Controlling market power and price spikes in electricity networks: Demand-side bidding

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In this article we report an experiment that examines how demand-side bidding can discipline generators in a market for electric power. First we develop a treatment without demand-side bidding; 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 supracompetitive prices that would result from only selling its baseload units. In a converse treatment, ownership of some of the intermediate cost generators is transferred from each of these firms to two other firms such that no one firm could unilaterally restrict output to spawn supracompetitive prices. 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 even in the presence of structural market power.

electric power deregulation | experimental economics

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 joined this trend when California and other states 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 6 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 United Kingdom 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 (1).

Earlier articles have reported experimental studies of the effect of transmission constraints on market power (2), compared the competitiveness of three versus six generation companies (3, 4), or analyzed market power arising from either small numbers or transmission constraints (5). These studies used spot market auctions with demand-side bidding. Wolfram (6) evaluates the applicability of various oligopoly models that have been applied to electricity markets. She finds that Cournot behavior (see e.g., refs. 7 and 8) and supply-function equilibrium (see e.g., ref. 9) 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 noncooperative equilibria. In some cases the prices we observe are not as high as Pareto-superior noncooperative equilibria would predict, and in others they are greater. Unlike field studies, we can exert exact control over the factors that influence demand and supply.

In this article 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 measure and analyze the effect on market prices by introducing demand-side bidding with and without the presence of market power. We find that an active demand eliminates price spikes and lowers prices.

The article is organized as follows. *Market Structure and Design* defines market power in a sealed bid-offer market and outlines our market structure and design for the experiment. *Procedures* discusses the procedures of our experiment, and *Results* presents our findings. *Conclusions* summarizes the implications for public policy.

Market Structure and Design

We examine a very simple environment, relative to actual electric power systems: (*i*) a three-node radial network[†] (in line such that power from any source flows on a single path to any sink); (*ii*) transmission losses are negligible; (*iii*) generators have no sunk or avoidable fixed costs, no minimum capacities, and no maximum ramp (acceleration) rates; (*iv*) buyers (wholesalers) incur no avoidable (penalty) costs from failing to serve all of their "must-serve" demand; and (*v*) security reserves to protect demand from outages are ignored. Other simplifications, relative to traditions that are common in experimental studies but characteristic of observed power systems, include (*a*) no demand-side bidding and (*b*) a trading institution that is a one-price sealed-bid auction. The earlier articles cited above are not restricted to simplifications *ii–iv*, whereas Olson *et al.* (10) study a nine-node regional grid in the U.S. based on industrial parameters that are constrained by none of conditions *i–v* and *a–b*. In our major treatment variable 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.

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[†]However, there are many power systems that are essentially radial: e.g. Australia, New Zealand, and the United Kingdom. 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.

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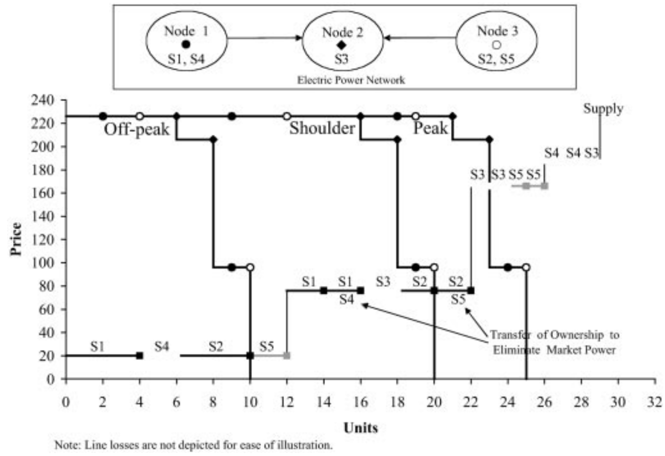

Fig. 1. Market structure and design. Note that line losses are not depicted for ease of illustration.

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 (11) 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 submit 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 Fig. 1 as an illustration of how market power can be represented in electricity markets in which firms submit offer schedules to a central spot market coordinator, who dispatches injections to maximize the gains from exchange, given demand. 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 generation capacity and four units of low-cost baseload capacity at opposite ends of the network. S3 owns two units of intermediate capacity and three units of high-cost generation peak capacity at the center node. The final two sellers, S4 and S5, each have two units of baseload 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 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 by means of a fully demand-revealing robot at each of the three demand nodes. In *Demand-Side Experimental Design*, however, we introduce demand-side bidding by replacing a robot with an active human subject buyer who is profit-motivated. In these treatments, buyers (as well as sellers) are free to use their discretion to underreveal true resale demand (or supply) in a two-sided sealed bid-offer auction.

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 [$(76 - 20) \times 4$ units]. If S1 or S2 raises his offer on his intermediate units to 166, the price-setter's profit rises to 584 [$(166 - 20) \times 4$ units].[‡] This unilateral deviation is even profitable at a price of 96, the third shoulder demand step, where the profit of S1 and S2 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 the peaking 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.[§] However, any equilibrium that has a price of 166 Pareto dominates all others that have prices less than 166.

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 (12) use 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 supracompetitive levels in the shoulder period and consequently raise the market price above the competitive level.[¶] 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 decide to raise the offer on the intermediate capacity, then a supracompetitive price would emerge. However, the competitive price, as an offer on the intermediate capacity, is part of a pure-strategy Nash equilibrium.

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

‡The firm that does not raise its offer realizes a profit of 944 [$(166 - 20) \times 4$ units + $(166 - 76) \times 4$ units].

§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.

¶It should be noted that a seller can submit any offer up to 96 for intermediate cost generators and hence set the price above the marginal cost of 76, but this action does not reduce efficiency. All the gains from trade are still realized with this deviation from the strict Bertrandesqe competitive equilibrium.

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Table 1. 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.

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.

Demand-Side Experimental Design. In this subsection 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 underrevealing their demand, just as in the markets analyzed above sellers were free to underreveal supply. We note that in our parameterization of demand no more than 16% of peak demand can be interrupted voluntarily by the wholesale buyers. We incorporate active demand-side bidding into the market by giving four human bidders most of the demand. 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 1.

We know from previous studies that two-sided markets in electricity can be very competitive (see refs. 3, 4, and 10), 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, will be substantially eliminated.

Procedures

To test how demand-side bidding in electricity markets contributes singly and in tandem with the exercise of market power, we conducted 16 market experiments using undergraduate students at the University of Arizona (Tucson). Four sessions for each cell of the 2 × 2 design were conducted by using the POWER 2K software that we developed. Each session lasted ≈90 min.

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 in the no demand-side bidding treatments, the computer acted as a robot buyer, submitting bids that exactly revealed the demand. In the demand-side bidding treatments, four subjects submitted bids for the units reported in Table 1.

The subjects were told that the costs and generating capacities for each seller would not change during the experiment but 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 14 market days, each day of which was comprised of a four-period cycle. A day began with a shoulder period, followed by one peak, one shoulder, and last, 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 1 min to submit offers or bids each period. An offer (bid) 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 (buy). A subject, at any time within the 1 min, could revise the offer or bid. When the clock expired, the offers and 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 2 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 Fig. 1.) The best performers in the trainer session were used 2 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 were $17.00.

Results

Fig. 2 illustrates the average price paths for the four sessions in each cell of the experimental design. All 14 days of data by level

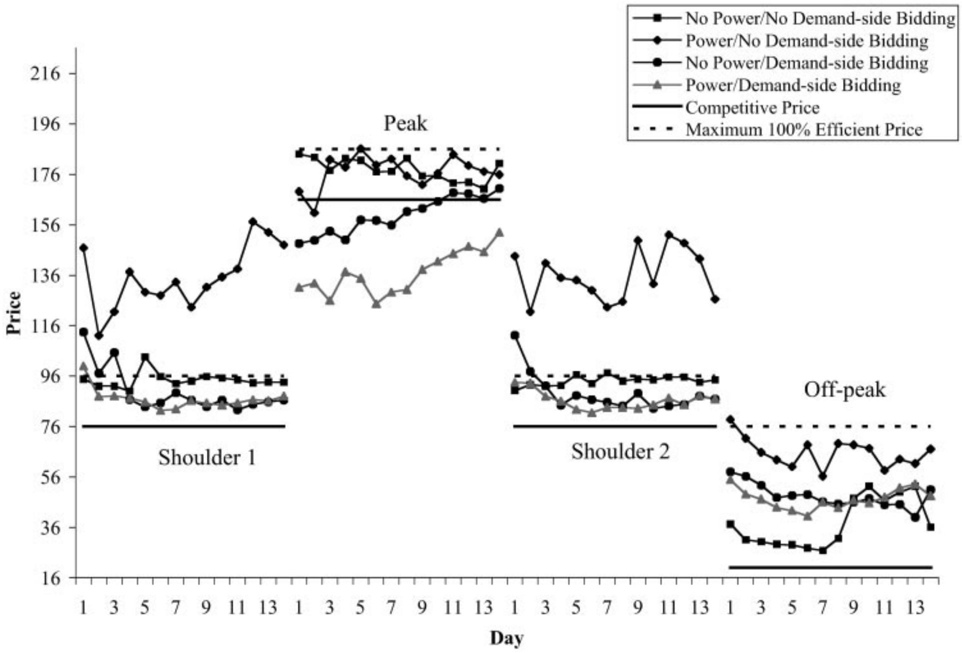

Fig. 2. Average prices.

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.‖ 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.

From the figure it is apparent that the power condition affects performance markedly without demand-side bidding. For sessions conducted under the baseline no-power/no demand-side bidding 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/no demand-side bidding treatment. (Data at the session level will also be presented below.) 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 four findings. In addition to the qualitative results displayed in Fig. 2, we use a mixed-effects model for analyzing data with repeated measures (over 14 market days) as the basis for quantitative support (see ref. 13). The results from estimating this model by period type (shoulder 1, peak, shoulder 2, and off-peak) are given in Table 2. 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 demand-side bidding treatment, which is largely a benchmark calibration result not among our prior predictions.

Finding 1. *Markets in the no-power/no demand-side bidding 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 is most noticeable in the shoulder periods.*

Support: Fig. 3 displays with squares the prices for all four sessions in the no-power/no demand-side bidding treatment. Only for 7 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 five occasions, save session 3, which is able to support slightly supracompetitive prices for the first nine periods. In off-peak periods, prices are drawn at first 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 2 reports that the prices in the no-power/no demand-side bidding treatment are statistically greater than the strict competitive predictions at marginal cost in Fig. 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: $\mu = 20$, $P = 0.3595$ in shoulder 1, and $P = 0.5791$ 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 in which signaling is frequently observed and often successful (see e.g., refs. 14–16). For example, pricing in session 2 after the price spike in day 5, period 1, illustrates the strong drawing power of the competitive outcome in the no-power design (see Fig. 3). In the first shoulder period on day 5, 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.

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

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Table 2. Estimates of the linear mixed-effects model of treatment effects

	Estimate	SE	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

$Price_{ij} - P^c = \mu + e_i + \beta_1 power_i + \beta_2 demand\text{-}side\ bidding_i + \beta_3 power_i \times demand\text{-}side\ bidding_i + \varepsilon_i$, where $e_i \approx N(0, \sigma_1^2)$, $\varepsilon_{ij} = \rho\varepsilon_{ij-1} + u_{ij}$, and $u_{ij} \approx N(0, \sigma_2^2)$. Note that the linear mixed-effects model is fit by maximum likelihood with 160 original observations (last 10 periods) on 16 groups. For the purpose of brevity, the session random effects are not included.

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/no demand-side bidding treatment has no effect on prices in peak periods, where no market power should be expressed.*

Support: Figs. 2 and 3 clearly illustrate that for the shoulder periods market prices in the power design (with diamonds) 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, supracompetitive 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 2. In the shoulder 1 (shoulder 2) periods, the power treatment significantly raises prices above the no-power level by 50.39 (40.66) experimental dollars [$P = 0.0000$ (0.0000)]. The total primary effect of power is to raise the prices above the competitive level by 69.48 = 19.09 + 50.39 (59.59 = 18.93 + 40.66) experimental dollars. The prices in peak periods are not significantly greater in the power treatment ($P = 0.4235$). In the off-peak period, prices are 45.56 experimental dollars greater than the no-power baseline ($P = 0.0066$).

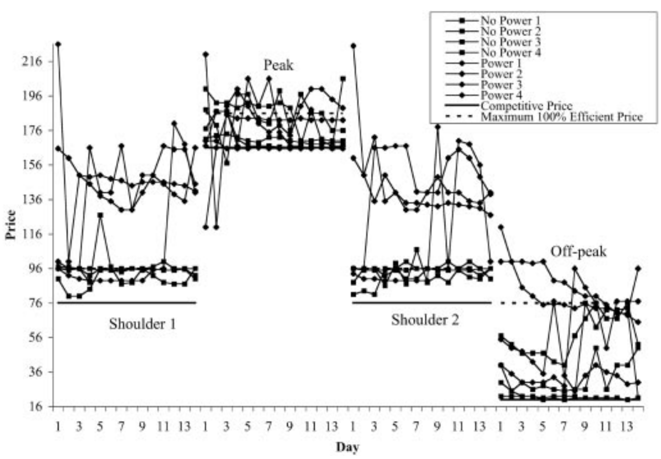

Fig. 3. Session prices with no demand-side bidding.

The ability to exercise market power unilaterally is less apparent to the sellers in the third power session, in which for 9 days the price is well within the 100% efficient range. In period 3 of day 9, 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 11 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 refs. 12, 14, and 17 for examples of posted-offer markets in which Edgeworth price cycles were observed in unilateral market-power environments).

Under the conditions of no demand-side bidding, our results indicate that the distribution of ownership of a given set of generating assets can contribute markedly 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.

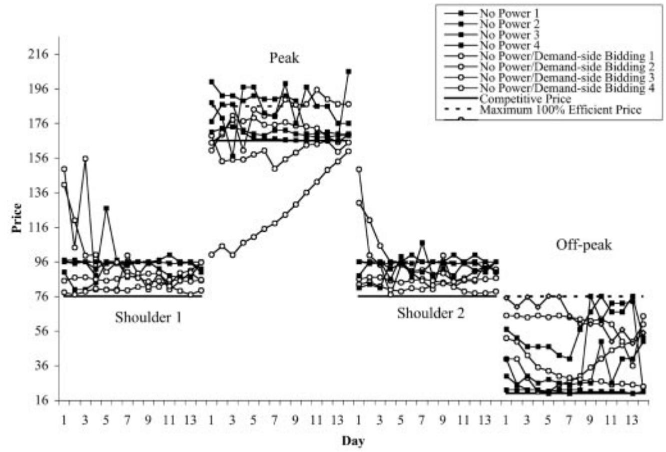

Fig. 4. Session prices with no power.

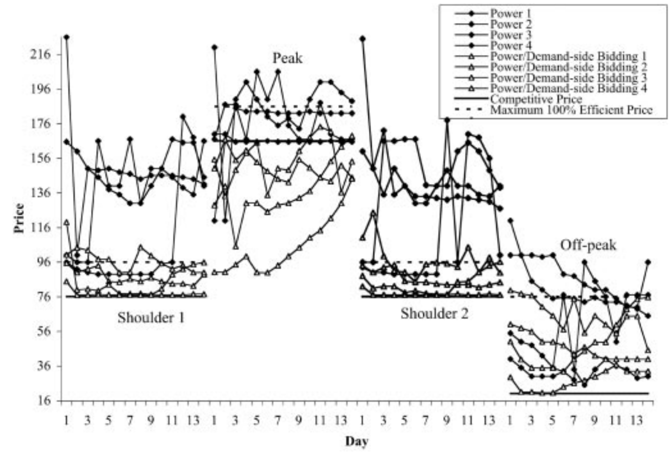

Fig. 5. Session prices with power.

Having established a well controlled data set with price spikes paralleling those observed in the naturally occurring economy, we turn our attention to our primary finding on the demand-side bidding treatment. The qualitative and quantitative supports for *Finding 2* are presented in Figs. 4 and 5 and Table 2. In the interest of brevity we focus our attention exclusively on the shoulder periods.

Finding 3. *In the no-power treatment, demand-side bidding reduces prices within the range of* 100% *efficient prices.*

Support: Recall that without demand-side bidding in *Finding 1*, sellers push up their offers to capture all the surplus between the last demand step and the marginal cost in shoulder periods. Fig. 4 illustrates that with demand-side bidding, the buyers push back to capture more than half of this surplus in shoulder periods. Table 2 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 $P = 0.0000$).

Finding 4. *Demand-side bidding utterly neutralizes market power in the power treatment and eliminates the occurrence of price spikes.*

Support: With rather striking contrast, Fig. 5 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. The striking differences in Fig. 5 are statistically significant, as Table 2 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).

Conclusions

Our results in this article indicate that the distribution of ownership of a given set of generating assets can contribute markedly to the exercise of market power by well positioned players in deregulated one-sided sealed-offer auction markets. Moreover, having established this, we also find that 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.

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1. Littlechild, S. (1995) in *Utility Regulation: Challenge and Response*, ed. Beesley, M. E. (Institute of Economic Affairs, London), pp. 101–114.
2. Backerman, S., Rassenti, S. & Smith, V. (2000) *Pac. Econ. Rev.* **5,** 331–347.
3. Backerman, S., Denton, M., Rassenti, S. & Smith, V. (2001) *J. Decis. Support Syst.* **30,** 357–381.
4. Denton, M., Rassenti, S. & Smith, V. (2001) *J. Econ. Behav. Organ.* **44,** 435–453.
5. Zimmerman, R., Bernard, J., Thomas, R. & Schulze, W. (1999) *Proc. 32nd Hawaii Int. Conf. Sys. Sci.*
6. Wolfram, C. (1999) *Am. Econ. Rev.* **89,** 805–826.
7. Cardell, J., Hitt, C. & Hogan, W. (1997) *Resour. Energy Econ.* **19,** 109–137.
8. Borenstein, S. & Bushnell, J. (1999) *J. Ind. Econ.* **47,** 285–323.
9. Green, R. & Newberry, D. (1992) *J. Pol. Econ.* **100,** 929–953.
10. Olson, M., Rassenti, R., Smith, V., Rigdon, M. & Ziegler, M. (1999) *Proc. 32nd Hawaii Int. Conf. Sys. Sci.*
11. Holt, C. (1989) *J. Law Econ.* **32,** S107–S130.
12. Davis, D. & Holt, C. (1994) *Rand J. Econ.* **25,** 467–487.
13. Longford, N. T. (1993) *Random Coefficient Models* (Oxford Univ. Press, New York).
14. Davis, D. & Wilson, B. (2000) *Econ. Theory* **16,** 545–565.
15. Wilson, B. (1998) *Exp. Econ.* **1,** 133–145.
16. Cason, T. & Williams, A. (1990) *J. Econ. Behav. Organ.* **14,** 331–352.
17. Kruse, J., Rassenti, S., Reynolds, S. & Smith, V. (1994) *Econometrica* **62,** 343–371.