Controlling Market Power and Price Spikes in Electricity Networks: Demand-Side Bidding[*]

by

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July, 2001

[*] We thank Richard Kiser and Jody Toutant for writing the *Power 2K* software for these experiments, and Tolga Ergun, Simona Lup, Jia Jing Liu and Stephen Sosnicki for help with running the experiments and testing the software. This paper has benefited from comments from Kevin McCabe, Mark Olson, Dave Porter, and Stan Reynolds, but all errors are our own. The data are available upon request from the authors.

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Abstract:

In this paper we report experiments that examine how two structural features of electricity networks contribute to the exercise of market power in deregulated markets. The first feature is the distribution of ownership of a given set of generating assets. In the market power treatment, two large firms are allocated baseload and intermediate cost generators such that either firm might unilaterally withhold the capacity of its intermediate cost generators from the market to benefit from the supra-competitive prices that would result from only selling its baseload units. In the converse treatment, ownership of some of the intermediate cost generators is transferred from each of these firms to two other firms, so that no one firm could unilaterally restrict output to spawn supra-competitive prices. The second feature explores how the presence of line constraints in a radial network may segment the market and promote supra-competitive pricing in the isolated market segments. We also consider the interaction effect when both of these structural features are present. Having established a well-controlled data set with price spikes paralleling those observed in the naturally occurring economy, we also extend the design to include demand-side bidding. We find that demand-side bidding completely neutralizes the exercise of market power and eliminates price spikes.

JEL Classifications: L13, L94, C92

Keywords: electric power, deregulation, experimental economics

1. Introduction

The privatization movement in the electricity industry began in Chile and the United Kingdom in the 1980s, and spread to many other countries by the mid 1990s. The U.S. industry has recently joined this trend as California and other states have legislated the introduction of competition in the production of electrical energy. This deregulation, however, has dealt most immediately with the wholesale market, not the prices paid by the end use consumer, whose rates typically are not time variable throughout the day, week and season. This has been the crux of the problem, because wholesale energy costs alone vary from peak to off peak by a factor of six or more on normal summer days of high load demand. Consequently, the local distributor provides a time average cost buffer, which, in effect, subsidizes peak consumption while taxing off-peak consumption. In one of our experimental treatments we relax this artificial constraint by introducing price responsive demand side bidding, which we use to compare with the usual supply side auction mechanism both with and without the presence of market power in generation ownership

Market power was an issue in the United Kingdom from the outset of privatization, which created five independent sources of energy: two private generation companies, the nuclear units retained by the Crown, and import competition on transmission lines connecting the UK grid with France and Scotland. Competition, however, was compromised by three considerations. Capacity on the interconnect lines to Scotland and France was too small to be a competitive factor. Nuclear energy provided only low cost baseload capacity and was not competitive at the short run margin. All load following capacity, which represents the critical marginal generator units, was owned by the two new generator companies created by privatization. Finally, no technical provision was made under privatization to mandate or encourage demand-side bidding implemented by interruptible delivery technologies [Littlechild (1995)].

Earlier papers have reported experimental studies of the effect of transmission constraints on market power [Backerman, Rassenti and Smith (1997), compared the competitivity of three versus six generation companies [Backerman, Denton, Rassenti, and Smith (1996) and Denton, Rassenti and Smith (1997)], or analyzed market power arising from either small numbers or transmission constraints [Zimmerman et al., (1999)]. These studies used spot market auctions with demand-side bidding. Wolfram (1999) evaluates the applicability of various oligopoly models that have been applied to electricity markets. She finds that Cournot behavior [see e.g., Cardell et al (1997) and Borenstein and Bushnell (1999)] and supply function equilibrium [see e.g., Green and Newbery

(1992)] predict prices that are greater than what she finds by measuring price-cost markups in several ways. In a controlled laboratory setting we can design the environment so that we know exactly the range of prices that can be supported as competitive or non-cooperative equilibria. In some cases the prices we observe are not as high as Pareto-superior noncooperative equilbria would predict, and in others they are greater. Unlike field studies, the advantage of the laboratory experiment is that we can analyze the offer curves under different treatments, not just the price-cost margin. Although offer schedules are available for study in some field environments, in none can the effect of controlled treatments, such as demand-side bidding, be assessed. Furthermore, we can exert exact control over the factors that influence demand.

In this paper we measure the effect of market power in a demand cycle in which the number of generators is held fixed, but the distribution of their ownership is altered in controlled comparisons that are designed to allow market power to be expressed. We also evaluate the effect of transmission constraints on market power. Finally, we measure and analyze the effect on market prices of introducing demand-side bidding with and without the presence of market power, and in the absence of transmission constraints.

The paper is organized as follows. Section 2 defines market power in a sealed bid-offer market and outlines our market structure and design for the experiment. Section 3 discusses the procedures of our experiment, and Section 4 presents the results. Having established a well-controlled data set with price spikes paralleling those observed in the naturally occurring economy, we then in Section 6 extend the design to include demand-side bidding. Section 6 summarizes the implications for public policy and offers directions for future work.

2. Market Structure and Design

We examine a very simple environment, relative to actual electric power systems: (1) a three-node radial network[1] (in line, so that power from any source flows on a single path to any sink); (2) transmission losses are negligible; (3) generators have no sunk or avoidable fixed costs, no minimum capacities, and no maximum ramp (acceleration) rates; (4) buyers (wholesalers) incur no avoidable (penalty) costs from failing to serve all of their "must serve" demand; and (5) security reserves to protect demand from outages are ignored. Other simplifications, relative to traditions that are

[1] However, there are many power systems that are essentially radial; e.g. Australia, New Zealand, and the U.K. The latter is similar to the network we study here, with London as the main demand center to which power is transmitted from large supply sources to the North and a smaller source to the South.

common in experimental studies, but that are characteristic of observed power systems, include: (a) no demand-side bidding, and (b) the trading institution is a one-price sealed-bid auction. The earlier papers cited above are not restricted to the simplifications (2) – (4), while Olson, Rassenti, Smith, and Rigdon (1999) study a 9-node regional grid in the United States based on industrial parameters that are constrained by none of the conditions (1) – (5) and (a) – (b).

In Section 6 we relax condition (a) by introducing human agents as wholesale buyers who, symmetrically with generator owners, submit sealed bid schedules for the purchase of energy to deliver to their customers.

2.1 Unilateral Market Power

A firm is conventionally said to have market power when it can set a price greater than the marginal cost and still make positive sales. In the context of 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. If firms compete by posting prices, then market power exists when the competitive price cannot be supported as a pure strategy Nash equilibrium. In a deregulated world for electricity, firms will be submitting offer schedules as opposed to single price-quantity offers as means of expressing willingness to supply electricity. With a fixed set of generating capacities, a corresponding definition of market power can be applied to a market where firms submit offer schedules. If, for a given distribution of ownership of capacity, a firm *profitably* and *unilaterally* can submit an offer schedule above its marginal costs (or equivalently withdraw some generating capacity) such that the market price rises above the competitive level, then a firm is said to be able to exert market power in a sealed bid-offer market.

Consider figure 1 as an illustration of how market power can be represented in electricity markets where firms submit offer schedules to a central spot market coordinator, who dispatches injections to maximize the gains from exchange, given demand. Tables 1 and 2 list the marginal costs and values, respectively, for the arrays depicted in figure 1. We follow (a) from above in assuming that the buyers perfectly reveal their willingness to pay. In our three node radial network there are five firms (or sellers), denoted by an "S" and an identification number. In what we will call the "power treatment," *S1* and *S2* each own four units of intermediate cost (Type *C*) generation capacity and four units of low cost (Type *A*) baseload capacity at opposite ends of the network. *S3* owns two units of intermediate (Type *C*) capacity and three units of high cost generation peak (2 Type *D* and 1

Type *E*) capacity at the center node. The final two sellers, *S4* and *S5* each have two units of baseload (Type *B*) capacity and two units of peak capacity and are also located at opposite ends of the network.

The second and third steps of the demand in Table 2 represent interruptible units of demand, whereas the units on the first step at 226 are “must serve” or inelastic units. Think of the interruptible demand steps of each wholesale buyer as being implemented by contracts with their customers allowing energy flow to be interrupted if the wholesale price rises to the level of the step or greater. We implement the demand steps in Table 2 by means of a fully demand revealing robot at each of the three demand nodes. In Section 6, however, we implement demand-side bidding by replacing each robot with an active human subject buyer who is profit motivated. In this final set of treatments, buyers (as well as sellers) are free to use their discretion to under-reveal true resale demand (or supply) in a two-sided sealed did-offer auction.

Table 1. Marginal Costs of Production

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	

During the shoulder periods, the competitive price is equal to the marginal cost of the intermediate generators. However, both *S1* and *S2* can unilaterally withdraw (not submit offers for) four units of production entirely so that the price rises to the third step of the supply curve (166), where supply is contested by four units of peaking generation capacity. Alternatively, either *S1* or *S2* can increase the offer price for his intermediate capacity so that his offer sets the market price. It is important to note that it requires only one of *S1* or *S2* to undertake this profitable action that reduces his load but benefits all other sellers. Either one of them who does not withhold units will be even better off by not having reduced his sales volume. Unless they tacitly coordinate their offers, each has an incentive to free ride on the increased offer of the other.

At the competitive price of 76, *S1* and *S2* both earn a profit of 224 [(76 – 20) × 4 units]. If *S1* or *S2* raises his offer on his intermediate units to 166, the price-setter’s profit rises to 584 [(166 –

20) × 4 units].[2] 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. Unlike a posted price market in which a unique mixed strategy equilibrium can often be calculated, there are a plethora of equilibria when firms submit sealed supply schedules. Any offer on the intermediate generating units can be supported as an equilibrium up to 166, where Type *D* generators contest any higher price. Moreover, any combination of offers on the baseload units that are less than the marginal offer can also be included in various families of equilibria.[3] However, any equilibrium that has a price of 166 Pareto dominates all others that have prices less than 166.

Table 2. 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

These market power incentives can be eliminated simply by transferring two of *S1*'s and two of *S2*'s intermediate units to *S4* and *S5*. Davis and Holt (1994) employ a related design in their study of market power in posted offer markets. We will call this the "no power" treatment. With this seemingly minor reallocation of capacity at Nodes 1 and 3, not a single seller can increase profit by offering units at supra-competitive levels in the shoulder period and consequently raise the market

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

[3] The Cournot equilibrium involves any combination of *S1* and *S2* outputs such that total output is 18, all baseload capacity is included in the equilibrium, and the price is 166. This concept of organizing behavior can be rejected if *S1*and *S2* offer quantities such that the aggregate quantity exceeds 18.

price above the competitive level.[4] If a single seller raises his offer above 96, that seller will surely not sell his intermediate units of capacity, and furthermore, he will not raise the price for his baseload units. In this case it is not profitable for any seller to deviate unilaterally from the competitive outcome. If two firms, however, tacitly decided to raise the offer on the intermediate capacity, then a supra-competitive price would emerge. However, the competitive price, as an offer on the intermediate capacity, is part of a pure strategy Nash equilibrium.

The Herfindahl-Hirschman Index (HHI) for the *No Power* treatment is 2010, but it only rises to 2200 when *S4* and *S5*'s capacity is reallocated to *S1* and *S2* in the *Power* treatment. This aggregate (and institution-free) measure of market power fails to account for how generating capacity is distributed among the firms along the supply curve, and moreover, is not sensitive to which firms control the marginal units of production. Hence the magnitude of the predicted price effects may differ dramatically from what a 190-point (9.5%) change in the HHI would infer, considering that the market is already considered to be concentrated with only five sellers.

Notice that in both the *Power* and *No Power* treatments no firm can exercise market power during peak demands; all unilateral deviations are unprofitable. Even in the *Power* treatment, unilateral increases in offers by *S1* and *S2* to raise the price from the competitive level of 166 to the peak production costs of 186 result in a loss of profit of 360 [$(166 - 76) \times 4$ units] from the intermediate units of production and yield a gain of only 80 [$(186 - 166) \times 4$ units] on the baseload units.

S1 and *S2* can exert some market power during off-peak demands by raising the offers on two units of baseload 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 generating capacity. We included the market power incentives in the off-peak demand so that the subjects in the experiment would earn some profit during the off-peak demand, and as a common control providing some market power incentives across sessions in all treatments.

2.2 Line Constraints and Market Segmentation

Our second treatment, using a structural feature that also introduces market power into an electricity network, is a capacity constraint on the right transmission line. In the "no line constraint"

[4] It should be noted that a seller can submit any offer up to 96 for a Type *C* generators and hence set the price above the marginal cost of 76, but this action does not reduce efficiency. All of the gains from trade are still realized with this

treatment, the maximum capacity of the transmission lines was set at seven units so as not to be close to a binding constraint for any level of demand for the market structure in figure 1. During off-peak periods, at most 4 units would travel across the left and right transmission lines, and for the shoulder demand, 6 units need to flow from the wings of the network to Node 2. (In both cases half of that power could originate from each wing of the network.) For peak demand periods, 3 units would flow from Node 1 into Node 2 and 4 units from Node 3 to Node 2.[5]

Panels (a) and (b) in figure 2 depict how imposing a line constraint of three units on the right transmission line partially segments the network in figure 1. During the peak demand four units of intermediate generating capacity will flow to Node 2 on an unconstrained line. The line constraint, however, bifurcates the network into two separate markets, with different clearing prices: The first market includes Nodes 1 and 2 on the left, where excess demand of three units in the local market is satisfied by the importation of three units on the constrained line from Node 3. This constrained competition from lower cost units at Node 3 drives up the pooled price at Nodes 1 and 2 to the local unit supply cost, 186. In the second market, Node 3, the local supply price is 76 based on four intermediate cost units. (The Node 3 market, however, does not clear at 76 because either *S2* or *S5* can unilaterally and profitably raise their offer to 166, where the price is contested by local peaking units. Hence, the constraint alone grants local market power to *S2* and *S5* to set the local price at 166, the unconstrained competitive equilibrium.) The congestion rent that traditional optimization theory implies should be allocated to the right side line, 186 – 76 = 110, assumes full local competition, but such an allocation is not sustainable as an equilibrium. What is sustainable as an equilibrium is a congestion rent in the amount, 186 – 166 = 20. Thus, does the constraint allow local generators with market power at Node 3 to capture most of the "competitive line congestion rent."

The line constraint also affects the offering behavior with the shoulder demand in both the *No Power* and *Power* designs. Notice in figure 1 that without a line constraint, there are two units of excess capacity beyond the two units of interruptible demand valued at 96. However, panel (c) in figure 2 illustrates that with a line constraint, given that three units flows from Node 3 to Nodes 1 & 2, the Node 1 and 2 market only has *one* unit of excess capacity beyond the *one* unit of demand valued at 96. This provides *S1* with an additional incentive to raise his offers because only two units

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deviation from the strict Bertrandesqe competitive equilibrium.

[5] Price differences due to small line losses were considered insignificant relative to the treatment effects; hence, they were ignored in the experiments reported here. Line losses can be significant (15% or higher) on long lines. Backerman, Rassenti, and Smith (1997) study a high loss radial network with and without a constraint on one of two lines.

(as opposed to four units when there is no line constraint) are left out of the market when he exercises market power. More importantly, the line constraint interacts with the *No Power* design so that every seller except *S3* has an incentive to offer intermediate capacity at a price greater than its marginal cost.

2.3 Experimental Design and Hypotheses

Table 3 summarizes our 2×2 experimental design. We conclude section 2 with a summary of the hypotheses, stating our treatment effects in Table 4. We will analyze the data using a mixed-effects model for repeated measures [see e.g., Longford (1993)]. The results from estimating this model by level of demand are given in Table 5. The dependent variable is the difference between the observed price and the competitive price, P^c. The line constraint segments the network into two local, but connected markets so that separate prices may clear the market on either side of the constraint. When assessing the impact of the line constraint, we focus on the comparing the prices at Nodes 1 and 2. The treatment effects (*Power* vs. *No Power*, and *Line Constraint* vs. *No Line Constraint*) and an interaction effect from the 2×2 design are modeled as (zero-one) fixed effects, whereas the sessions are modeled as random effects, e_i. Specifically we will estimate the model

$$Price_{ij} - P^c = \mu + e_i + \beta_1 Power_i + \beta_2 LineConstraint_i + \beta_3 Power_i \times LineConstraint_i + \varepsilon_{ij},$$

where the sessions are indexed by i and the repeated market days by j. Note the distinction we maintain between a priori predicted one-tailed tests (e.g., $\beta_1 > 0$ for shoulder periods), and two-tailed tests (e.g., $\beta_1 \neq 0$, for peak periods).

Table 3. 2×2 Experimental Design

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

	No Line Constraint	***Line Constraint***	Total
No Power	(4; 14; 56)	(4; 14; 56)	(8; 28; 112)
Power	(4; 14; 56)	(4; 14; 56)	(8; 28; 112)
Total	(8; 28; 112)	(8; 28; 112)	(16; 56; 224)

Table 4. Hypotheses of Treatment Effects by Level of Demand

Level of Demand	*Power Treatment*	*Line Constraint Treatment*	*Interaction Effect*
Shoulder	$H_0: \beta_1 = 0$ $H_a: \beta_1 > 0$	$H_0: \beta_2 = 0$ $H_a: \beta_2 > 0$	$H_0: \beta_3 = 0$ $H_a: \beta_3 < 0$
Peak	$H_0: \beta_1 = 0$ $H_a: \beta_1 \neq 0$	$H_0: \beta_2 = 0$ $H_a: \beta_2 > 0$	$H_0: \beta_3 = 0$ $H_a: \beta_3 \neq 0$
Off-peak	$H_0: \beta_1 = 0$ $H_a: \beta_1 \neq 0$	$H_0: \beta_2 = 0$ $H_a: \beta_2 \neq 0$	$H_0: \beta_3 = 0$ $H_a: \beta_3 \neq 0$

3. Procedures

To test how these two different structural features of electricity markets contribute singly and in tandem to the exercise of market power, we conducted sixteen market experiments using students from the Business College 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.

We provided the subjects in each market with complete and full information on the market supply structure; i.e., every firm's generating capacity, marginal costs of production, and the position in the network were public information. Information on demand, however, was not given to the subjects. Because our primary interest is in firm behavior and the ability to exercise market power when demand is controlled, the computer acted as robot buyer submitting bids that exactly revealed the demand.

The subjects were told that the costs and the generating 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, with 'Medium Demand' indicating a willingness to buy more units at higher prices, and with '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. Thus, for each day we have two shoulder period observations on the treatment effect of allocating intermediate capacity to generate the *Power* and *No Power* treatments.

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 produce.[6] A subject could at any time within the one minute revise his offer. When the clock expired, the offers and the computerized bids were 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 uniform nodal prices that maximize surplus, taking into account minor losses in transmission and any line constraints. Tied offers (at the same node) were broken on a first-submitted, first-served basis.

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 session was $17.00.

4. Results

Figure 3 illustrates the average price paths at Nodes 1 and 2 for the four sessions in each cell of the 2×2 experimental design. 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.[7] Given that the buyers are simulated with a fully revealing robot, we expect ex ante that the sellers will push up their offers to the nearest unit of interruptible demand. These prices, however, are still 100% efficient.

[6] 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.
[7] For brevity, the results are presented exclusively in terms of price outcomes. Results for efficiency parallel our price observations.

From the figure, it is apparent that the *Power* condition affects performance markedly. For sessions conducted under the baseline *No Power*/*No Line Constraint* treatment, the mean price path in the shoulder periods tends to hover within the efficient price range without much variance. Higher and much more variable prices are observed in sequences conducted under the *Power* treatment. (Data at the session level will also be presented below.) Further evident from the figure is that in the peak periods the line constraint raises prices, regardless of the *Power* and *No Power* treatment. Differences exist in the off-peak period prices even though all 16 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 experimental results are summarized as a series of 5 findings (based primarily upon our prior predictions in Table 2) and 2 comments. In addition to the qualitative results displayed in Figure 3, we employ a mixed-effects model for analyzing data with repeated measures (over 14 market days) as the basis for quantitative support. The results from estimating this model by period type (shoulder 1, peak, shoulder 2, off-peak) are given in Table 5. The sessions are indexed by $i = 1,\ldots,16$ and the days by $j = 1,\ldots,14$. We begin with a consideration of pricing performance in the *No Power*/*No Line Constraint* treatment, which is largely a benchmark calibration result not among our prior predictions.

Finding 1: *Markets in the* No Power/No Line Constraint *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 4 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 5 reports that the prices in the *No Power*/*No Line Constraint* treatment are statistically greater than the strict competitive predictions at marginal cost in figure 1. However, in the shoulder periods, the prices are not significantly different from the value of the last interruptible unit of demand, 96 (For H_0:μ = 20, *p-value* = .4003 in shoulder 1, and *p-value* = .3554 in shoulder 2).■

Recall that if two sellers each restrict output by two units, then the coordinated attempt is profitable in the *No Power* design. Finding 1 indicates that the feature of a single price in the sealed bid-offer institution is apparently quite robust to signaling attempts, unlike posted offer environments where signaling is frequently observed and often successful [see e.g., Davis and Wilson (1999), Wilson (1998), and Cason and Williams (1990)]. For example, pricing in session 2 after the price spike in day five, period one, illustrates the strong drawing power of the competitive outcome in the *No Power* design (see figure 4). In the first shoulder period on day five, *S3* offers his first three units at a price of 190. Having effectively withdrawn his units from the market, the price rises to 127 for that period. *S3* quickly returns to lower offers and on only one other day does the price ever rise substantially above the 100% efficient range.

Consider now the effects of introducing market power. We summarize our results for this treatment.

Finding 2: *Ceteris paribus, the redistribution of the ownership of supply units to introduce market power significantly raises prices in shoulder and off-peak periods. The* Power *treatment has no effect on prices in peak periods, where no market power should be expressed.*

Support: Figures 3 and 4 clearly illustrate that for the shoulder periods market prices in the *Power* design (in red) are greater than in the *No Power* design when the transmission lines are unconstrained. In the first and fourth *Power* sessions, every market price in the shoulder periods is considerably greater than the value of the last interruptible unit. In the second sessions, supra-competitive prices are observed in all shoulder periods after day 3. Prices in the third session are competitive in shoulder periods through day 9, after which time they rise substantially. There is no discernable separation in peak period prices. Off-peak prices are initially much higher in the *Power* treatment, but this difference fades in later days. These qualitative observations are supported by estimates from the mixed-effects model in Table 5. In the shoulder 1 (shoulder 2) periods, the *Power* treatment significantly raises prices above the *No Power* level by 42.6 (42.2) experimental dollars [*p-value* = .0003 (.0001)]. The total primary effect of *Power* is to raise the prices above the competitive level by

60.9 = 18.3 + 42.6 (60.0 = 17.8 + 42.2) experimental dollars. The prices in peak periods are not significantly greater in the *Power* treatment (*p-value* = .7660). In the off-peak period, prices are 30.4 experimental dollars greater than the *No Power* baseline (*p-value* = .0070).■

The ability to exercise market power unilaterally is less apparent to the sellers in the third *Power* session, in which for nine days, the price is well within the 100% efficient range. In period three of day nine S2 drastically cuts back his output causing the price to spike to 178. After a couple more periods of low prices, the price shoots back up again in day eleven and continues to erode until the session ended. Even though this is a uniform price market, we conjecture that the price variability in the *Power* sessions can be attributed to a lack of a pure strategy Nash equilibrium at the competitive price [see Davis and Holt (1994), Davis and Wilson (1999), Kruse et al. (1994), and Wilson (1998) for examples of posted-offer markets in which Edgeworth price cycles were observed in unilateral market power environments].

While it is individually profitable for either *S1* or *S2* to manipulate the market price, the resulting supra-competitive price also benefits all of the remaining sellers in a uniform price market. In particular, the other large seller benefits the most by continuing to sell his units at the higher prices.

Our third finding reports that all sellers inflate their entire offer curves even though it is only the marginal offer that affects the price.

Finding 3: *When unilateral market power exists, the revealed surplus drops considerably as all sellers submit less aggressive offer schedules for all of their units, including baseload capacity.*

Support: Figure 5 provides the support pertinent to this finding. This figure displays the average market offer curves for the *Power* and *No Power* treatments (without any line constraints). The k^{th} step of the average market offer curves is the average offer for the k^{th} step across all shoulder periods and all sessions in the treatment. Hence, there are total of 112 observations (14 days × 2 shoulder periods per day × 4 sessions) included in the average at each step. Two standard deviations in either direction of the average are also displayed in the figure. Notice that the *Power* offer curves are significantly greater for every step of the curve. The *Power* sessions reveal only 67.6% of the total available surplus as compared to 91.1% in the *No Power* treatment. ■

The *No Power* sessions exhibit to a small degree the well-known tendency to under-reveal in sealed bid-offer environments, but the *Power* treatment, as expected, induces even more under-revelation. Two other observations are worth noting on the difference in the offer curves. First, the competition of the *No Power* treatment induces sellers to submit offer curves for the first two units of intermediate capacity that are *less* than the cost of intermediate capacity. *S3*, who is in a tough position, often offers below cost as an aversion to being excluded from the final market allocation during shoulder periods. Second, the variance about the *No Power* offers for the 15th through 18th units is noticeably smaller than on the other units, particularly the first two extra-marginal units. In contrast, the variance of the 15th through 18th units in the *Power* treatment increases as the mean offer rises. Without market power, we can conclude that the sellers are quite competitive with a small variance in their offers.

Not only do *S1* and *S2* increase their offers on their baseload units in addition to exercising market power on the intermediate units, but more noteworthy is the observation that *S3*, *S4*, and *S5* inflate their offers as well. This comes at a substantial risk, considering that if *S1* or *S2* would undercut either *S4* or *S5*, valuable baseload units might be left out of the market entirely. Such sympathetic increases in offers (also bids), that have minor if any effects on efficiency, have been documented in real time uniform price auctions [see McCabe, Rassenti, and Smith (1993), pp. 307-332].

We turn our attention to the line constraint treatment, which we summarize as our fourth finding.

Finding 4: *Ceteris paribus, the* Line Constraint *treatment significantly raises prices in all types of demand- shoulder, peak, and off-peak.*

Support: Figure 6 sharply contrasts the price effects of constraining the right transmission line to a maximum capacity of 3 units. In peak periods the line constraint shifts prices above 186, the highest cost generators. There are only 3 instances out of 56 peak periods in which the price level is at or below 186. In shoulder periods, the price only falls to 96 on two occasions; all other prices are much greater than the competitive level. As with the *Power* treatment, off-peak prices are initially much higher even though the constraint is no longer binding during those periods, but this difference wanes in later days. Table 5 reports that the line constraint increases prices in peak periods by 19.4

experimental dollars (*p-value* = .0005), by 55.4 and 61.0 experimental dollars in shoulder periods (*p-values* = .0001 and .0000), and by 40.4 in the off-peak periods (*p-value* = .0010).■

Segmenting the market during the shoulder demand by restricting inflow by one unit (3 units maximum versus 4 units in the unconstrained design) has a dramatic impact on prices in the *No Power* design. Recall that with the line constraint, *S1*, *S4*, and either *S2* or *S5* can unilaterally raise the offer on intermediate units and this may explain why the *No Power/Line Constraint* prices are so volatile. Raising the marginal offer is unilaterally profitable for all but *S3*, but each seller does not want to be the sole price-setter when four different sellers can do so. Hence, the different sellers have different assessments for weighing the likelihood of setting the price and not selling the units versus not setting the price and selling the units (but holding it above the competitive level in case they are the price-setter). This results in a high variance in the market price over time.

Our findings of market power and supra-competitive prices in the shoulder and peak periods have an unpredicted effect on prices in the off-peak periods. We summarize this as the following comment.

Comment 1: *A history of market power, either by the transfer of ownership or by line constraints or both, foments less competitive supply behavior and concomitant higher prices in off-peak periods.*

Support: Findings 2 and 4 and Table 5 provide the qualitative support that there is a treatment effect of higher prices in the off-peak periods even though the market structure and demand are identical in all 16 sessions. Figure 7 displays the average offer curves for the 4 cells of this experimental design. For ease of illustration the $\pm 2\sigma$ (2 standard deviation) bands are included only for the *No Power*/*No Line Constraint* case. However, none of the unplotted lower bands of the other treatments ever overlap with the $+2\sigma$ band of the *No Power*/*No Line Constraint* sessions. We postulate that the history of less aggressive pricing in the other periods has a hysteresis effect in the off-peak periods such that the offers are much less aggressive. Likewise, a history of aggressive pricing in other periods carries over into the off-peak period. Notice that the mean offers on the first two units of the *No Power/No Line Constraint* sessions are less than marginal cost. Nearly all of the surplus, 98.1%, is revealed in the *No Power/No Line Constraint* sessions, which stands in contrast to the 82.8%, 81.7%, 79.9% that is revealed in the other sessions.■

Lastly we consider the interaction effect when both structural features are present in the network.

Table 5. Estimates of the Linear Mixed-Effects Model of Treatment Effects

$$Price_{ij} - P^c = \mu + e_i + \beta_1 Power_i + \beta_2 LineConstraint_i + \beta_3 Power_i \times LineConstraint_i + \varepsilon_{ij},$$

where $e_i \sim N(0,\sigma_1^2)$, $\varepsilon_{ij} = \rho\varepsilon_{ij-1} + u_{ij}$, and $u_{ij} \sim N(0,\sigma_2^2)$.

	Estimate	Std. Error	Degrees of Freedom	*t*-statistic	*p-value*	H_a
Shoulder 1						
μ	18.3	6.58	208	2.78	.0059	$\mu \neq 0$
Power	42.6	9.31	12	4.57	.0003	$\beta_1 > 0$
Line Constraint	55.4	9.31	12	5.95	.0001	$\beta_2 > 0$
Power × Line Constraint	-33.9	13.16	12	-2.57	.0121	$\beta_3 < 0$
ρ	.508		LR statistic	39.6	.0000	$\rho \neq 0$
Peak						
μ	12.2	3.13	208	3.89	.0001	$\mu \neq 0$
Power	-1.3	4.42	12	-0.30	.7660	$\beta_1 \neq 0$
Line Constraint	19.4	4.42	12	4.38	.0005	$\beta_2 > 0$
Power × Line Constraint	-0.2	6.25	12	-0.04	.9692	$\beta_3 \neq 0$
ρ	.275		LR statistic	10.5	.0012	$\rho \neq 0$
Shoulder 2						
μ	17.8	5.76	208	3.09	.0022	$\mu \neq 0$
Power	42.2	8.15	12	5.17	.0001	$\beta_1 > 0$
Line Constraint	61.0	8.15	12	7.49	.0000	$\beta_2 > 0$
Power × Line Constraint	-37.6	11.52	12	-3.26	.0034	$\beta_3 < 0$
ρ	.446		LR statistic	31.9	.0000	$\rho \neq 0$
Off-peak						
μ	17.4	6.61	208	2.63	.0093	$\mu \neq 0$
Power	30.4	9.35	12	3.25	.0070	$\beta_1 \neq 0$
Line Constraint	40.4	9.35	12	4.33	.0010	$\beta_2 \neq 0$
Power × Line Constraint	-31.6	13.22	12	-2.39	.0340	$\beta_3 \neq 0$
ρ	.742		LR statistic	106.7	.0000	$\rho \neq 0$

Note: The linear mixed-effects model is fit by maximum likelihood with 224 original observations on 16 groups. The results do not differ in any meaningful way if the model is estimated with autocorrelated errors by session, a random effect for a deterministic time trend, or session-wise heteroskedastic errors. For brevity, the session random effects are not included in the table.

Finding 5: *The* Power *and* Line Constraint *treatments have a statistically significant interaction effect in the shoulder and off-peak periods such that* Power *plus* Line Constraint *treatment is subadditive. In peak periods, the interaction effect is insignificant.*

Support: For this finding we rely on the estimates in Table 5 to isolate the interaction effects of the *Power* and *Line Constraint* treatments. Table 5 shows that the interaction effect (*Power* $\times$ *Line Constraint*) is statistically significant in the shoulder and off-peak periods. In shoulder 1 periods, prices are 64.1 (42.6 + 55.4 – 33.9) experimental dollars higher than in the *No Power/No Line Constraint* baseline treatment, and a similar result holds for shoulder 2 periods. The interaction treatment in off-peak periods raises prices by 39.2 (30.4 + 40.4 – 31.6) experimental dollars. There is no significant interaction effect in the peak periods (*p-value* = .9692), where either treatment by itself is enough to boost prices the short distance to the highest interruptible demand step. ■

Finally we comment on the offer revelation in the peak demand periods.

Comment 2: *The* Power *and* Line Constraint *treatments decrease revelation for peak demand.*

Support: Figure 8 depicts the average market curves for peak demand. Again, for ease of illustration the $\pm 2\sigma$ bands are included only for the *No Power/No Line Constraint* case. As with Comment 1, *No Power/No Line Constraint* sessions clearly reveal the most surplus, 78.9% versus 52.5%, 56.6%, and 46.2%. For the 3rd through 17th units of the offer curve, the -2σ band of the *Power/No Line Constraint* sessions (in red) is strictly greater than the $+2\sigma$ band of the *No Power/No Line Constraint* sessions (in blue). Similarly, for the 13th through 21st units the -2σ band for the *No Power/Line Constraint* sessions (in green) is strictly greater than the $+2\sigma$ band without the line constraint (in blue). When both treatments are present (the *Power/Line constraint* sessions in orange), the -2σ band of the offer curve is *always* greater than the $+2\sigma$ band of the *No Power/No Line Constraint* sessions.■

Under the conditions of no demand-side bidding, our results indicate that the *distribution* of ownership of a given set of generating assets can markedly contribute to the exercise of market power by well-positioned generator owners in supply side auctions in which demand is fully revealed and not subject to strategic bid behavior—only generators can behave strategically, and they do so to the disadvantage of buyers. In addition, small changes in line capacity can affect prices individually and interact with the distribution of ownership to introduce market power and spawn supra-competitive prices.

5. Demand-Side Bidding

In this Section we reexamine the above conclusions by introducing demand-side bidding in a symmetric two-sided auction institutional environment by replacing the robotically revealed expression of demand by profit motivated human subjects who have the discretionary option of under-revealing their demand, just as in the markets analyzed above sellers were free to under-reveal supply. We note that in our parameterization of demand no more than 16 percent of peak demand can be interrupted voluntarily by the wholesale buyers.

We know from previous studies that two-sided markets in electricity can be very competitive,[8] but what has been missing is a rigorously controlled test explicitly examining the effect of introducing demand-side bidding, while holding constant all other conditions in the market. We hypothesize that demand-side bidding will have three primary effects on the results reported above for the one-sided market in which only the supply side is active: Prices will be lower and more competitive under both the market "power "and "no power" treatment conditions, and price volatility, as represented by the high incidence of price spikes in Figures 4 and 6, will be substantially eliminated.

To see why we expect these dramatic effects from demand-side bidding we refer to Figure 9 showing the anatomy of a price spike. Figure 9 illustrates the market offer curves for the two Day 2 shoulder periods of Power 4 session. In the first shoulder period, the market price is 100 with *S1* offering 3 units at each of the prices 99 and 100 and one unit at each of the prices 110 and 120. In the next shoulder period, *S1* offers 4 units at 99 and 4 units 150, with the last offer clearly setting the price. Without demand-side bidding, *S1*'s offer results in a 50% increase in the price.

5.1 Demand -Side Experimental Design

Table 6 shows our extended 2 × 2 experimental design in which market power is varied between two of the same conditions shown in Table 3, but this is now crossed with *No Demand-side Bidding* versus *Demand-side Bidding*. We incorporate active demand-side bidding into the market by giving 4 human bidders most of the demand given in Table 2. The remaining demand assigned to the robot bidder is fully revealed in every period. The distribution of values for the demand-side bidding sessions is given in Table 7.

[8] See Backerman et al. (1997), Denton et al. (1997), and Olson et al. (1999).

Table 6. Extended 2 × 2 Experimental Design
(No. of Sessions; No. of Trading Days; No. of Trading Periods)

	No Demand-side Bidding	***Demand-side Bidding***	Total
No Power	(4; 14; 56)	(4; 14; 56)	(8; 28; 112)
Power	(4; 14; 56)	(4; 14; 56)	(8; 28; 112)
Total	(8; 28; 112)	(8; 28; 112)	(16; 56; 224)

Table 7. Distribution of Demand Values with Demand-side Bidding

	Step 1 Value = 226		Step 2 Value = 206		Step 3 Value = 96	
	Robot Quantity	Human Quantity	Robot Quantity	Human Quantity	Robot Quantity	Human Quantity
Node 1						
Off-peak	1	1 (*B1*)*	0	0	0	1 (*B1*)
Shoulder	3	2 (*B1*)	0	0	0	1 (*B1*)
Peak	4	3 (*B1*)	0	0	0	1 (*B1*)
Node 2						
Off-peak	0	1 (*B2*), 1 (*B3*)	0	1 (*B2*), 1 (*B3*)	0	0
Shoulder	2	2 (*B2*), 2 (*B3*)	0	1 (*B2*), 1 (*B3*)	0	0
Peak	4	2 (*B2*), 2 (*B3*)	0	1 (*B2*), 1 (*B3*)	0	0
Node 3						
Off-peak	1	1 (*B4*)	0	0	0	1 (*B4*)
Shoulder	3	2 (*B4*)	0	0	0	1 (*B4*)
Peak	3	3 (*B4*)	0	0	0	1 (*B4*)

*Bidder identification is listed in parentheses.

5.2. Findings

We present two findings on the effect of demand-side bidding. The qualitative and quantitative support for these findings are presented in Figures 10-12 and Table 8, respectively. Table 8 reports the estimates of the mixed effects model for the design in Table 6. In the interest of brevity we focus our attention exclusively on the shoulder periods.

Finding 6: *In the* No Power *treatment demand-side bidding reduces prices to within the 100% efficient outcome range.*

Support: Recall that without demand-side bidding in Finding 1, sellers push up their offers to capture all of the surplus between the last demand step and the marginal cost in shoulder periods. Figure 10 illustrates that with demand-side bidding, the buyers push back to capture more than half of this surplus in shoulder periods. Table 8 reports that this effect is statistically significant. In the shoulder periods, the *Demand-side Bidding* coefficient indicates that prices are 12.5 and 13.3 experimental dollars lower than in the *No Power* baseline treatment (both *p-values* are 0.0000). ■

Finding 7: *Demand-side bidding utterly neutralizes market power in the* Power *treatment and eliminates the occurrence of price spikes.*

Support: With rather striking contrast, Figure 11 shows that demand-side bidding almost completely counteracts the *Power* treatment. Prices are consistently within the 100% efficient outcome range. Furthermore, the time series of prices with demand-side bidding markedly lacks the volatility of the sessions without demand-side bidding. Figure 12 exemplifies why demand-side bidding eliminates price spikes and disciplines sellers. Notice in contrast to Figure 9, 11 units of capacity, including 1 unit of baseload capacity, would need to be withheld in order to spike the price to 150. By under-revealing, buyers protect themselves against the sellers exerting market power; demand-side bidding makes it too costly for the sellers to restrict output and raise the price.

The striking differences in Figure 11 are statistically significant, as Table 8 shows. The *Power* × *Demand-side Bidding* interaction effect is highly significant in shoulder periods (both *p-values* are 0.0000). Moreover, the point estimate of the interaction effect effectively offsets the *Power* treatment effect (50.4 – 49.8 = 0.6 in shoulder 1 periods and 40.7 – 37.8 = 2.9 in shoulder 2 periods). ■

6. Conclusions

Our results in this paper indicate that the *distribution* of ownership of a given set of generating assets can markedly contribute to the exercise of market power by well-positioned players in deregulated one-sided sealed offer auction markets. In addition, small changes in line capacity can affect prices individually and interact with the distribution of ownership to introduce market power and spawn supra-competitive prices. However, having established this, we also find the introduction of demand-side bidding in a two-sided auction market completely neutralizes the exercise of market power and eliminates price spikes. The obvious policy conclusion is that empowering the wholesale buyers provides a completely decentralized approach to the control of supply-side market power, and the control of price volatility. In the next generation of experiments we will investigate how demand-side bidding interacts with line constraints.

Table 8. Estimates of the Linear Mixed-Effects Model of Treatment Effects

$$Price_{ij} - P^c = \mu + e_i + \beta_1 Power_i + \beta_2 Demand\text{-}sideBidding_i + \beta_3 Power_i \times Demand\text{-}sideBidding_i + \varepsilon$$

where $e_i \sim N(0,\sigma_1^2)$, $\varepsilon_{ij} = \rho\varepsilon_{ij-1} + u_{ij}$, and $u_{ij} \sim N(0,\sigma_2^2)$.

	Estimate	Std. Error	Degrees of Freedom	*t*-statistic	*p-value*
Shoulder 1					
μ	19.09	0.99	144	19.22	0.0000
Power	50.39	2.17	12	23.20	0.0000
Demand-side Bidding	-12.49	1.81	12	-6.91	0.0000
Power × *Demand-side Bidding*	-49.75	2.93	12	-16.97	0.0000
ρ	0.78		LR statistic	52.75	0.0000
Peak					
μ	4.27	4.65	144	0.92	0.3602
Power	-3.97	4.79	12	-0.83	0.4235
Demand-side Bidding	-29.26	14.33	12	-2.04	0.0637
Power × *Demand-side Bidding*	33.05	16.30	12	2.03	0.0655
ρ	0.97		LR statistic	56.68	0.0000
Shoulder 2					
μ	18.93	2.02	144	9.39	0.0000
Power	40.66	3.82	12	10.65	0.0000
Demand-side Bidding	-13.30	2.58	12	-5.16	0.0002
Power × *Demand-side Bidding*	-37.75	4.51	12	-8.38	0.0000
ρ	0.76		LR statistic	43.96	0.0000
Off-peak					
μ	7.01	9.48	144	0.74	0.4608
Power	45.56	13.88	12	3.28	0.0066
Demand-side Bidding	14.07	12.15	12	1.16	0.2694
Power × *Demand-side Bidding*	-45.44	17.67	12	-2.57	0.0245
ρ	0.92		LR statistic	80.12	0.0000

Note: The linear mixed-effects model is fit by maximum likelihood with 160 original observations (last 10 periods) on 16 groups. For purposes of the brevity the session random effects are not included in the table.

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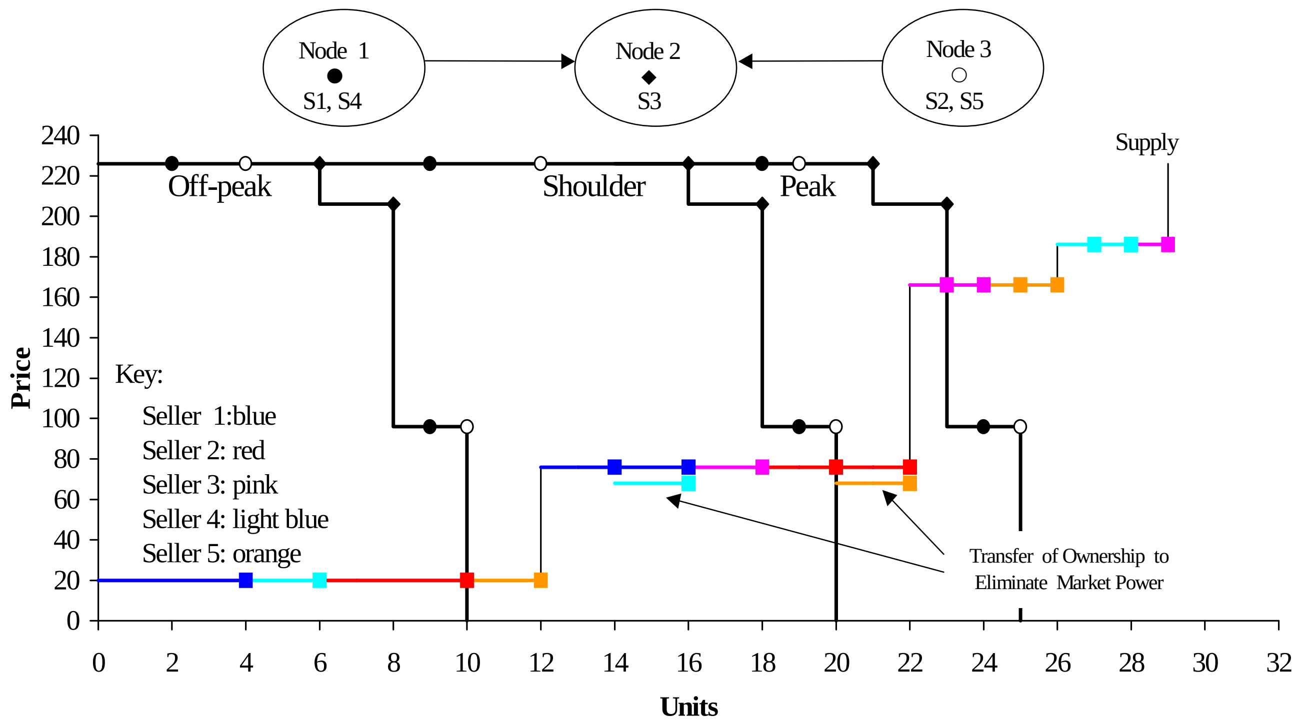
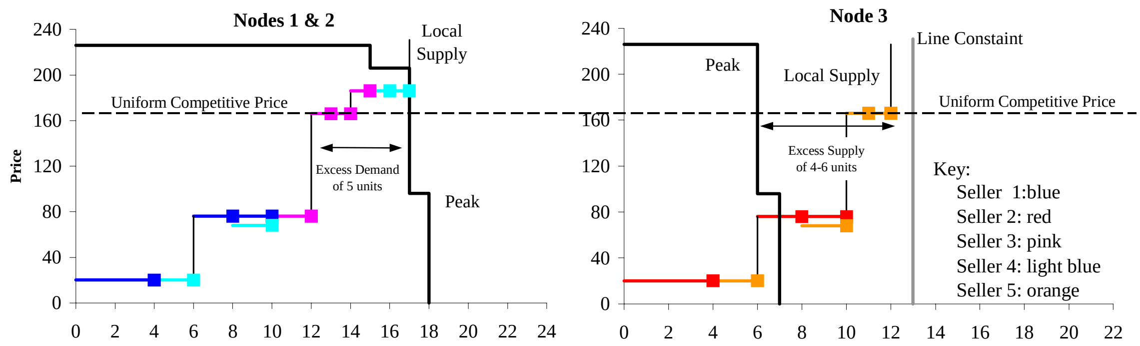
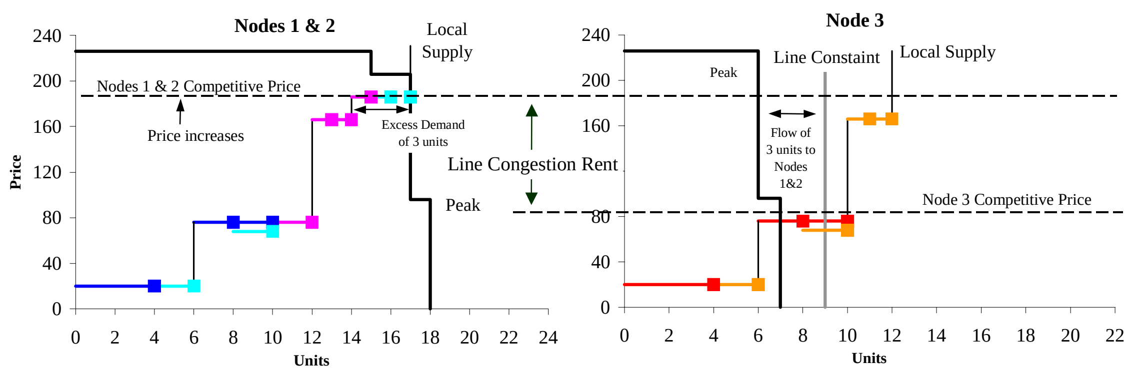


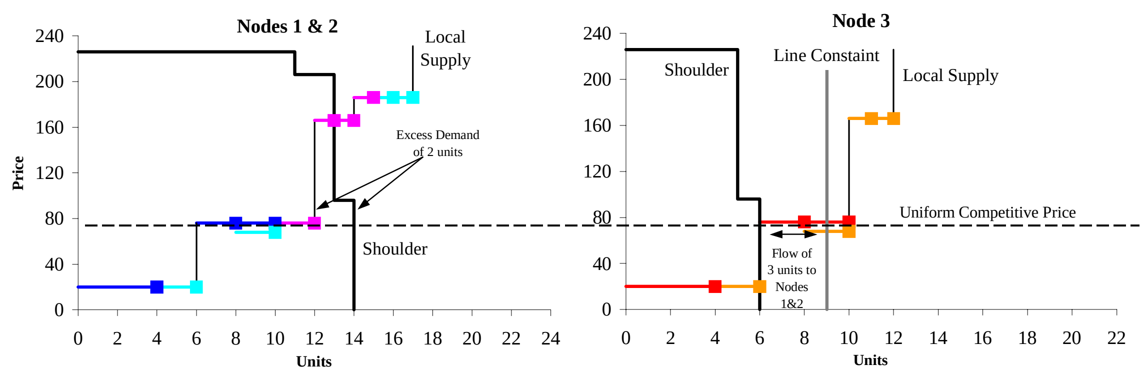
Figure 1. Market Structure and Design



Panel (a): Peak Demand with Nonbinding Line Constraint



Panel (b): Peak Demand with Binding Line Constraint



Panel (c): Shoulder Demand with Binding Line Constraint

Figure 2. Market Segmentation with Constrained Right Transmission Line

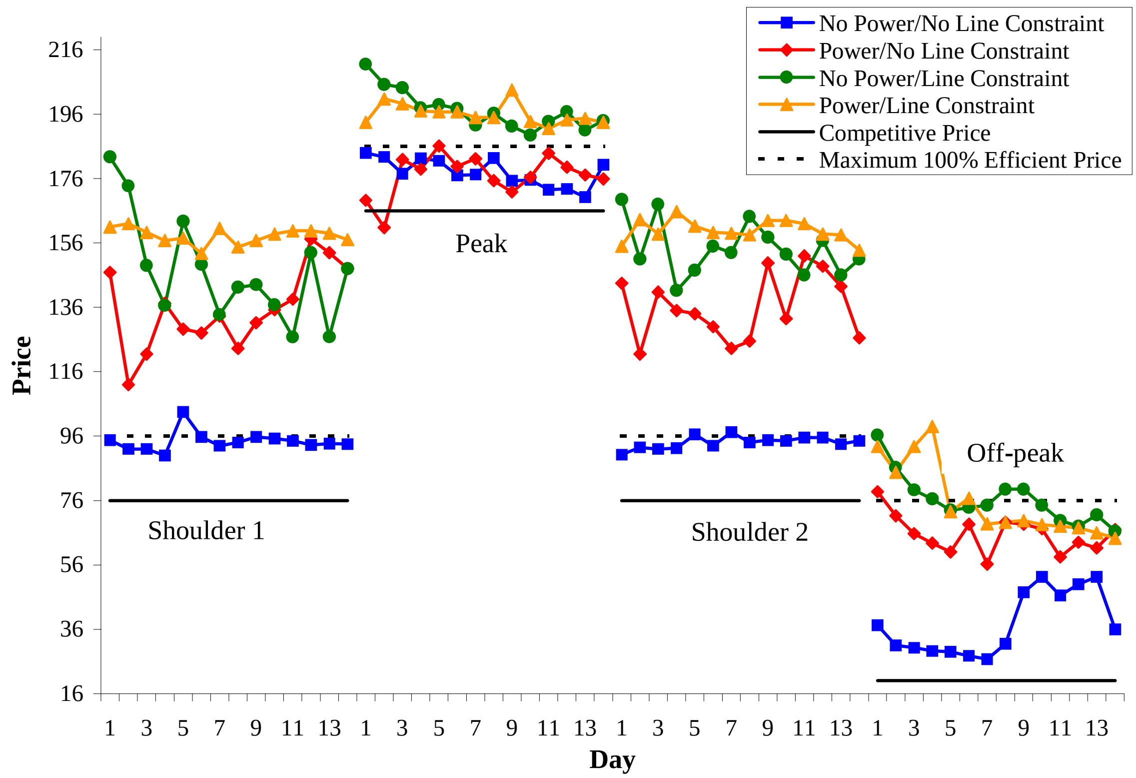


Figure 3. Average Prices at Nodes 1 and 2

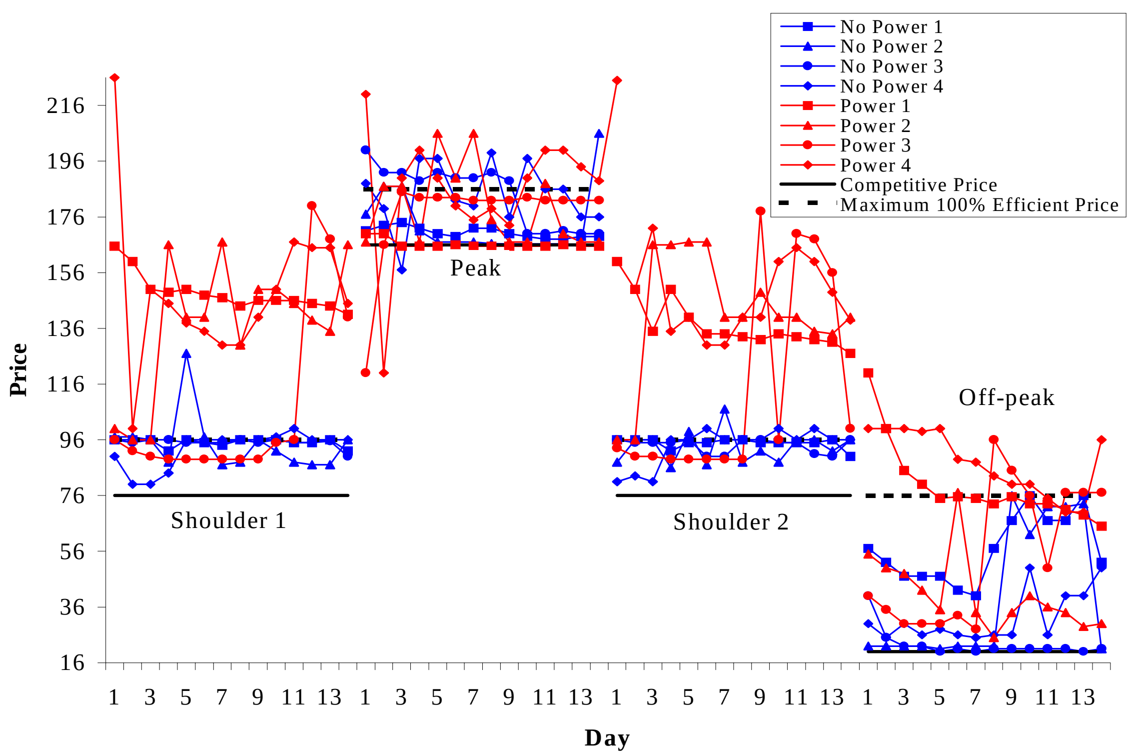


Figure 4. Session Prices in the *Power* and *No Power* Designs with No Line Constraint

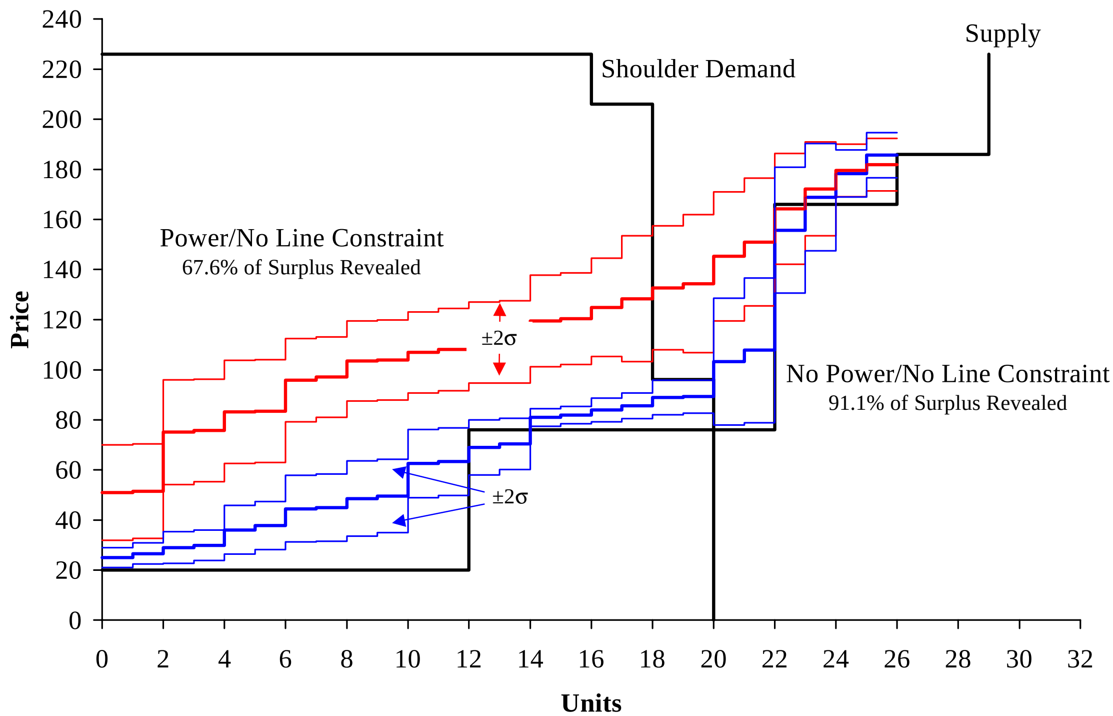


Figure 5. Market Offer Curves for Shoulder Demand

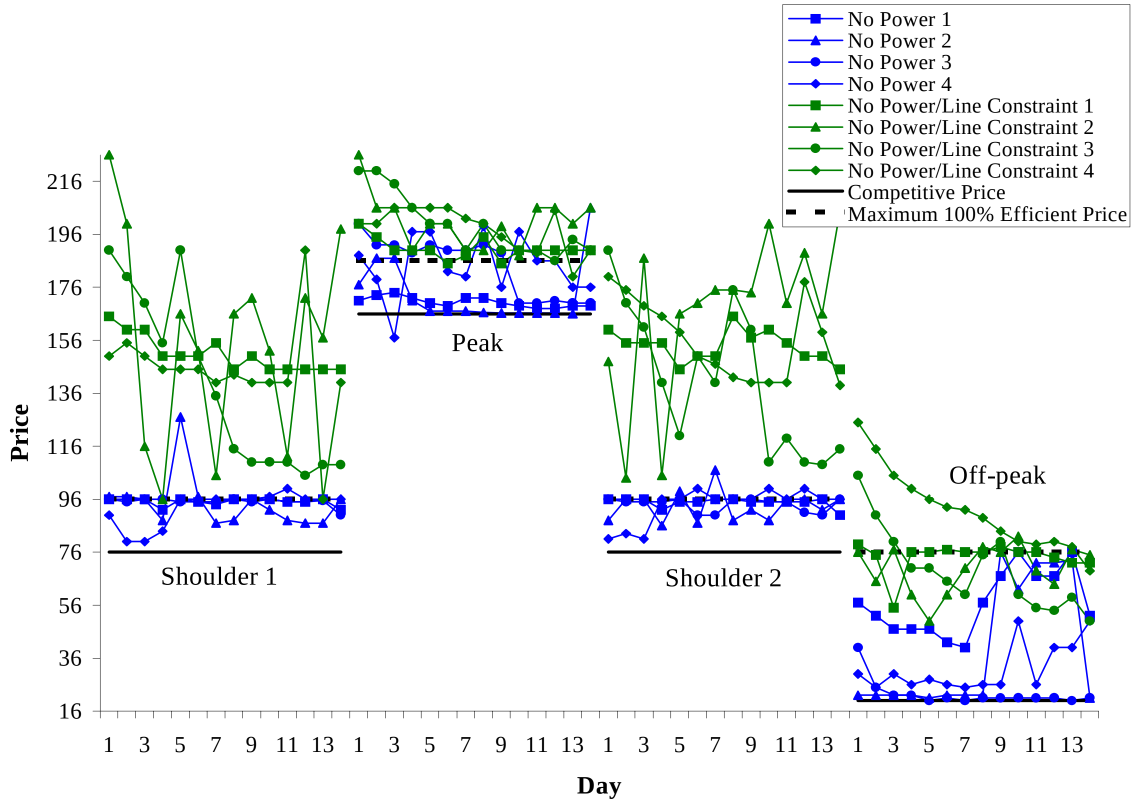


Figure 6. Session Prices With and Without the *Line Constraint* and *No Power*

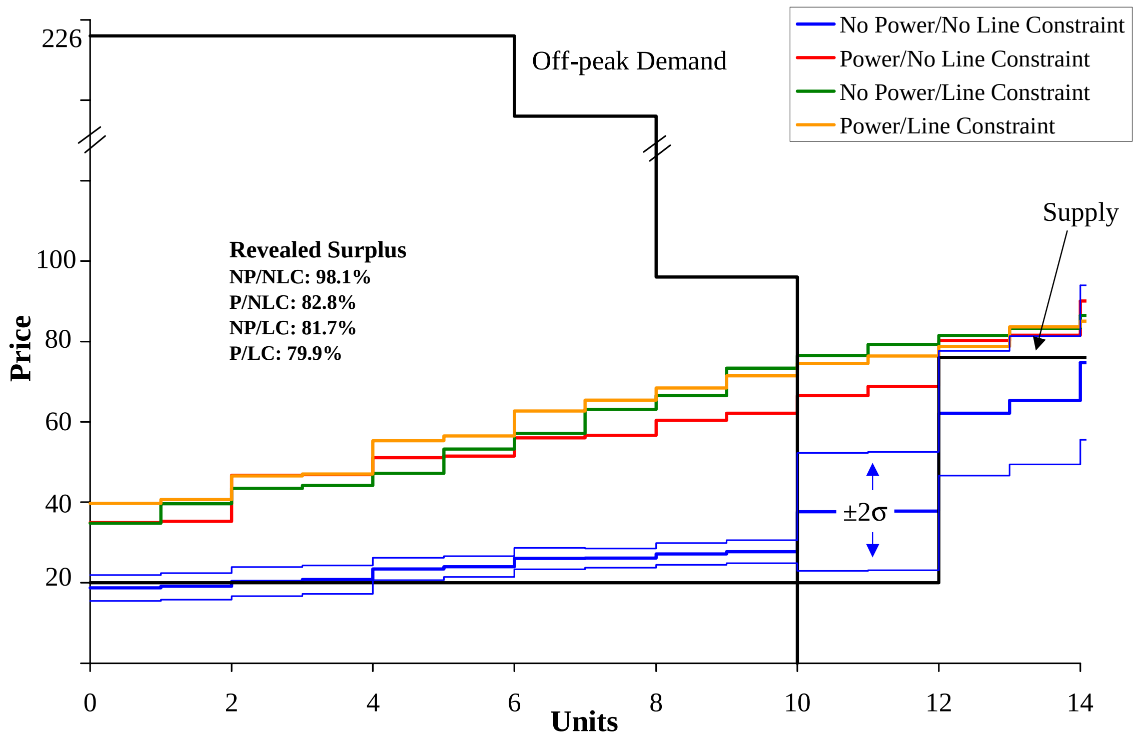


Figure 7. Market Offer Curves for Off-peak Demand

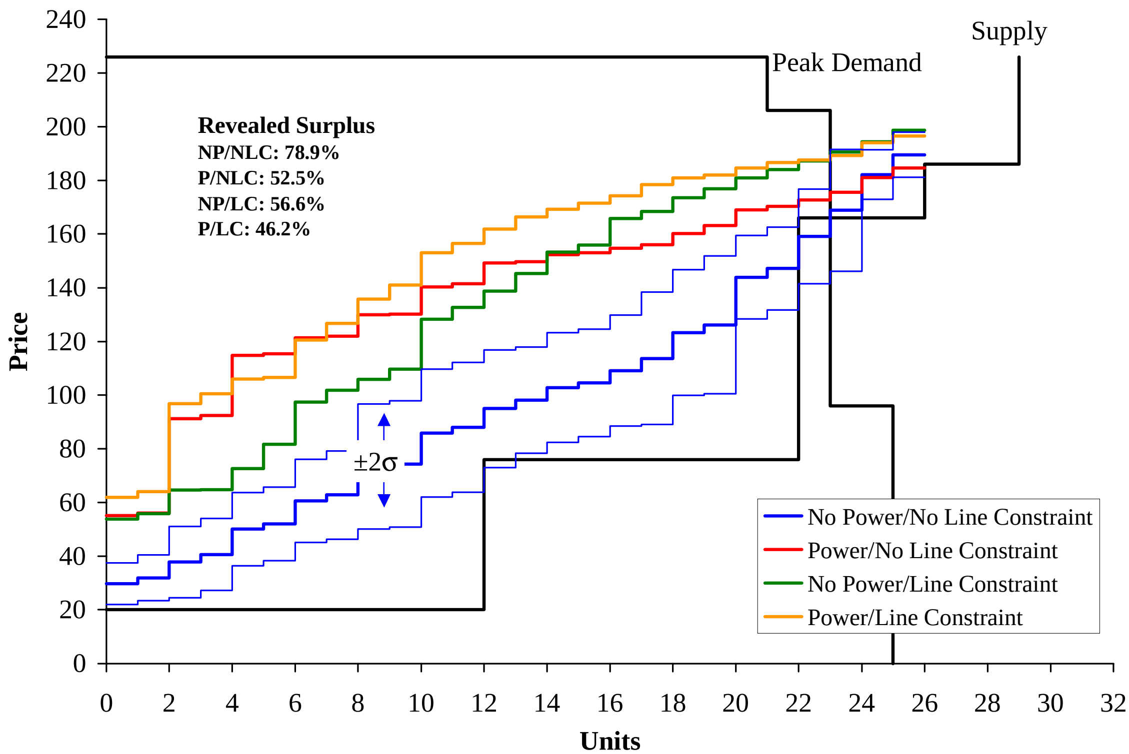


Figure 8. Market Offer Curves for Peak Demand

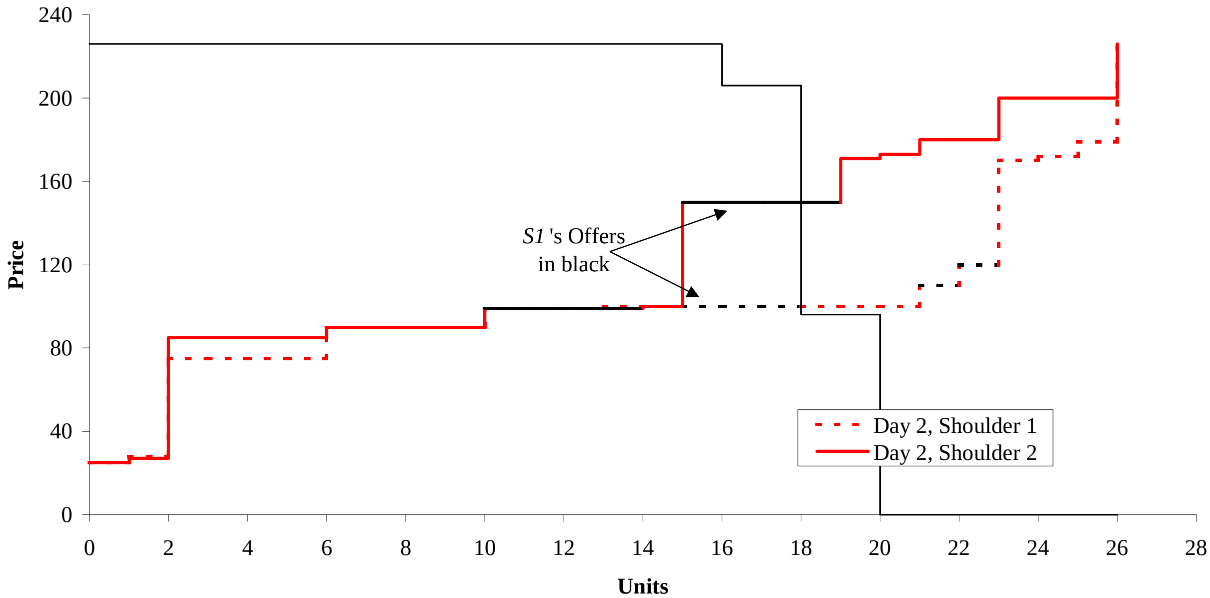


Figure 9. Example of a Price Spike without Demand-side Bidding
(Session: Power 4)

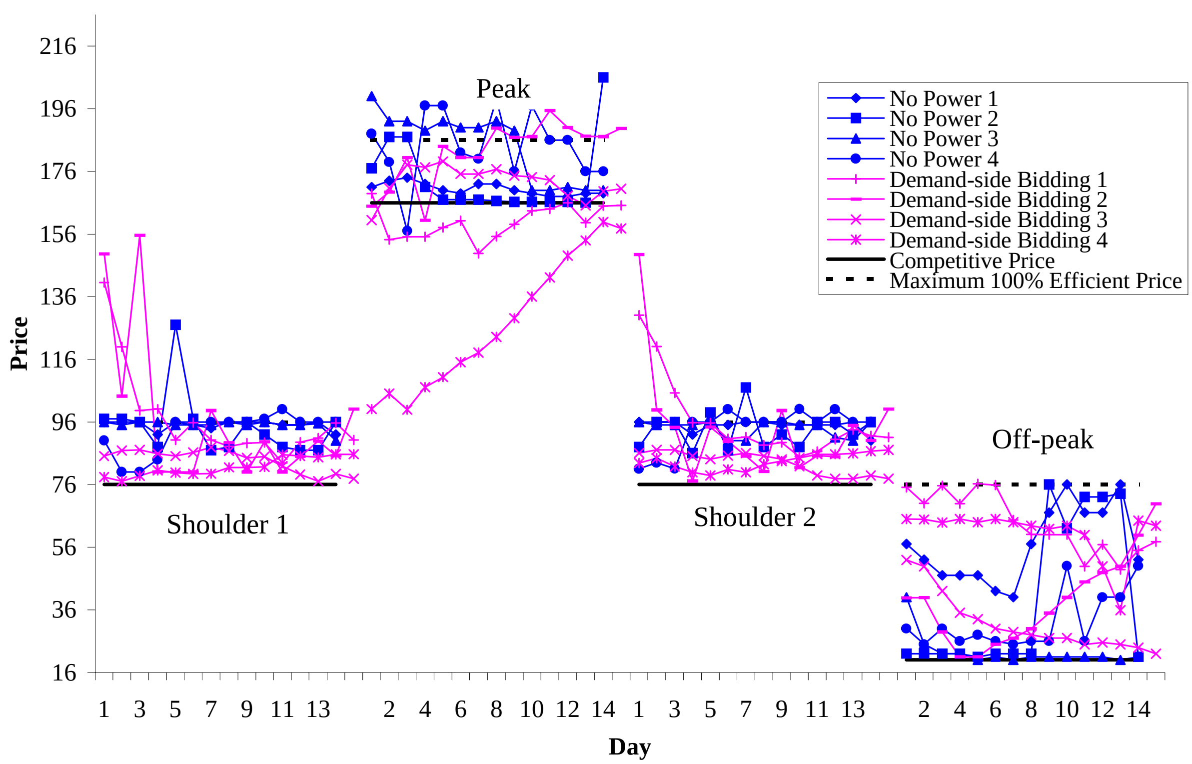


Figure 10. Session Prices With and Without *Demand-side Bidding* in the *No Power* Treatment

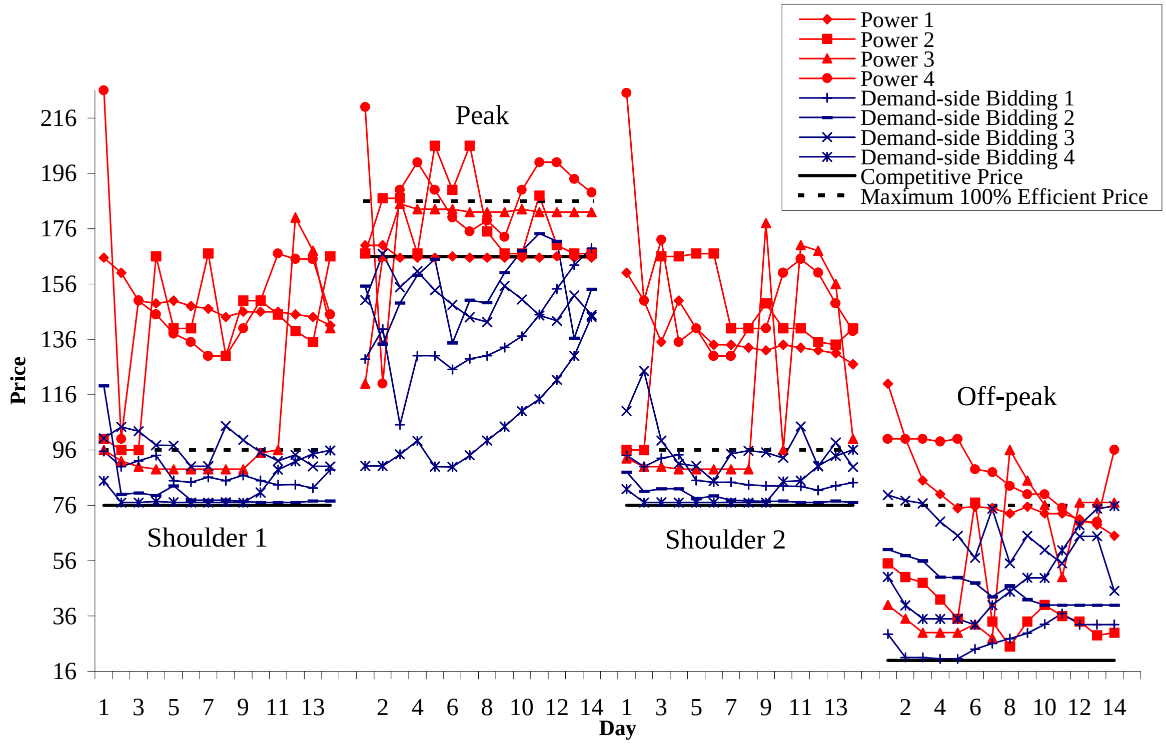


Figure 11. Session Prices With and Without *Demand-side Bidding* in the *Power* Treatment

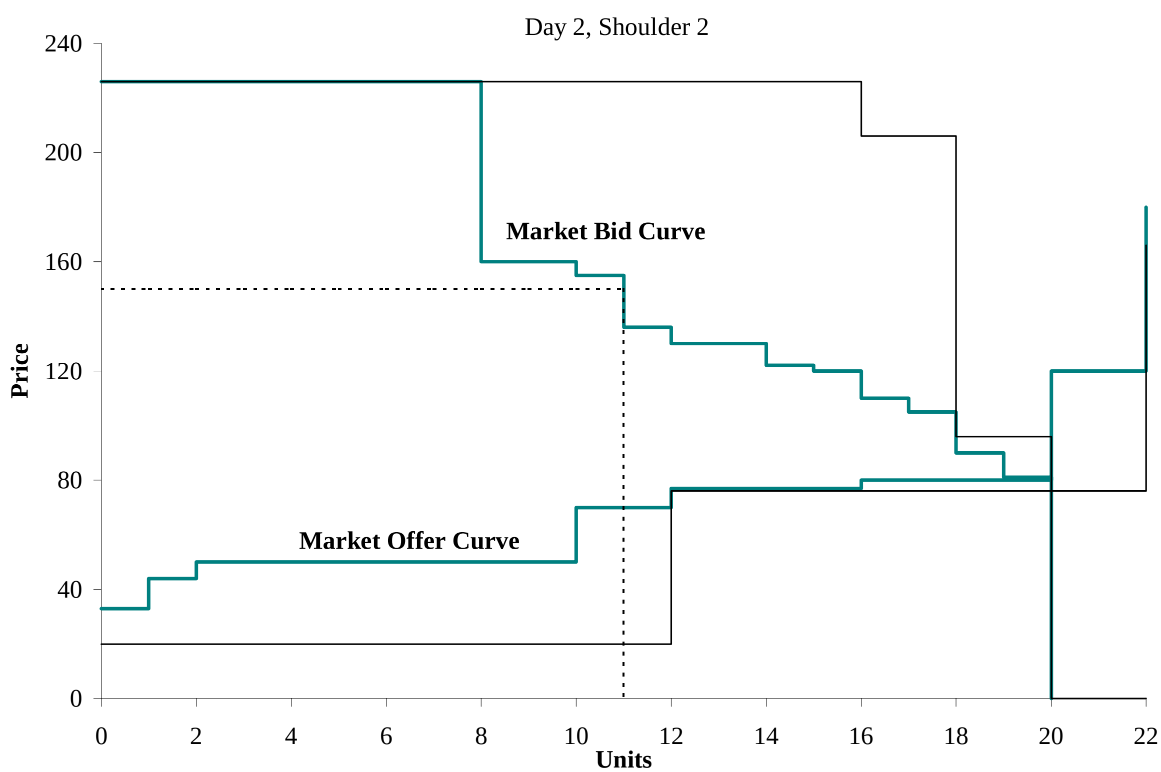


Figure 12. Disciplining Sellers with Demand-side Bidding
(Session: *Power*/*Demand-side Bidding* 1)