ECONOMIC SCIENCE LABORATORY

# SPOT MARKET MECHANISM DESIGN AND COMPETITIVITY ISSUES IN ELECTRIC POWER

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We report new experiments which compare the sealed bid offer (SBO) market mechanism, studied in Backerman, Denton, Rassenti and Smith (1997; hereafter BDRS), with a uniform price double auction mechanism (UPDA) that updates nodal prices and allocations continuously as new bids and offers arrive in real time down to the close when the market is "called" and all standing accepted bids and offers become binding spot contracts. We compare the performance of the SBO and UPDA institutions in terms of their impact on incentives affecting market efficiency (the ability to exhaust the gains from exchange), generator and wholesale buyer profitability, and delivery price. Under each of the two trading institutions we compare markets in which the available generator capacities and their costs are held by three versus six independent companies. We also vary the minimum loaded capacity of baseload units below which avoidable fixed cost penalties are incurred. Wholesale buyers also face large penalties if they fail to serve all of their noninterruptible demand. These nonconvexities combine to produce a very stressful market for buyers on peak, and for sellers off peak. Finally, in UPDA only, we study the impact of varying the proportion of peak demand that is noninterruptible and subject to must-serve avoidable fixed cost penalties. We do not address the effect of a transmission line constraint – this is central to the market power issue – because it is already addressed in Backerman, Rassenti and Smith, 1997. Also we do not address the so-called "loop-flow" issue in triangular and more complex networks, because (a) it is essential to first examine mechanism design and nonconvexity issues in a baseline that controls for loop flow effects, and (b) such issues constitute one of the next steps in our research program underway.[1]

## 1. Experimental Environment

In all experiments we use a three-node radial network consisting of 4 wholesale buyers at the center demand node, B, 2 (or 4) generators companies at the left supply node, $G_1$, and 1 (or 2) generators at the right node, $G_2$. (Refer to the network diagram below in Figure 2).

### Generator Parameters

Most large capacity turbine generators have minimum and maximum loaded capacity constraints, with modestly increasing marginal heat rates (and fuel costs) over the range from minimum to maximum capacity. Average cost varies little on baseload units over this capacity range, most often declining slightly until maximum capacity. Minimum loaded capacity is typically 40-50% of maximum capacity, often more. This is in part because marginal cost is declining up to "minimum" capacity and it is not generally optimal, in terms of minimizing energy cost, for on-line generators to operate where output exhibit declining marginal cost.[2] We approximate these characteristics with the cost and capacity parameters for all generators shown in Table 1. Each power plant facility consists of three generators whose respective marginal costs are constant up to maximum capacity: (i) a low cost baseload unit with a minimum loaded "must-run" (the industry term) capacity of 50% of maximum in one treatment condition, and 100% of maximum capacity in a second treatment; (ii) a medium level marginal cost unit which can operate at any output up to the maximum capacity; and (iii) a high marginal cost unit also operable at any capacity up to maximum. Thus, generator (plant) 2-1, at node $G_2$ consists of a baseload unit whose maximum capacity is 450MW at a marginal cost of 122 (tokens/Mwh). Each baseload unit also incurs an avoidable fixed penalty cost of 125,000 (tokens) if output falls below 50% (100%) of maximum capacity. This penalty is intended to account for all startup, ramping and suboptimal operational costs whenever the unit is operated below its capacity specifications. The owners of such units are therefore under considerable cost pressure to offer them in the spot market on terms that assure commitment at outputs that are not below the minimum specified.[3] The medium and high cost units are flexible and incur no such avoidable fixed cost whatever might be their commitment levels. Finally, each three-generator unit plant incurs an unavoidable sunk cost of 25,000 tokens per operating period.

Demand Representation and Parameters

Demand is a 6-phase cycle consisting of two peak levels, then one shoulder mid-level demand, followed by two off-peak demands, and ending with another shoulder demand. Each of these six phases is one simulated hour long, so that selling all of the output from a 450 MW baseload generator results in 450 MWh of energy injected into the transmission system. These cycles correspond to the typical industry urban peaks in the range from about 11am-5pm, weekdays, off-peak at nighttime from about 11pm-5am, with intermediate levels on the shoulders between troughs and peaks. In the current environment, resale prices are constant and regulated for the “must-serve” portion of demand which cannot be interrupted without political/regulatory penalties if people “lose their lights”. This is indicated in Table 2 for 4 identical wholesale buyers with blocks of must-serve demand at 900, 610 and 370 MWh at peak, shoulder and off peak respectively over the daily demand cycle, with resale values fixed at 450 (tokens per MWh) for all buyers. Interruptible demands are 80 and 60 MWh at lower corresponding values. Any wholesale buyer who fails to purchase all of the required must-serve demand incurs an avoidable fixed cost of 250,000 (tokens).[4]

## Supply and Demand

The resulting supply (marginal cost) and demand (marginal valuation) schedules are shown in Figure 1. Note that this environment is particularly stressful on-peak for buyers because they must bid above resale value for a current account loss to attract the necessary peaking generator capacity. It pays to do this in order to avoid a substantially larger penalty cost for failing to meet all must-serve demand; i.e. optimization requires minimizing losses. The maximum-willingness-to-pay to avoid these penalties is shown dotted (Avg WTP) in Figure 1. Hence, the loss minimizing on-peak competitive equilibrium spot price is 475 rather than the resale value, 450. Several of the experiments reported below relaxed this severe demand condition by reducing the must-serve demand spike to 70% of the amounts shown in Table 2. Under this demand treatment the on-peak competitive equilibrium price is 450 (tokens/MWh), and buyers need not bid their resale values to acquire enough energy to meet their peak demand.

Similarly, this environment motivates the suppliers (generators) to accept prices less than their marginal cost in the off peak phases in order to avoid must run penalties. These theoretical willingness-to-accept schedules are also shown dotted ($WTA_{100}$ and $WTA_{50}$) in Figure 1.

## Transmission and Nodal Pricing

Transmission is never constrained and is a free-access common carrier open to all generation plants and buyers, with a zero probability of outage in all experiments. Transmission pricing is based on marginal losses on each of the two lines. The loss on line i is $c_i X_i^2$ where

$X_i$ is the power injected at node i. Letting $B_i(Y_i)$ be the resale value (benefit) schedule of buyer i, and $G_{1j}(X_{1j})$ and $G_{2k}(X_{2k})$ be the variable cost functions of seller j and k at generator nodes 1 and 2 respectively, the allocation problem is to

(1) $$\underset{Y_i, X_{1j}, X_{2k}}{Max} \; \sum_i B_i(Y_i) - \sum_j G_{1j}(X_{1j}) - \sum_k G_{2k}(X_{2k}) + \lambda\,[X_1 + X_2 - Y - c_i X_1^2 - c_2 X_2^2],$$

where $X_1 = \sum_j X_{1j}$, $X_2 = \sum_k X_{2k}$, $Y = \sum_i Y_i$, and the expression in brackets is the conservation condition on total energy flows. At a surplus maximizing interior competitive equilibrium we have:

(2) $$\begin{aligned} &\lambda^0 = B'_i(Y_i^0) = \frac{G'_{ij}(X_{1j}^0)}{1 - 2c_1 X_1^0} = \frac{G'_{2k}(X_{2k}^0)}{1 - 2c_2 X_2^0},\ \forall \mathrm{i,j,k};\\ &\mathrm{X}_j^o + X_2^0 - Y^0 - c_1(X_1^0)^2 - c_2(X_2^0)^2 = 0. \end{aligned}$$

Equations (2), or their inequality form for boundary optima (see BDRS, p. 10) are used to define a competitive equilibrium, against which we compare the realizations based on agent bids to buy or offers to sell. Using the discrete forms in Tables 1 and 2 for the marginal value and cost functions in (2), the corresponding competitive equilibrium $\lambda^0$ (buyer node price), allocations, efficiency, and buyer and seller total profits are computed for the 100% must-serve, and the 50% and 100% must-run conditions. These are shown in Table 3.[5]

In implementing the optimization the computer uses only the buyer bid schedules rather than the true $B'_i(Y_i)$ functions, the seller offer schedules in place of the $G'_{1j}(X_{1j})$ and $G'_{2k}(X_{2k})$ marginal cost functions, and the energy conservation equation with loss coefficients $c_1$ and $c_2$. Hence, for the realizations, letting $P_B^*$ be the marginal bid price, and $P_{G1}^*$ and $P_{G2}^*$ be the marginal asking prices we have

(3) $$P_B^* = \frac{P_{G1}^*}{1-2c_1X_1^*} = \frac{P_{G2}^*}{1-2c_2X_2^*};\ X_1^* + X_2^* - Y^* - c_1(X_1^*)^2 - c_2(X_2^*)^2 = 0,$$

where the transmission loss factor at generator node m is defined by $TF_m \equiv 1/(1-2c_mX_m^*) < 1.$ (See BDRS, Section 2, for a more complete discussion of the optimization, and for the revenue settlement equations).

## 2. Two Computer Based Spot Market Trading Mechanisms

We compare two alternative call market mechanisms for organizing a spot market for energy with all demand and supply information decentralized and dispersed among 4 buyers and either 3 or 6 generator company sellers. In each institution the market is called after the elapse of a specified preset time period. Although these periods are typically implemented in the field at hourly (or half-hourly) intervals, in the experiments below the periods are 4 minutes since we abstract from commitment and operational implementation and focus entirely on the market process. Both mechanisms generate a single uniform price for all buyers at node B, and a single uniform price for all sellers at each of the nodes $G_m$, $m = 1,2$ which are related as shown in equation 3.

### Sealed Bid Offer Mechanism

All buyers (sellers ) submit a single round of bids (offers) in a series of price-quantity steps chosen at their discretion. These steps can be above, equal to, or below the buyer (seller) valuation (cost) steps and do not need to coincide with the resale or generator capacity steps. Thus the baseload capacity can be subdivided into multiple parts, and similarly for the buyer resale capacity steps.

Letting the buyer's node serve as the reference price node, bid prices and corresponding quantities of all buyers are pooled and ordered from highest to lowest according to bid prices, yielding the realized bid schedule, B(Y). Similarly, the price-quantity offer schedules of sellers at each generator node are ordered from lowest to highest according to asking prices, yielding realized generator node supply schedules, $a_m(X_m)$, $m = 1,2$. These schedules are then location adjusted to the reference buyer node using the endogenous transmission discount factors $TF_m(X_m)$, $m = 1,2$, yielding a net supply schedule A(Y) at node B, with prices and allocations computed so as to satisfy discrete optimization conditions analogous to (3). Where agent bid (offer) allocations must be rationed (prices are tied) we use time of submission to determine the priority. For additional details on SBO, the reader is referred to BDRS (Section 3). Figure 2 shows the bids and offers for messages #22 through #33 submitted in market period 27.

Uniform Price Double Auction

UPDA is a uniform price version of the real time double auction that characterizes stock and commodity trading. In the latter, however, compatible bids and offers yield binding bilateral contracts, at prices that normally differ across contracts in sequence, but tend to converge over time to one price and total quantity. In UPDA the same information conditions apply; i.e. bids and offers form price-quantity pairs that are time tagged as they arrive in real time. Instead of being matched to form contracts when compatible, the bids are continuously resorted from highest to lowest, and the location-adjusted offers are continuously resorted from lowest to highest. At each time, t, until the market is called, that is when t = T, the length of the bidding period, there is a tentative market clearing price, $P_B^*(t)$, based on the intersection of $B(Y(t))$ and $A(Y(t))$, and corresponding individual allocations based on tentatively accepted bids and offers.

Thus, at each t there are tentative allocations exactly as in the SBO mechanism. At any t < T, agents can alter their bids (offers), except that bids and offers can only be improved; i.e. a buyer can increase his or her bid price and/or increase the quantity specified at any bid price, while a seller can decrease his or her bid price and/or increase the quantity specified at any bid price. At t = T, the market is "called," and the tentative price and quantity allocations that apply at t, all become binding.

This mechanism has various versions some of which have yielded efficiencies as high or higher than the continuous double auction in convex environments. The (less efficient) version used here allows bids and offers, that dominate currently accepted bids and offers, immediate price priority over those currently accepted in the standing supply and demand "cross." Thus, quotations from both sides of the market can displace dominated bids and offers currently accepted. This is called the "both sides" rule in McCabe, Rassenti and Smith (1993, p. 312-316). This is in contrast to the "other side" rule: any bid (offer) which has not been accepted as of time t, must first meet the terms of (or be met by) a offer (bid), also not accepted, on the other side of the market before it can be sorted into the acceptance set. Hence, accepted bids and offers enjoy a temporary time priority. The other side rule is significantly more efficient in static supply and demand electricity markets than the both sides rule. (Backerman, , Rassenti and Smith, 1997, Table 2).[6]

Table 4 lists all experiments conducted using the SBO and UPDA institutions, under the various demand and supply side capacity constraints. All subjects in the experiments reported here were experienced University of Arizona undergraduates in business and economics. They were recruited, and required to commit, for three two-hour sessions. A $5 per session show up fee and all cumulative profits earned in the experiments were paid privately to each subject at the end of the third session. The first session data set was not analyzed because it served primarily as a training session. Many subjects had net trading losses from the first session, but more than made up these losses in the second session by which time they had become quite proficient. The highest paid subject earned $267.50

## 3. Prior Hypotheses

In presenting the experimental results the primary objectives are to compare the effect of the following discrete treatment variables: (1) Three versus six generating suppliers, and (2) the SBO versus UPDA trading mechanisms. Secondary objectives are to compare (3) the 50% versus 100% must-run baseload generator constraint, and (4) the 70% versus 100% must-serve demand condition (UPDA data only).

We use four measures of performance: (1) efficiency (% of producer plus consumer surplus realized by a trading mechanism), (2) seller surplus (profit), (3) buyer surplus (profit), (4) price at demand node.

Our prior hypotheses based on past studies of SBO or UPDA in nonelectrical environments, were as follows.

$H_1$: Three firms will display greater market power than six firms. This implies that the six firm treatment will show higher efficiency, lower seller profits, higher buyer profits and lower prices than the three-firm treatment. The experimental results for SBO have already provided falsifying evidence on these predictions, as reported in BDRS (Section 6). Therefore, we are concerned here with whether $H_1$ is supported by the more flexible UPDA institution.

$H_2$: SBO will yield lower efficiency than UPDA. We also expect the two institutions to behave differently with respect to seller and buyer profits, and buyer prices: UPDA was expected to follow shifts in the competitive equilibrium more closely than SBO. These hypotheses are based on previous findings in markets, without supply side and demand side avoidable fixed cost nonconvexities, in which UPDA was found to be comparable to the continuous double auction (McCabe, Rassenti and Smith, 1993), which in turn is known to be superior to various forms of the SBO mechanism (Smith, Williams, Bratton and Vannoni, 1982). Since it was discovered in BDRS that the SBO mechanism performed unexpectedly well under the stressful must-run supply and must-serve demand conditions we impose, it is an open question whether these previous results will be maintained under UPDA trading rules.

$H_3$: Moving from the 50% to the 100% must-run baseload generator conditions, efficiency, seller profits and prices will decline, while buyer profits will increase.

$H_4$: Moving from the 70% to the 100% must-serve demand condition will decrease efficiency and buyer profits while seller profits and prices will increase.

## 4. Results

Our results are quantified using OLS regressions of the various independent treatment (dummy) variables on each of the dependent variables: efficiency, seller profits, buyer profits and buyer node delivery price, each measured in <u>deviations</u> from their corresponding competitive equilibrium values. The dummy variables are as follows[7]: $D_2$, 6 ($D_2 = 1$) versus 3 ($D_2 = 0$) generator companies; $D_3$, peak ($D_3 = 1$) versus not peak ($D_3 = 0$) demand; $D_4$, off peak ($D_4 = 1$) versus not off peak demand ($D_4 = 0$); $D_5$, must-run penalty at 100% capacity ($D_5 = 1$) versus 50% capacity ($D_5 = 0$); $D_6$, must-serve penalty at 100% of uninterruptible demand ($D_6 = 1$) versus 70% ($D_6 = 0$); $D_7$, institution is SBO ($D_7 = 1$) versus UPDA ($D_7 = 0$). In addition to these primary treatments, we include three interaction dummy variables which are essential to interpreting the results: (1) the interaction between number of generators and the institution, $D_2D_7$, 6 generators and SBO ($D_2D_7$ = 1) versus not; (2) $D_4D_5$, off peak and 100% must-run penalty cost versus not; (3) $D_3ND_6$, for the UPDA data only, comparing peak demand and buyer penalty at 70% uninterruptable demand ($D_3ND_6$ = 1) versus not ($D_3ND_6$ = 0). Note that the $D_2D_7$ dummy enables us to distinguish any differential market power effects between the two different institutions. The $D_4D_5$ dummy allows us to separate the expected result that the 100% must-run penalty cost will have a particularly important impact when demand is off peak, stressing baseload generator commitment. Finally, in all the regressions we include each dependent variable lagged one period as an independent variable to help correct for autocorrelation in behavior through time. By measuring the dependent variables in deviations from the competitive equilibrium, we take into account the forcing function that constitutes the demand cycle, but lagged behavioral reactions can still cause auto correlation in the dependent variables (e.g. see the charts plotting the dependent variables in Figure 4-6 with stationary demand in BRS).

Using this regression model, and combining the comparable SBO and UPDA data, Table 5 provides the estimated coefficients on each independent variable in the rows, and for each dependent variable defined by the columns.[8] The t value levels are shown in parenthesis corresponding to each coefficient and the coefficients that are significant are printed in bold faced type. Table 6 provides the regression coefficients for the UPDA only data set, allowing a comparison of the 100% and 70% must-serve buyer constraint. Finally, Table 7 provides the estimates for the SBO only data set.

$H_1$: Three firms exert more market power than six under the UPDA rules, but there is no economically or statistically significant difference under the SBO rules.

This is indicated by comparing the coefficients in row $D_2$ with row $D_2D_7$ in Table 5. Note that for seller and buyer surplus, and for price, the $D_2D_7$ coefficients (and t values) are of almost equal but opposite sign to those of $D_2$. That is, the high significance of these $D_2$ coefficients is attributable to UPDA only, not SBO. This is confirmed by running the regression separately for UPDA as can be seen in Table 6 and for SBO in Table 7. To summarize: market power has no significant effect on efficiency under either SBO or UPDA. But UPDA yields a significant decrease in seller profits, increase in buyer profits, and decline in price, when we increase the number of firms from 3 to 6. Under the SBO rules the number of firms has no statistically significant effect on buyer or seller profits, or on market price.

$H_2$: From the row of coefficients for $D_7$ in Table 5, contrary to $H_2$, SBO yields a significant increase in efficiency over UPDA. This we attribute to the improved revelation properties of SBO when both buyer and sellers incur large avoidable fixed cost penalties (associated with minimum buyer must-serve capacities and minimum seller must-run capacities). Under the UPDA rules, however, there is less uncertainty with respect to price discovery than under SBO rules, and this induces more attempts to manipulate outcomes with a consequent impact on prices and buyers' and sellers' profit. Thus SBO yields significantly lower seller surplus, higher buyer surplus and lower prices than UPDA, measured as deviations from their corresponding competitive equilibrium values. That is, relative to UPDA, SBO redistributes surplus from sellers to buyers, while increasing efficiency.

$H_3$: An increase in the must-run minimum baseload capacity to 100% from 50% reduces efficiency off-peak, as indicated in Table 5 by the efficiency coefficient for the interaction dummy, $D_4D_5$; otherwise efficiency is not significantly impacted, as indicated in the row for the $D_5$ dummy. Also, as indicated in row $D_5$, increasing the must-run capacity reduces seller profit and prices and increases buyer profits, but only for peak and shoulder demands (i.e., not off peak). Off peak, as shown by the results for the dummy, $D_4D_5$, seller profits and prices increase and buyer profits decrease, as sellers successfully avoid competing (Bertrand style) the off peak price down to zero under the 100% must-run condition. This result holds after taking out the effect of the institutions ($D_7$) and therefore holds in both SBO and UPDA. This is further confirmed in Table 6 and 7 where the regressions are for SBO and UPDA only. These results are not only statistically significant but show up as economically important.

$H_4$: In Table 6 refer to the row ($D_3ND_6$) of coefficients measuring the effects of the reduction of must-serve peak demand from 100% to 70%, note that this treatments yields significant and large increases in efficiency and buyers' profit, and decreases in sellers' profit and prices. As expected, reducing the peak demand stress on buyers, increases efficiency by greatly reducing missed trades and the concomitant penalties, and redistributes income from sellers back to buyers.

The greater reliability of SBO relative to UPDA, in this nonconvex environment, is made particularly evident by comparing the adjusted $R^2$ and F statistics in Tables 6 and 7. Both of these measures are uniformly higher, across all measures of performance, for SBO than for UPDA.

## 5. Summary and Discussion

Contrary to previous comparisons showing UPDA's high performance in classical environments, it performs very poorly in the current nonconvex environment where SBO does quite well. This is explained by the greater incentives to reveal, and to avoid manipulation strategies, in SBO, where there is no feedback of within-period information and the cost of a missed trade is very high – high for sellers off peak, and for buyers on peak. But even the shoulder demand levels do not rescue the version of UPDA studied here.

Are there rule "fixes" that would improve UPDA? We have little doubt that there are many. The other side rule used in BRS is an obvious candidate. Also needed is a close rule that will promote earlier and better revelation, e.g. a random close, or endogenous close, fixed-interval call, rule (See McCabe, Rassenti and Smith, 1992, p. 311). Under the latter the market is called when no new tentatively accepted bid or offer arrives for a specified elapsed time. Another fix would be the Wilson (1997) or other stronger forms of other side rules.

The severity of the must-run generator constraint (50% vs 100%) and the must-serve demand constraint (100% vs 70%) are significant and important. We chose this parameterization because it roughly characterizes the existing situation in the electric power industry, which is largely a product of command/regulatory environments and has a history of poor incentives. The ongoing deregulation of several aspects of this industry may drastically change these constraints. For this reason it is particularly important that the system not be hamstrung by rules that hardwire assumptions that the future will look like the past. Time-of-day pricing technologies including network metering and switching devices will increase the deployment of voluntary, interruptible demand options, an efficient substitute for both generator and transmission capacity. Generator technologies that are already upon us, and new ones on the horizon will gradually alter the stock of generator assets, introducing more flexible cost efficient means of electrical energy production. (Thomas and Schneider, 1997). Besides reducing nonconvexities, these technologies will increase reliability by reducing dependence on supply side generator spinning reserves, and increasing dependence on demand side flexibility.

Footnotes

* We are indebted to the Progress and Freedom Foundation for financial support and the large number of utility executives and engineers who participated in several PFF workshops and consulting sessions directed to the experimental design developed in this paper and in Backerman, Denton, Rassenti and Smith (1997). Their input, prior to conducting the experiments, was central in determining the design features that were incorporated into the final plan.

1. We found it interesting that industry representatives, while recognizing that academics are memorized by network externalities (loop flow problems), consider this a lower priority issue than studying market performance and behavior in the context of generator supply inflexibilities and the limited current technical ability of local distribution companies (wholesale buyers in our market) to interrupt demand. Hence, they were comfortable with the simple quadratic loss, radial network, used below, provided that the supply and demand inflexibilities were incorporated into the system.

2. If you have $n \geq 2$ generator facilities, it is never optimal to operate more than one of them at declining marginal cost, and "if one facility is operated at declining marginal cost the rate of decrease of its marginal cost curve must be smaller in absolute value than the rate of increase of the horizontally summed marginal cost curves of all other facilities." (Smith, 1961, p. 247).

3. This specification was strongly endorsed by our industry critics as a means of capturing their insistence that such baseload units should never be ramped below their minimum capacities – a fact they believe market mechanisms must contend with. These avoidable fixed cost penalties, designed to induce the appropriate behavior, represent all the fuel, ramping, start-

up, lost output, and extraordinary wear costs associated with partial or complete shut down, and subsequent recommitment, consequent to a failure to maintain minimum loaded capacity. (They are not a cost that is avoided at zero output by not producing, but rather a cost that is avoided by keeping the unit on line and running). More important, they represent the perceived opportunity cost of failing to run. We have software which models generator dynamics more "realistically" as a multistate facility: cold, warm, hot, running at minimum or anywhere up to maximum capacity, with ramp rates and associated cost of state transition, and wear and outage probabilities, related to use history. But this reductionist dynamic complexity was seen by many in the industry as washing down to an urgent "must-run" imperative for decision makers. Most of these dynamic costs are unknown, because they are never experienced as units are operated in the must-run state between scheduled outages for maintenance. Our view is that this imperative is a consequence of the technological and regulatory history of the industry, which has already changed and will continue to change in the future. The existing large stock of inflexible thermal baseload units (in foreign countries as well as the U.S.) will be (and already are being) replaced by much more flexible machines appropriate to the developing market environments.

4. This means of capturing the demand side was also strongly endorsed by our industry critics who see must-run imperatives as a core feature of the political and public pressures which they face in the transition to a deregulated power market. Penalty costs avoidable by bidding high enough to acquire sufficient capacity to satisfy the spike in must-serve demand was viewed as providing incentives that appropriately reflected the opportunity costs as they perceive them. Our view is that the market, with full time-of-day costs reflected in prices,

will ultimately incentivize and transform the demand side to make voluntary arrangements for interruptibility, at a price, much more prevalent.

5. The off peak 100% must-run entries shown in Table 3 reflect a boundary optimum since sellers could not enter negative price offers. The interior competitive equilibrium for this case occurs at p = - 184. We favor permitting baseload units to enter negative asking prices (as in the Australian market) indicating how much they are willing to pay to avoid the cost of ramping below minimum capacity.
6. Wilson (1997) and Plott (1997) have tested a strong version of this "other side" rule in which bids (offers) outside the initial supply and demand cross are required to be raised (lowered) to the initial clearing price plus (minus) one unit, or cannot thereafter be changed. The idea behind all this rule fine-tuning is to increase the incentive to reveal value (cost). However, a seller (buyer) who believes that the initial price is too high (low), and that the price will subsequently decline (increase) can underreveal units below the initial price in an attempt to prevent the price from falling (rising). Consequently, the price may adjust sporadically. This may account for the phenomena of "stuttering" observed by Plott (1997). In McCabe, Rassenti and Smith (1993) we observed such response inertia under the both sides rule when initial prices were out of equilibrium, which is what motivated our relatively light-handed other side rule.
7. We used $D_1$ as an experience dummy (= 1, if twice experienced, 0 if once experienced), but including $D_1$ in the regressions had no significant effects, so we pooled all experienced groups for this report. In BRS we found significant effects in twice-experienced subjects, but the environment studied was static – the same supply and demand conditions were replicated for 30 trials in both experienced groups.

8. In Tables 6 and 7 we report regressions including the interaction dummies $D_2D_4$ and $D_2D_5$. In the full data set these two interactions yield only one marginally significant coefficient (the coefficient of buyers surplus on $D_2D_4$, with $p = 0.044$), and reduce the F statics substantially. Therefore, we omitted these interactions in Table 4.

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**Table 1.**

## Induced Supply Schedule

### 6 Generator Treatments

(Supply schedule constant across all periods)

| Generator Numbers[a] | Sunk Cost (tokens per period) | Maximum Output (Mwh) | Marginal Cost (tokens/Mwh) |
|---|---|---|---|
| 1-1, 1-2, 1-3, 1-4 | 25,000 | 420[b] | 121 |
| | | 150 | 231 |
| | | 100 | 406 |
| 2-1, 2-2 | 25,000 | 450[b] | 122 |
| | | 170 | 233 |
| | | 110 | 413 |

a. - Each generator has one owner. In treatments with 3 power suppliers, each generator combination (1-1 and 1-2, 1-3 and 1-4, 2-1 and 2-2) has one owner.
b. - Each generator incurs a "must-run" avoidable cost of 125,000 tokens if output falls below 50% (100%) of this first step

**Table 2.**

## Induced Demand Schedule

| | | Peak Load | | Mid Load | | Off Peak Load | |
|---|---|---|---|---|---|---|---|
| Buyer | Sunk Cost (tokens per period) | Units (Mwh) | Resale Value (tokens/Mwh) | Units (Mwh) | Resale Value (tokens/Mwh) | Units (Mwh) | Resale Value (tokens/Mwh) |
| 1 | 12,500 | 900* | 450 | 610* | 450 | 370* | 450 |
| | | 80 | 435 | 80 | 435 | 80 | 435 |
| | | 60 | 185 | 60 | 185 | 60 | 185 |
| 2 | 12,500 | 900* | 450 | 610* | 450 | 370* | 450 |
| | | 80 | 410 | 80 | 410 | 80 | 410 |
| | | 60 | 225 | 60 | 225 | 60 | 225 |
| 3 | 12,500 | 900* | 450 | 610* | 450 | 370* | 450 |
| | | 80 | 385 | 80 | 385 | 80 | 385 |
| | | 60 | 275 | 60 | 275 | 60 | 275 |
| 4 | 12,500 | 900* | 450 | 610* | 450 | 370* | 450 |
| | | 80 | 360 | 80 | 360 | 80 | 360 |
| | | 60 | 320 | 60 | 320 | 60 | 320 |

* Must-serve demand; if buyer failes to serve, buyer incurs an avoidable fixed cost of 250,000 tokens.

## Table 3
## CE Prices, Loads and Agent Profits (Surplus)

| | | Price | | Load | | Total Surplus | | Buyer Surplus | | Seller Surplus | | Transm. Surplus | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Must-Run Penalty** | 3 Sellers | 6 Sellers | 3 Sellers | 6 Sellers | 3 Sellers | 6 Sellers | 3 Sellers | 6 Sellers | 3 Sellers | 6 Sellers | 3 Sellers | 6 Sellers |
| **Peak** | **50%** | 475.3 | 475.3 | 3,600 | 3,600 | 945,380 | 945,380 | (91,080) | (91,080) | 907,430 | 907,430 | 129,030 | 129,030 |
| **Demand** | **100%** | 475.3 | 475.3 | 3,600 | 3,600 | 945,380 | 945,380 | (91,080) | (91,080) | 907,430 | 907,430 | 129,030 | 129,030 |
| **Mid Level** | **50%** | 260.4 | 260.4 | 2,880 | 2,880 | 839,340 | 839,340 | 510,880 | 510,880 | 284,700 | 284,700 | 43,760 | 43,760 |
| **Demand** | **100%** | 260.4 | 260.4 | 2,880 | 2,880 | 839,340 | 839,340 | 510,880 | 510,880 | 284,700 | 284,700 | 43,760 | 43,760 |
| **Offpeak** | **50%** | 131.5 | 131.5 | 2,040 | 2,040 | 596,040 | 596,040 | 585,250 | 585,250 | 56 | 56 | 10,734 | 10,734 |
| **Demand** | **100%** | 0.0 | 0.0 | 2,040 | 2,040 | 535,560 | 535,560 | 918,000 | 918,000 | (382,440) | (382,440) | 0 | 0 |

**Table 4**
**Experimental Design Showing**
**Must-Run Penalty Condition and Experience Level,**
**by Number of Sellers and Market Mechanism**

| Number of Sellers, Mechanism | 50% of First Step Must Run Penalty Condition | | 100% of First Step Must Run Penalty Condition | |
|---|---|---|---|---|
| | Once Experienced Subjects | Twice Experienced Subjects | Once Experienced Subjects | Twice Experienced Subjects |
| 3 Sellers | | | | |
| SBO | 1 of 30 periods | 1 of 24 periods<br>2 of 30 periods | 2 of 30 periods | 2 of 24 periods<br>1 of 30 periods |
| UPDA | 1 of 30 periods<br>1 of 12 periods | 1 of 30 periods | 1 of 28 periods† | 1 of 28 periods†<br>1 of 20 periods |
| 6 Sellers | | | | |
| SBO | 1 of 29 periods†<br>1 of 30 periods<br>2 of 12 periods | 1 of 30 periods<br>1 of 12 periods | 1 of 30 periods | 2 of 30 periods<br>3 of 12 periods |
| UPDA | 1 of 30 periods<br>1 of 12 periods | 1 of 28 periods†<br>1 of 12 periods | 1 of 29 periods† | 1 of 30 periods<br>1 of 20 periods |

† indicates a recording error that resulted in the elimination of one or two periods of data

The UPDA data utilizing a 70% of first step must-serve penalty condition was generated in four experiments of 30 periods each, which are not included above. These four cases comprised the factorial design for 3 vs. 6 sellers, and once vs. twice experienced subjects.

## Table 5
## SBO and UPDA Market Mechanisms, 100% Must Serve Penalty Condition Only

Coefficient estimates and (t – statistics)

| Independent Variables | Dependant Variables: Total Efficiency | Seller Surplus | Buyer Surplus | Buyer Price |
|---|---|---|---|---|
| Constant | **0.715**<br>**(24.07)** | **12,788**<br>**(7.845)** | **-22,213**<br>**(-9.659)** | **71.38**<br>**(11.67)** |
| Dependent variable, lagged one period | **0.105**<br>**(3.214)** | **0.307**<br>**(10.189)** | **0.324**<br>**(10.84)** | **0.316**<br>**(12.46)** |
| D2: Number of Sellers, 6 vs 3: 1/0 | 0.009<br>(0.374) | **-11,365**<br>**(-6.344)** | **13,146**<br>**(6.112)** | **-53.89**<br>**(-8.472)** |
| D3: Peak Demand, peak vs not: 1/0 | **-0.183**<br>**(-9.956)** | **-4,931**<br>**(-3.709)** | **-12,816**<br>**(-8.075)** | **-17.34**<br>**(-3.662)** |
| D4: Off Peak Demand, off peak vs not: 1/0 | **-0.081**<br>**(-3.354)** | **-7,428**<br>**(4.336)** | 2,828<br>(1.370) | -2.225<br>(-0.371) |
| D5: Must Run Penalty, 100% vs 50%: 1/0 | -0.007<br>(-0.371) | **-8,911**<br>**(-6.760)** | **8,511**<br>**(5.427)** | **-29.97**<br>**(-6.502)** |
| D7: Market Mechanism, SBO vs UPDA: 1/0 | **0.114**<br>**(5.165)** | **-9,749**<br>**(-6.039)** | **17,621**<br>**(8.720)** | **-59.98**<br>**(-10.20)** |
| D2D7: 6 Sellers & SBO Mechanism vs not: 1/0 | -0.002<br>(-0.057) | **10,993**<br>**(4.915)** | **-12,600**<br>**(-4.704)** | **55.92**<br>**(7.044)** |
| D4D5: Off peak & 100% Must Run Penalty vs not: 1/0 | **-0.215**<br>**(-6.910)** | **21,681**<br>**(9.703)** | **-30,680**<br>**(-11.45)** | **117.4**<br>**(14.95)** |
| Adjusted. $R^2$ | 0.282 | 0.339 | 0.433 | 0.603 |
| F – statistic | **37.72** | **50.85** | **75.15** | **148.3** |

n = 778, Boldface values are significant at 95%, or $p < 0.05$

**Table 6**
**UPDA Market Mechanism Only,**
**100% vs 70% Must Serve Penalty Conditions**

Coefficient estimates and (t – statistics)

| Independent Variables | Dependant Variables: Total Efficiency | Seller Surplus | Buyer Surplus | Buyer Price |
|---|---|---|---|---|
| Constant | **0.680** **(17.75)** | **14,994** **(7.418)** | **-27,848** **(-10.00)** | **71.62** **(8.899)** |
| Dependent variable, lagged one period | **0.099** **(2.207)** | **0.309** **(7.054)** | **0.324** **(8.017)** | **0.381** **(9.767)** |
| D2: Number of Sellers, 6 vs 3: 1/0 | 0.019 (0.676) | **-14,150** **(-6.450)** | **16,437** **(6.610)** | **-52.74** **(-6.669)** |
| D3: Peak Demand, peak vs not: 1/0 | **-0.167** **(-5.292)** | 232.7 (0.101) | **-18,290** **(-7.019)** | -0.237 (-0.029) |
| D4: Off Peak Demand, off peak vs not: 1/0 | **-0.131** **(-3.172)** | **-15,788** **(-5.237)** | **12,372** **(3.602)** | 2.442 (0.229) |
| D5: Must Run Penalty, 100% vs 50%: 1/0 | **0.064** **(2.073)** | **-12,358** **(-5.419)** | **17,185** **(6.649)** | **-46.97** **(-5.848)** |
| D2D4: 6 Sellers & Off Peak vs not: 1/0 | -0.001 (-0.030) | **11,539** **(3.281)** | **-13,313** **(-3.341)** | 16.91 (1.364) |
| D4D5: Off peak & 100% Must Run Penalty vs not: 1/0 | **-0.215** **(-4.203)** | **19,719** **(5.285)** | **-30,142** **(-7.111)** | **91.94** **(6.968)** |
| D3ND6: Peak & 70% Must Serve Penalty vs not: 1/0 | **0.180** **(3.701)** | **-11,009** **(-3.115)** | **31,952** **(7.893)** | **-48.06** **(-3.846)** |
| Adjusted. $R^2$ | 0.171 | 0.312 | 0.417 | 0.525 |
| F – statistic | **11.56** | **24.33** | **37.70** | **57.77** |

n = 412, Boldface values are significant at 95%, or $p < 0.05$

**Table 7**
**Sealed Bid-Offer Market Mechanism Only,**
Coefficient estimates and (t – statistics)

| Independent Variables | Dependant Variables: Total Efficiency | Seller Surplus | Buyer Surplus | Buyer Price |
|---|---|---|---|---|
| Constant | **0.843** **(21.540)** | 716.6 (0.522) | **-4,654** **(-2.665)** | 6.212 (1.389) |
| Dependent variable, lagged one period | **0.086** **(2.039)** | **0.192** **(5.631)** | **0.016** **(4.172)** | **0.133** **(5.170)** |
| D2: Number of Sellers, 6 vs 3: 1/0 | 0.042 (1.564) | -250.9 (-0.153) | 2,907 (1.470) | 0.305 (0.058) |
| D3: Peak Demand, peak vs not: 1/0 | **-0.189** **(-9.194)** | **-8,041** **(-6.334)** | **-8,593** **(-5.571)** | **-31.66** **(-7.550)** |
| D4: Off Peak Demand, off peak vs not: 1/0 | -0.045 (-1.361) | -1,522 (-0.769) | -1,484 (-0.618) | **14.45** **(2.259)** |
| D5: Must Run Penalty, 100% vs 50%: 1/0 | -0.034 (-1.310) | **-7,650** **(-4.784)** | **4,662** **(2.421)** | **-21.32** **(-4.113)** |
| D2D4: 6 Sellers & Off Peak vs not: 1/0 | -0.061 (-1.765) | **-6,258** **(-2.963)** | 3,297 (1.290) | **-23.10** **(-3.379)** |
| D2D5: 6 Sellers & 100% Must Run Penalty vs not: 1/0 | -0.028 (-0.853) | 3,970 (1.962) | **6,861** **(-2.795)** | **20.89** **(3.187)** |
| D4D5: Off peak & 100% Must Run Penalty vs not: 1/0 | **-0.189** **(5.447)** | **22,401** **(10.573)** | **-30,039** **(-11.637)** | **125.1** **(18.122)** |
| Adjusted. $R^2$ | 0.286 | 0.433 | 0.432 | 0.731 |
| F – statistic | **25.08** | **46.93** | **46.81** | **164.8** |

n = 482, Boldface values are significant at 95%, or $p < 0.05$

**Figure 1.**
**Induced Supply and Demand Schedules (at Buyer Node)**