand. Because accommodations for demand-side bidding have not been included in naturally occurring electricity markets, a computer is used to submit bids that exactly reveal the demand in all our experiments. In the *Uniform* treatment, sellers privately submit, in each (spot) pricing period, a schedule of offers or asking prices for their generation capacity. The offers and the computerized bids are then sent to an optimization algorithm to maximize the total gains from trade in the network. In essence this reduces, in this simple environment, to arranging the offers from lowest to highest and the bids from highest to lowest and finding the allocation of offers that maximizes surplus, taking into account minor losses in transmission. Where the bid-ask (reported demand and supply) schedules intersect determines what the uniform price is and how many units of electricity that each seller will sell. The market price paid to all sellers is equal to the price at which the bid and offer schedules cross. If an offer is less than the market price, then that unit sells at the market price. Tied offers (at the same generating location or "node") are accepted on a first-submitted, first-served basis. At each node all generators receive the same price. This treatment parallels the energy markets in most regions that have instituted hourly spot markets, except that in our markets we make no provision for bilateral contracts, secretly priced outside the exchange; all energy transfers pass through our spot market. In the second experimental treatment, the *Discriminatory* auction, generators do *not* receive the same price at each node. Information is solicited and processed in exactly the same manner as in the *Uniform* treatment, but the owner of each accepted offer receives as his/her price the amount of his/her offer.

2.2 Unilateral Market Power

For the strongest comparison of the *Uniform* and *Discriminatory* treatments, we desired an electricity network-trading environment that strictly controlled for structural features of market power. In a UPA for a given distribution of ownership of capacity, a firm is said to be able to exert unilateral market power when it can *profitably* and *unilaterally* submit an offer schedule above its marginal costs (or equivalently withdraw some generating capacity) causing the market price to rise above the competitive level.[2] We will assume that the benchmark auction institution is the UPA. Following this analysis, we will discuss the DPA.

To see how we control for potential market power incentives, consider aggregate supply and demand arrays reported in Tables 1 and 2 and depicted in Figure 1. As discussed above, we assume and implement the condition that the buyers perfectly reveal their willingness to pay. The second and third steps of the demand in Table 1 represent interruptible units of demand, whereas the units on the first step at 226 are the so-called "must serve" or inelastic units. The interruptible demand steps of each wholesale buyer represent contracts with retail customers who allow energy flow to be interrupted if the wholesale price rises to the level of the step or greater. The level of "must serve" demand varied among 3 levels: 6 units in off-peak periods, 15 units during shoulder periods, and 21 units during peak periods.

In our three node radial network there are five generation firms (or sellers) denoted by an "S" and an identification number. In what we will call the *No Power* treatment, two sellers, *S1* and *S2* own four units of low cost (Type *A*) baseload generation capacity at opposite ends of the network. *S3* owns three units of high cost generation peak capacity (2 Type *D* and 1 Type *E*) at the center node. The final two sellers, *S4* and *S5* each have two units of baseload (Type *B*) and two units of peak capacity and are also located at opposite ends of the network. Most importantly, note that each of the five sellers also owns two units of intermediate cost (Type *C*) generation capacity at their respective nodes. Our focus will be on these intermediate units during the shoulder demand periods.

During the shoulder periods, the competitive price is equal to the marginal cost of the intermediate generators. More importantly, in this *No Power* treatment, notice that not a single seller can unilaterally withdraw (not submit offers for) any units of generation so that the price rises above the competitive level. At the competitive price of 76, *S1* and *S2* both earn a profit of 224 [(76 –

[2] In the context of Bertrand, capacity-constrained competitors, Holt (1989) defines a game-theoretic formalization of market power arising when one or more firms can deviate *profitably* and *unilaterally* from the competitive outcome.

20) × 4 units]. If any one of the five sellers unilaterally raises his offer on his intermediate units, the price will remain at the competitive level; the competitive price is a pure strategy Nash equilibrium with a UPA.

Market power, however, can be introduced merely by transferring two of *S4*'s and two of *S5*'s intermediate units to *S1* and *S2*, respectively. We will call this the *Power* treatment. With this seemingly minor reallocation of capacity at Nodes 1 and 3, either *S1* or *S2* can unilaterally increase his profit by offering his four units of intermediate cost generation capacity at supra-competitive levels in the shoulder period and consequently raise the market price above the competitive level. Both *S1* and *S2* can unilaterally withdraw (not submit offers for) four units of generation entirely so that the price rises to the third step of the supply curve (166), where four units of peaking capacity contest any further attempted increase in price (see Figure 1). Alternatively, either *S1* or *S2* can increase the offer price for his intermediate cost generation capacity so that his offer sets the market price. At the competitive price of 76, *S1* and *S2* both earn a profit of 224 [(76 – 20) × 4 units]. If either *S1* or *S2* raises his offer on his intermediate units to 166, the price-setter's profit rises to 584 [(166 – 20) × 4 units].[3] This unilateral deviation is even profitable at a price of 96, the third shoulder demand step, where *S1* and *S2*'s profit would be 384. It is important to note that it requires only one of the two sellers *S1* or *S2* to undertake this profitable action that reduces his volume sold but, in a UPA, creates benefits all other sellers. Either one of *S1* or *S2* will be even better off by not having reduced his sales volume if the other seller withholds supply to raise the price. Thus, each has an incentive to free ride on the increased offer price of the other.

Notice that in both the *No Power* and *Power* treatments no firm can exercise market power during peak demands; all unilateral deviations are unprofitable. *S1* and *S2* can exert some market power during off-peak demands by raising the offers on two units of baseload generation capacity, regardless of the allocation of intermediate capacity. The theoretical upper bound on the price during off-peak demand is 76, the cost of intermediate generation capacity. The market power incentives in the off-peak demand provide the subjects with a profit opportunity during the off-peak periods, and function as a common control across sessions in both the *No Power* and *Power* treatments.

For the DPA we are unaware of any explicit theoretical predictions for such a rich and strategically complex environment as this. The purpose of our experiment is to compare the UPA to the DPA, holding a standard organizing concept, the competitive prediction, constant in all treatments for a given level of demand. With this benchmark we examine in particular how the DPA affects the offering behavior of the sellers in the *No Power* design in the shoulder period. We hypothesize that since the sellers receive a price equal to their offer, sellers no longer have an incentive to reveal the costs of their baseload units. Sellers have an incentive to bid ε less than the last accepted offer on *all* of their units, baseload and marginal. Moreover, the competitive price no longer has the same drawing power, even in the *No Power* design, because the incentive is to bid ε less than the last accepted offer, which may or may not coincide with the competitive price.

2.3 Experimental Design

Table 3 summarizes our experimental design. We originally planned to conduct a balanced 2 × 2 design with four sessions in each cell. However, we did not run any sessions with the interaction of the *Power* and *Discriminatory* treatments because as we report below, the results of the *No Power/Discriminatory* treatment, the DPA case least favorable to price manipulation, were so strongly anti-competitive that there was little room to observe a statistically significant *Power/Discriminatory* effect. If we had not observed such consistently high prices in the *No Power/Discriminatory* treatment, then we would have completed the 2 × 2 design with four sessions of the *Power/Discriminatory* treatment.

3. Procedures

To test how the behavior and market performance differs in electricity networks with UPA and DPA, we conducted twelve market experiments using students at the University of Arizona. Four sessions for each cell in Table 3 were conducted using the *Power 2K* software we developed. Each session lasted approximately ninety minutes. The combined eight sessions for the *No Power/Uniform* and *Power/Uniform* treatments were previously reported in RSW. The four new sessions for the *No Power/Discriminatory* treatment are reported here and compared with the RSW baselines.

We provided the subjects in each market with complete and full information on the market supply structure; i.e., every firm's generation capacity, marginal costs of generation, and the position in the network were public information. Information on demand, however, was not given to the subjects.

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[3] The firm that does not raise his offer realizes a profit of 944 ((166 – 20) × 4 units + (166 – 76 × 4 units).

The subjects were told that the costs and the generation capacities for each seller would not change during the experiment, but that the maximum number of units that the buyers may purchase and the willingness to pay for those units would vary by period. In particular, the subjects were informed that the buyers would have three different levels of demand during each "market day", with 'Low Demand' indicating a willingness to buy fewer units at lower prices, 'Medium Demand' indicating a willingness to buy more units at higher prices, and 'High Demand' indicating a willingness to buy the most units at the highest prices. Each session lasted for fourteen market days where each day was comprised of a four period cycle. A day began with a shoulder period, followed by one peak, one shoulder, and lastly, one off-peak period.

A subject had one minute to submit his offer each period. An offer was expressed as a step function indicating a schedule of prices and the maximum number of units at each of those prices that the subject was willing to generate.[4] A subject could at any time within the one-minute period revise his offer.

Each subject had participated in one trainer session two days earlier in the week. (The trainer session was comprised of six subjects in symmetric positions in a three node radial network that differed from the design in figure 1.) The best performers in the trainer session were used two days later to participate in the above designs, with the top performers assigned to the roles of *S1* and *S2*. Subjects were paid $15 total for showing up on time for both the trainer sessions and the sessions reported here. In addition to this show-up fee, the average earnings per subject for the data discussed here was $21.25.

4. Results

Figure 2 illustrates the production-weighted price paths for the four sessions in each of the three treatment cells. All fourteen days of data by level of demand (period) are grouped together and then sequenced by how the demand varied over a market day: shoulder 1, peak, shoulder 2, and off-peak. We evaluate the results with respect to the competitive prediction, and the value of the nearest unit of interruptible demand, shown as a solid and dotted line, respectively.[5] Given that the computerized demand submits fully revealing bids, we expect ex ante that the sellers will push up

[4] The one-minute time frame was not binding because the subjects had prior experience with a three-minute period that was far from binding in the trainer session.

[5] For brevity, the results are presented exclusively in terms of price outcomes. Results for efficiency parallel our price observations.

their offers to the nearest unit of interruptible demand. These prices, however, are still 100% efficient.

From the figure, it is apparent that the *Discriminatory* condition affects performance markedly. For sessions conducted under the baseline *No Power*/*Uniform* treatment, the mean price path in the shoulder periods tends to hover within the efficient price range without much variance. Higher prices are observed in sequences conducted under the *No Power*/*Discriminatory* treatment. (Data at the session level will also be presented below.) Further evident from the figure is that in the peak periods prices do not differ in the *No Power*/*Uniform* and *No Power*/*Discriminatory* treatment, but differences exist in the off-peak period prices even though all 8 sessions make identical predictions under off-peak demand conditions. These latter observations provide measures of spillover or hysteresis effects on periods that are theoretically immune from all treatment effects.

In what follows, our new experimental results are summarized as a series of four findings. In addition to the qualitative results displayed in Figure 2, we analyze the data using a mixed-effects model for repeated measures on each of several sessions using different subjects [see e.g., Longford (1993)]. The results from estimating this model by level of demand are given in Table 4. As a common metric across treatments, the dependent variable is the difference between the observed price (*Price*) and the competitive price, P^c. For each period, *Price* is defined as the production-weighted price received by all of the sellers in the network. In the *Uniform* treatment, all units generated at each node trade at the same price, but in the *Discriminatory* treatment, the sellers are paid the price of their bid for each unit. The treatment effects (*Power* and *Discriminatory*) are modeled as (zero-one) fixed effects, whereas the sessions are modeled as random effects, e_i. Specifically, we will estimate the model:

$$Price_{ij} - P^c = \mu + e_i + \beta_1 Power_i + \beta_2 Discriminatory_i + \varepsilon_{ij} \, ;$$

where the sessions are indexed by i and the repeated market days by j. The sessions are indexed by $i = 1,\ldots,12$ and the days by $j = 1,\ldots,14$. We begin with our previous finding of pricing performance in the *No Power*/*Uniform* treatment.

Previous Finding *[RSW]*: *Markets in the* No Power/Uniform *treatment quickly stabilize in the 100% efficient outcome range, but above the strict Bertrandesqe competitive equilibrium. This is true for all levels of demand, but most noticeably in the shoulder periods.*

Support: Figure 2 displays in blue the prices for all four sessions in the *No Power/No Line Constraint* treatment. Only for 7 out of 112 observations in shoulder periods (4 sessions × 2 shoulder periods/day × 14 days) does the price exceed the value of the last interruptible units of demand (96). Single sellers in each of the second and fourth sessions are unable to maintain higher prices by restricting output by four units or more. For the peak demand periods, prices are only above competitive levels on 5 occasions, save session 3, which is able to support slightly supra-competitive prices for the first 9 periods. In off-peak periods, prices are at first drawn to the competitive and zero profit level of 20, but *S1* and *S2* are successful in three of the sessions in pushing the price toward 76 ($\mu > 0$), the marginal cost of the intermediate capacity. Quantitatively, Table 4 reports that the prices in the *No Power/Uniform* treatment are statistically greater than the strict competitive predictions at marginal cost in figure 1. However, in the shoulder periods, the prices are not greater than the last interruptible unit of demand, 96.■

Consider now the effects of changing the auction institution from a UPA to a DPA. We summarize our results for this treatment.

Finding 1*: *Ceteris paribus, changing the auction institution from a UPA to DPA significantly raises prices in shoulder and off-peak periods. The* Discriminatory *treatment has no effect on prices in peak periods, where relatively considerable excess capacity exists.

Support: Panel (a) in Figure 2 clearly illustrates that for the shoulder periods market prices in the *No Power/Discriminatory* design (in brown) are greater than in the *No Power/Uniform* design. In each of the four *No Power/Discriminatory* sessions the production-weighted price starts low with two of the sessions starting at the same price level as the *No Power/Uniform* sessions. However, within two or three trading days, the price shoots up and remains stable across days. There is no discernable separation in peak period prices. Off-peak prices are initially much higher in the *No Power/Discriminatory* treatment, and remain higher on average even though two of the *No Power/Uniform* sessions experience increases in off-peak prices. These qualitative observations are supported by estimates from the mixed-effects model in Table 4. In the shoulder 1 (shoulder 2) periods, the *No Power/Discriminatory* treatment significantly raises prices above the *No Power/Uniform* level by 47.5 (50.7) experimental dollars [*p-value* = 0.0000 (0.0000)]. The total primary effect of *No Power/Discriminatory* is to raise the prices above the competitive level by 66.8

= 19.0 + 47.8 (69.2 = 18.5 + 50.7) experimental dollars. The prices in peak periods are not significantly greater in the *No Power/Discriminatory* treatment (*p-value* = 0.5067). In the off-peak period, prices are 43.8 experimental dollars greater than the *No Power/Uniform* baseline (*p-value* = 0.0014). ■

Why are the prices so much higher with a DPA than a UPA? Our third finding reports that all sellers submit substantially higher offers curves for all units, baseload and marginal.

Finding 2: *Relative to a UPA, the revealed surplus drops considerably in a DPA as all sellers submit higher offer schedules for all of their units.*

Support: Figure 3 provides the support pertinent to this finding. This figure displays the average market offer curves for the shoulder periods for each of the 4 *No Power/Uniform* and the 4 *No Power/Discriminatory* sessions. The k^{th} step of the average market offer curves is the average offer for the k^{th} step across all shoulder periods in a session. Hence, there are a total of 28 observations (14 days × 2 shoulder periods per day) included in the average at each step. Notice that the *No Power/Discriminatory* offer curves are always higher for every step of the curve, save the first step of one session. Although it appears that the two types of offer curves are converging at high quantity levels, these quantity levels are extra-marginal by considerable amounts. While not displayed for the purposes of brevity, similar behavior is observed in both the off-peak and peak periods. ■

One dimension that is lost in Finding 2 and Figure 3 is the extent to which sellers increase their offers over the course of 14 market days. Figure 4 displays the average of the four *No Power/Discriminatory* sessions for four distinct shoulder 1 periods, Day 1, 2, 7, and 14 (early, middle, and last days). Notice that the offer curves for the 10-18th units are distinctly higher than the offers for the initial day, and that process quickly begins in Day 2. Furthermore, as the market days progress, the offers for more baseload units rise to within a few experimental dollars of the highest price received.

For some perspective in the magnitude of treatment effects, we compare the changeover to DPA pricing to the introduction of market power in a UPA.

Finding 3: *In shoulder periods, the DPA is as anti-competitive as a distribution of ownership that creates market power in a UPA.*

Support: Panel (b) in Figure 2 plots the production-weighted prices for the *No Power/Discriminatory* sessions discussed above with the *Power/Uniform* sessions. For all levels of demand, it is evident that prices are as high in the *No Power/Discriminatory* treatment as they are in the *Power/Uniform* treatment. Quantitatively, the estimated effects for the *Discriminatory* and *Power* effects are 52.5 vs. 47.5 in shoulder 1 and 43.9 vs. 50.7 in shoulder 2, respectively (see Table 4). These economically similar effects are statistically different using a LR ratio test (p-values = 0.0501 and 0.0150 for shoulder 1 and shoulder 2, respectively. For the peak periods, both the *Discriminatory* and *Power* coefficients are insignificant individually (p-values = 0.7202 and 0.5067, respectively) and from each other (p-value = 0.7760). A LR ratio test also indicates that the two effects are indistinguishable in off-peak periods (p-value = 0.1342). ■

Because the prices are so anti-competitive in the *No Power/Discriminative* treatment, there is little room for a *Power/Discriminative* interaction, and hence cadit quaestio, for completing a 2 × 2 design. Finally, we consider the chief publicized justification for implementing a DPA in electricity markets—reduced price volatility.[6]

Finding 4: *The variance of price changes from day to day for the same level of demand is substantially lower with a DPA than with a UPA, though in shoulder periods the variance is essentially the same, holding the* No Power *design constant.*

Support: Figure 5 presents the summary statistics for the twelve sessions presented here. We use the last 10 days of each session to allow for the convergence of the observed prices evident in Figures 2 and 4. It is clear that the DPA reduces the volatility of prices in the off-peak and peak periods. In the shoulder period, the variances are nearly the same holding the *No Power* design constant (56 for the UPA and 52 for the DPA). ■

The DPA performs favorably on the dimension for which it was proposed—price volatility. However, it clearly comes at a substantial cost. Holding the *No Power* design constant, prices rise by 85% in the off-peak periods (76 vs. 41) and 56% in shoulder periods (148 vs. 95). Only in the peak periods does the volatility fall while the level of prices remains the same. We conjecture that this is

[6] See, e.g., Mount (2001).

due to the greater excess capacity of our peak design (6 units), but significant excess capacity is not the situation for which the DPA was proposed to solve the volatility problem.[7] The germane level of demand to consider is the shoulder period in which we find that the DPA in a *No Power* environment is actually as anti-competitive, with respect resulting prices, as a UPA with structurally introduced market power.

5. Conclusions

In the dynamic electricity-trading environment tested in these experiments, the DPA reduces price volatility, at the cost of producing prices that converge, not to the competitive level, but to the level of the highest prices occasionally observed in the UPA with structural market power. Average prices in shoulder and off-peak periods increase, as the DPA constantly reminds participants that whenever their offers were accepted they almost always left money on the table. Under the conditions of cyclic and revealed inelastic demand, the DPA invites sellers to tacitly collude, coordinating their offers without explicit communication at the highest previously observed price in a similar period. Having established that such coordination is not present in the UPA, our experiment demonstrates that it is the incentive structure of the DPA institution that promotes this "tacit collusion."

For policy makers the lesson is clear: experiments can demonstrate what the best reasoned of arguments may not be able to forecast in such complicated exchange environments. In the present case of wholesale electricity markets, the effort to ultimately insulate retail customers from price increases and volatility by using the suggested institutional manipulation, switching from UPA to DPA, will fail (ceteris paribus). Regulators should be mindfully aware that the trading rules they choose will affect the behavior of the agents, leading to market outcomes that may substantially diverge from the intended objectives.

[7] This design, with generation competitive at peak demand levels, but not at intermediate levels, illustrates the important principle that market power need not be associated only with peak demand conditions. Market power is about the ownership distribution of different generators classed by marginal cost, given a fixed and unresponsive demand.

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Table 1. Demand Values

	Step 1 Value = 226	Step 2 Value = 206	Step 3 Value = 96
	Quantity	Quantity	Quantity
Node 1			
Off-peak	2	0	1
Shoulder	5	0	1
Peak	7	0	1
Node 2			
Off-peak	2	2	0
Shoulder	6	2	0
Peak	8	2	0
Node 3			
Off-peak	2	0	1
Shoulder	5	0	1
Peak	6	0	1

Table 2. Marginal Costs of Generation

Generator Type (Number)	Maximum Load	Total Load	Marginal Cost
A (2)	4	8	20
B (2)	2	4	20
C (5)	2	10	76
D (4)	1	4	166
E (3)	1	3	186
	Total	29	

Table 3. Experimental Design

(No. of Sessions; No. of Trading Days; No. of Trading Periods)

	Uniform	***Discriminatory***	Total
No Power	(4; 14; 56)	(4; 14; 56)	(8; 28; 112)
Power	(4; 14; 56)	(foregone, see p. 5)	(4; 14; 56)
Total	(8; 28; 112)	(4; 14; 56)	(12; 42; 168)

Table 4. Estimates of the Linear Mixed-Effects Model of Treatment Effects

$$Price_{ij} - P^c = \mu + e_i + \beta_1 Power_i + \beta_2 Discriminatory_i + \varepsilon_{ij},$$
$$\text{where } e_i \sim N(0, \sigma_1^2) \text{ and } \varepsilon_{ij} \sim N(0, \sigma_{2,i}^2).$$

	Estimate	Std. Error	Degrees of Freedom	H_a	*t*-statistic	*p*-value
Shoulder 1						
μ	19.00	0.27	156	$\mu \neq 0$	70.92	0.0000
Power	52.48	1.65	9	$\beta_1 > 0$	31.87	0.0000
Discriminatory	47.47	1.66	9	$\beta_2 \neq 0$	28.54	0.0000
			L.R. test	$\beta_1 \neq \beta_2$	3.84	0.0501
Peak						
μ	11.64	3.69	156	$\mu \neq 0$	3.15	0.0000
Power	-2.00	5.42	9	$\beta_1 \neq 0$	-0.37	0.7202
Discriminatory	-3.61	5.21	9	$\beta_2 \neq 0$	-0.69	0.5067
			L.R. test	$\beta_1 \neq \beta_2$	0.09	0.7660
Shoulder 2						
μ	18.47	0.36	156	$\mu \neq 0$	50.96	0.0000
Power	43.88	2.15	9	$\beta_1 > 0$	20.44	0.0000
Discriminatory	50.71	1.43	9	$\beta_2 \neq 0$	35.43	0.0000
			L.R. test	$\beta_1 \neq \beta_2$	5.91	0.0150
Off-peak						
μ	17.37	6.85	156	$\mu \neq 0$	2.53	0.0122
Power	28.72	9.76	9	$\beta_1 \neq 0$	2.94	0.0164
Discriminatory	43.78	9.65	9	$\beta_2 \neq 0$	4.54	0.0014
			L.R. test	$\beta_1 \neq \beta_2$	2.24	0.1342

Note: The linear mixed-effects model is fit by maximum likelihood with 168 original observations and 12 sessions. For purposes of the brevity the session random effects are not included in the table.

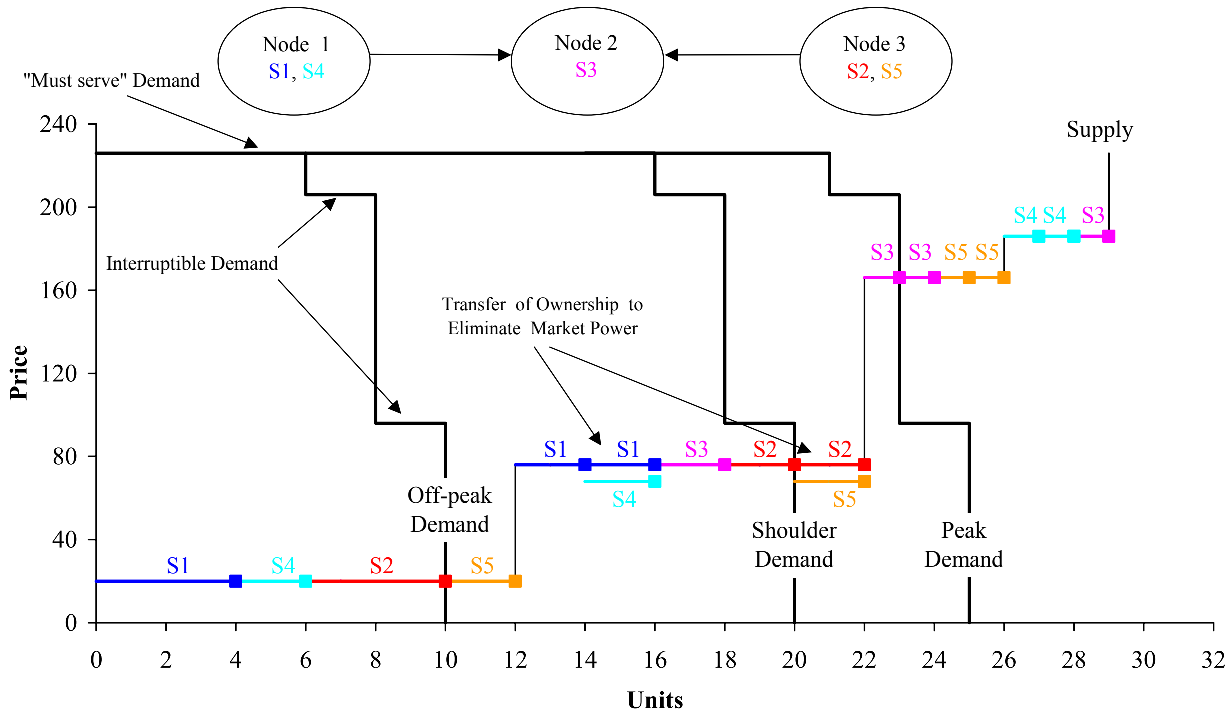
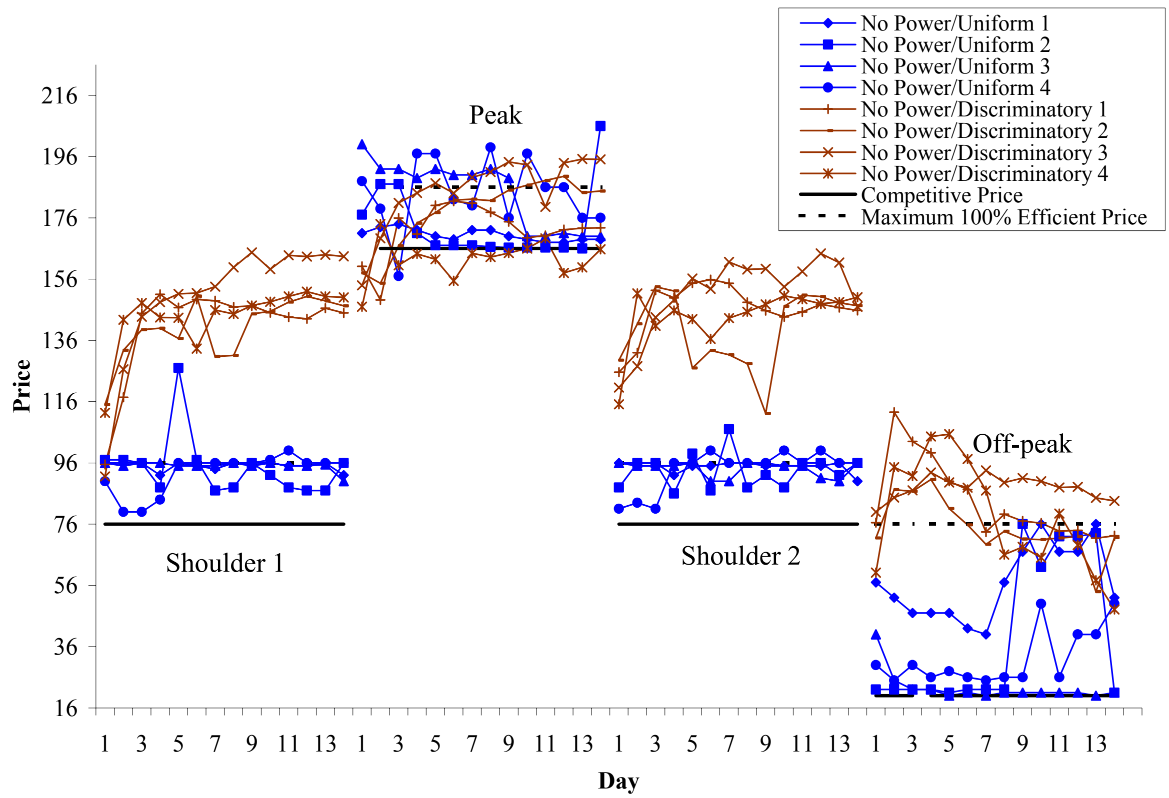
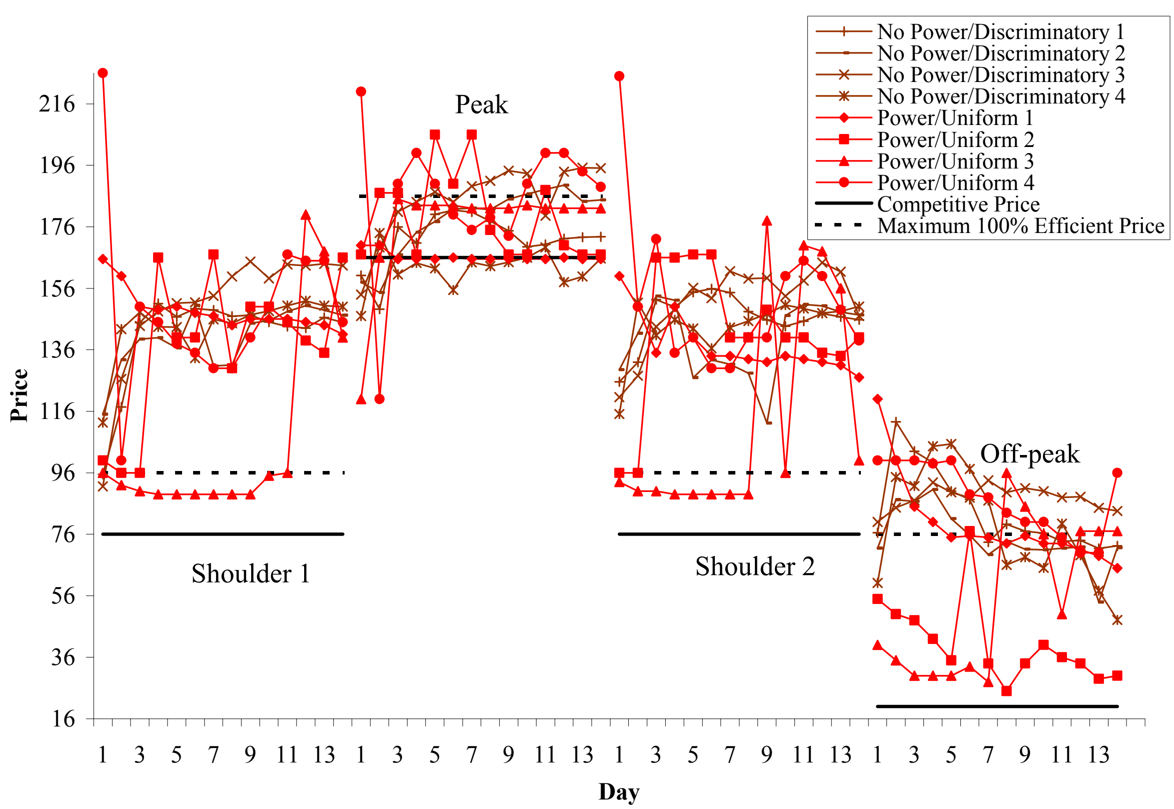


Figure 1. Market Structure and Design



(a) ***No Power/Uniform*** **vs.** ***No Power/Discriminatory***



(b) ***No Power /Discriminatory*** **vs.** ***Power/Uniform***

Figure 2. Production-weighted Session Prices by Level of Demand

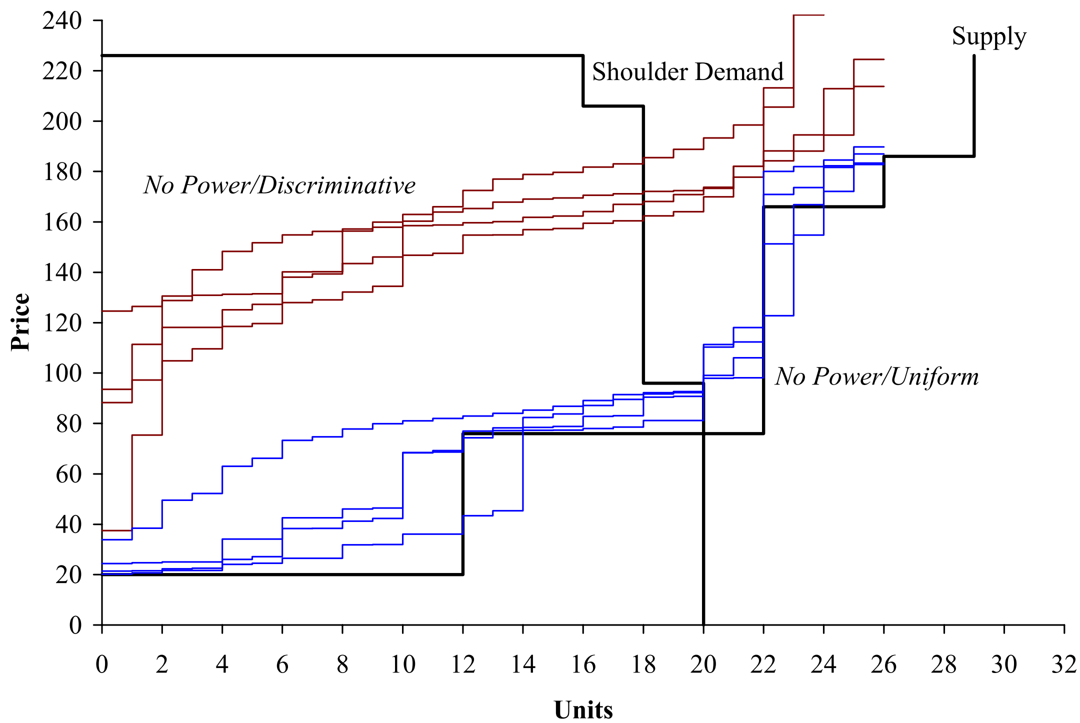


Figure 3. Average Market Offer Curve by Session

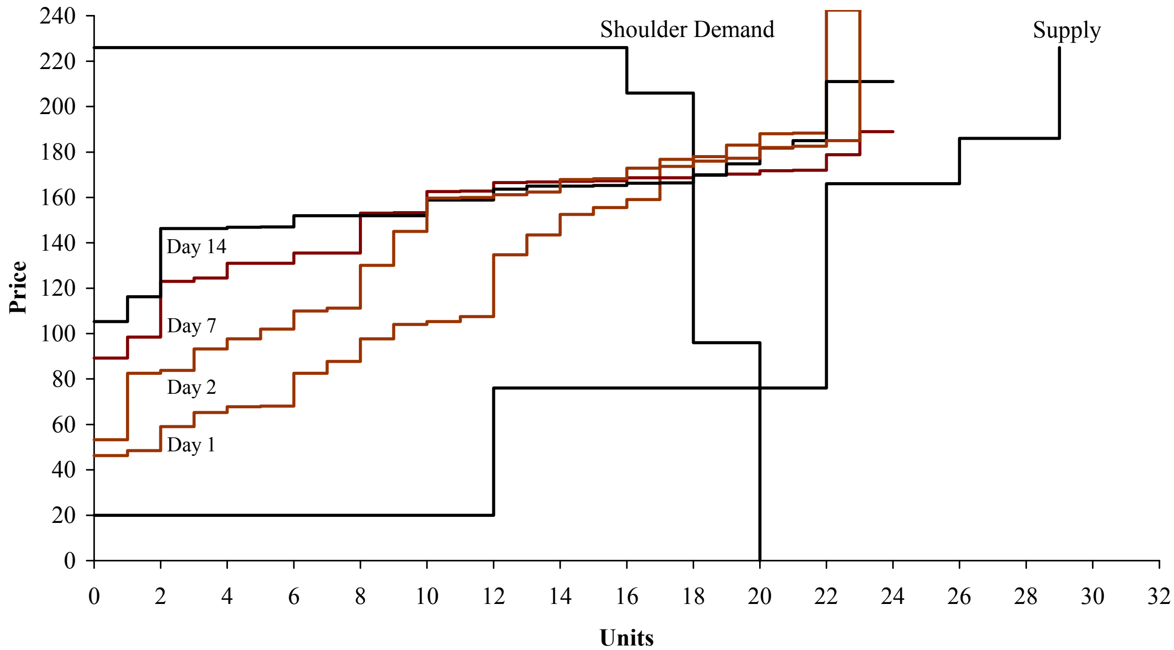
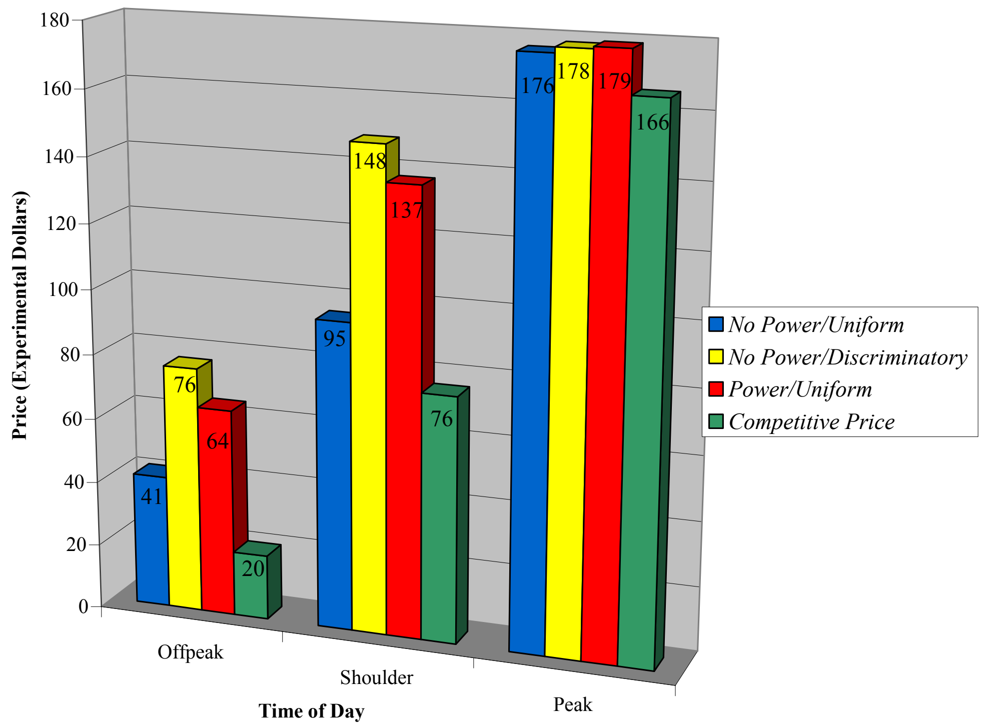
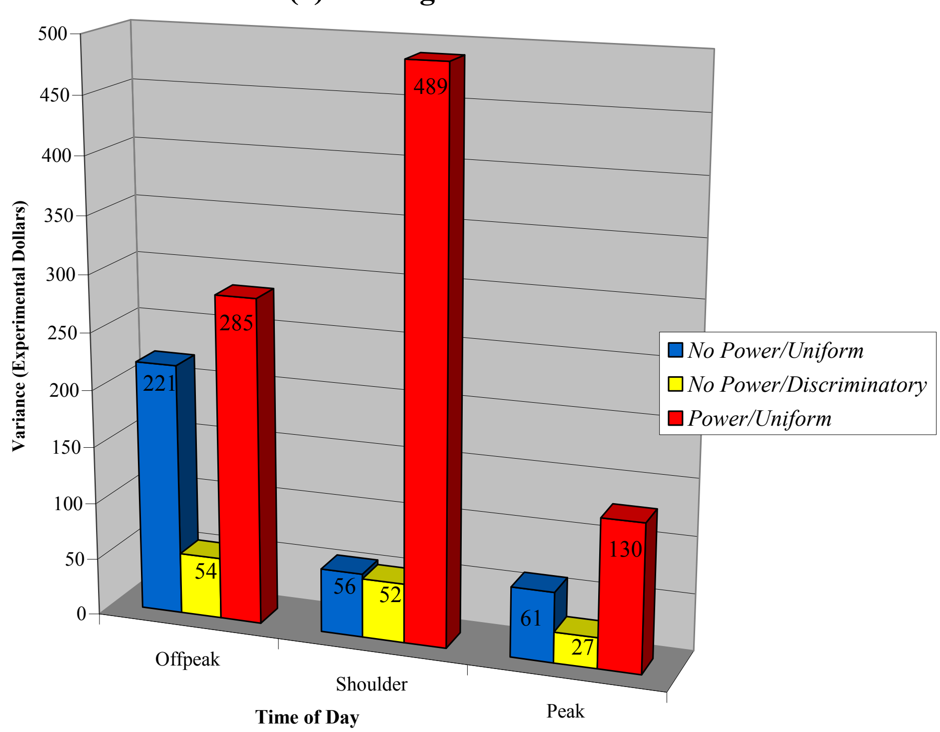


Figure 4. Convergence of Offer Curves
(Average of 4 Sessions)



(a) Average Prices



(b) Variance of Price Changes

Figure 5. Summary Results by Treatment for the Last 10 Market Days