Strategic Behavior in Smart Markets with Avoidable Fixed Costs: an Experimental Study

Rimvydas Baltaduonis

Gettysburg College, 300 N Washington St, Campus Box 391, Gettysburg, PA 17325, USA
Phone: (717) 337-6671
Fax: (717) 337-6638
E-mail: rbaltadu@gettysburg.edu

Abstract Previous research of complex-offer auctions designed for deregulated electricity markets finds that offer complexity allows great deal of strategic behavior, which consequently leads to anti-competitive and inefficient outcomes. In these smart markets that employ complex-offer auctions, the sellers submit not only quantities and minimum prices at which they are willing to sell, but also start-up fees that are designed to reimburse the fixed start-up costs of the electric power generators. Using an experimental approach, I compare the performance of two complex-offer auctions against the performance of a simple-offer auction, in which the sellers have to recover all their generation costs – variable and fixed – through a uniform market-clearing price. I find that the simple-offer auction significantly reduces consumer prices and lowers price volatility. It mitigates anti-competitive effects that are present in complex-offer auctions and achieves allocative efficiency more quickly.

Keywords *Complex-offer auction, Electricity, Procurement, Efficiency, Two-part pricing, Avoidable fixed cost*

JEL Classification *C72, D4, D61, L94*

1 Introduction

11 billion kilowatt-hours were traded daily in the U.S. wholesale electric power markets in 2006. Average price ranged between a tenth of a mill and 50 cents per kWh[1]. Many of these markets employ auctions that differ from other widely used quantity-price offer auctions in their offer complexity. Besides the quantities and the minimum prices, at which the electric power producers are willing to sell, the sellers may also declare their

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[1] Energy Information Administration, Form EIA-861, Annual Electric Power Industry Report.

technical constraints and start-up fees that are designed to reimburse the fixed start-up costs of the generation plants. The start-up costs are avoidable fixed costs that create non-convex allocation problems. This paper investigates what value is gained from incorporating this complexity into deregulated electricity markets. The generation contracts are allocated daily by a sealed-offer auction that employs a computationally involved market-clearing algorithm. Besides applying a rule for offer selection, a market-clearing algorithm has to ensure that the system demand and reserve requirements are met over a particular time.

Baltaduonis (2007b) compares the performance of two such auctions with regard to consumer prices and efficiency by using a laboratory experiment. The major finding is that the sellers exploit the offer complexity to extract high payments from the buyers. Consequently, the outcomes result in substantial inefficiencies. In this paper, I use a laboratory experiment to contrast the performance of these complex-offer auctions (COAs) against the performance of a simple-offer auction (SOA) where the sellers can recover their generation costs – both variable and avoidable fixed – only through a uniform market-clearing price (MCP). The paper inquires if the SOA could mitigate the anti-competitive behavior that is present in the COAs.

Two COAs differ from each other in their market-clearing algorithms. An offer cost minimization (OCM) algorithm is currently used by independent system operators (ISOs) in the U.S. It relies on the traditional unit commitment approach.[2] The algorithm minimizes the total offered cost of electricity for a given demand as if all selected sellers would be paid their offered prices and fees. *Sequentially*, after the offers are selected, a

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[2] For a bibliographical survey on the unit commitment problem see Padhy (2004).

uniform MCP is determined as the highest accepted price for that period. All selected sellers receive their individual start-up fees and the *uniform* MCP for the supplied electricity during that period.

Yan and Stern (2002) point out that the OCM algorithm does not ensure the lowest procurement cost of electricity to consumers for a given set of offers. This motivated Luh et al. (2005) to develop a payment cost minimization (PCM) algorithm that minimizes the actual procurement cost of electricity *simultaneously* determining a MCP as the highest accepted price during that period. As in the OCM auction, the selected sellers would receive their individual start-up fees and the *uniform* MCP for the supplied electricity.

Electrical engineers have studied non-convex optimization problems, similar to the OCM and the PCM algorithms, for many years. Attempts to improve these mechanisms heavily depend on the assumption of complete information about the generation costs of electric power.[3] Baltaduonis (2007b) reports that in both the OCM and the PCM auctions, sellers significantly raise the start-up fees and prices over their true start-up costs and variable production costs even in an environment with many competitors. Such behavior leads to both allocative and production inefficiencies. Thus, the theoretical assumption of truthful production cost revelation seems to be unwarranted.

To analyze the performance of the SOA I hold constant all other characteristics of the system described by Baltaduonis (2007b). The SOA is a less computationally involved auction than the COAs and thus more transparent to market participants. On the other hand, the exact revelation of production costs is impossible in the SOA. The sellers have

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[3] For a recent work on mechanisms for markets with non-convexities that is motivated by electric power markets see O'Neill et al. (2004).

to mark up their offered prices to account for the fixed start-up costs or they might incur losses. A higher risk of losses becomes a concern.

Van Boening and Wilcox (1996), hereafter VW, report an experiment in which a continuous double SOA fails to converge and stabilize on 100% efficient allocations in an environment with avoidable fixed costs. Durham et al. (1996), hereafter DRSVW, explore two-part pricing competition in a sealed-offer auction experiment as a means of improving efficiency in the VW environment. DRSVW find that in a setting with experienced sellers and simulated buyers, this institution is effective in promoting full efficiency, however, still not immune to efficiency collapses. In a different environment with both fixed sunk and fixed avoidable costs, Durham et al. (2004), hereafter DMORS, examine the price levels under a SOA by varying the demand elasticity and the experience level of sellers. They observe the pattern of price signaling and responses which despite the presence of fixed costs help to maintain above normal profits. The authors do not comment on the efficiency performance of the auction or the magnitude of observed losses in the market.

All aforementioned studies model the market demand as static. This paper simulates a cyclical nature of the daily demand for electricity. Baltaduonis (2007b) points out that cyclical market demand might be essential in shaping strategic behavior in the COAs. As in Rassenti, Smith & Wilson (2003a, 2003b), hereafter RSW, my experiment allows for strategic behavior, controls for the level of unilateral market power, simulates trading environments with minimal demand elasticity, cyclical demand uncertainties and an absence of significant excess production capacity.

Concerns about market power in the electric power industry abound. One might want to know which trading rules are more effective in suppressing the exercise of market power. In the context of capacity-constrained competitors, Holt (1989) defines market power as the ability to deviate *profitably* and *unilaterally* from the competitive outcome. Baltaduonis (2007b) reports that both the OCM and the PCM auctions produce noncompetitive outcomes even in the treatments with no unilateral market power. Since the SOA reduces the scope of possible strategic behavior, I hypothesize that ceteris paribus, the SOA should increase competitiveness in the market. The COAs' intention to account for the non-convex cost structures of generation plants also opens opportunities to strategize over the different parameters of complex offers. The opportunities are fewer on that regard in the SOA. Baltaduonis finds that in the COAs, the offer complexity and the cyclical nature of market demand create incentives to start-up plants during the higher demand periods. Consequently, the incentives to compete for baseload or shoulder demand units vanish even with the presence of cheap excess production capacity. Opting for a SOA should eliminate these anti-competitive incentives.

An intention of this experimental study is to complement theoretical research of auctions where avoidable fixed costs are an important production characteristic. The study sheds some light on possible strategic behavior in smart markets that are proposed for wholesale electric power markets. The remainder of the paper is organized as follows. Section 2 outlines the market environment in the experiment and describes three auctions. Section 3 presents the experimental design and procedures. Section 4 reports the findings. Section 5 concludes and discusses the implications for public policy.

2 Market Institution, Structure and Environment

To isolate the institutional effects of the strategically complex auctions, I examine a very simple environment relative to actual electric power systems: (i) transmission constraints are negligible; (ii) generators have no physical ramping rates; (iii) security reserves and other ancillary services to protect the system from outages are ignored; and (iv) a trading institution accepts flat offer curves for each generating unit. Such an environment is most comparable to day-ahead wholesale markets of observed power systems. The performance of the SOA is measured against the OCM and the PCM auctions in a stationary supply and cyclical demand environment, controlling for unilateral market power.

2.1 Auction Institution

The sellers privately submit a schedule of offers; that is, plant start-up fees and prices for their production capacity for each pricing period of a day. The buyers submit a schedule of bids. Since active demand-side bidding is often absent in the naturally occurring spot markets for electricity, a computer is used to submit bids that perfectly reveal the demand at any point in time in the experiment[4]. The offers and the computerized bids are then sent to a market-clearing algorithm to allocate the production contracts for the next day. Currently, the dominant practice in the electricity spot markets is to employ uniform price auctions where each seller receives the same market price for the sold megawatts. The market price is usually the highest accepted price per megawatt among all the sellers. I retain these institutional features and put aside the discussion about the "pay-as-offered"

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[4] Same as in RSW, DRSVW and DMORS.

discriminatory price auctions.[5] In all experimental treatments, i.e. OCM, PCM and SOA, the sellers get paid *uniform* prices and their *individual* start-up fees. In the SOA, the start-up fees are simply constrained to be zero.

In case of a uniform price auction where sellers ask for fixed start-up fees, the mechanism of distributing these fees across consumers is important. One way to do that is to divide the borne fees equally over the units dispatched during the period for which the extra generation capacity was called. The markup on the highest accepted offered price creates a gap between a uniform price that all sellers receive and a uniform price that all buyers pay. In this experiment, both the OCM and the PCM algorithms employ this method to compute the buyer prices and to determine the corresponding levels of demand. Note that a uniform price that all sellers receive and a uniform price that all buyers pay are the same in the SOA due to the absence of start-up fees.

2.1.1 The OCM Auction

The OCM algorithm minimizes the total offer costs of electricity, as if all selected sellers would be paid their offer prices and fees:

$$\underset{q_i(t),x_i(t)}{\text{Min}} \sum_{t=1}^{T}\sum_{i=1}^{N} c_i(t)q_i(t) + f_i(t)x_i(t)$$

$$\begin{aligned} \text{subject to } \sum_{j=1}^{M} d_j(t) = \sum_{i=1}^{N} q_i(t) \quad & \forall t = 1,\ldots,T, \\ q_i(t) \le x_i(t)k_i(t) \quad & \forall i = 1,\ldots,N, \\ q_i(t) \ge x_i(t)l_i(t) \quad & \forall i = 1,\ldots,N, \\ x_i(t) \in \ 0,1 \quad & \forall i = 1,\ldots,N. \end{aligned}$$

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[5] For experimental investigations of uniform price versus discriminatory price auctions SOAs see Mount, Schulze, Thomas & Zimmerman (2001), and Rassenti, Smith & Wilson (2003b).

where $i = 1,\ldots,N$ indexes the generation plants;
$j = 1,\ldots,M$ indexes the buyers;
$t = 1,\ldots,T$ indicates the pricing periods during a day;

$$\text{Offers submitted by sellers:}\begin{cases} c_i(t) = \text{price per unit asked for plant } i; \\ f_i(t) = \text{start-up fee asked for plant } i; \\ k_i(t) = \text{max capacity of plant } i; \\ l_i(t) = \text{min capacity of plant } i; \end{cases}$$

$$\text{Decision variables:}\begin{cases} q_i(t) = \text{\# units produced in plant } i; \\ x_i(t) = \begin{cases} 1 \text{ if plant } i \text{ is chosen to produce,} \\ 0 \text{ if plant } i \text{ is not chosen to produce.} \end{cases} \end{cases}$$

After the offers are selected, a uniform MCP is determined as the highest accepted price for each period *t*:

$$MCP(t) = \max\ c_i(t), \forall i \text{ such that } q_i(t) > 0\ .$$

All selected sellers receive their individual start-up fees and the uniform MCPs for the supplied electricity.

2.1.2 The PCM Auction

The PCM algorithm minimizes the actual procurement cost of electricity, *simultaneously* determining a MCP as the highest accepted price for each period *t*:

$$\underset{q_i(t),x_i(t)}{\text{Min}} \sum_{t=1}^{T}\sum_{i=1}^{N} MCP(t)q_i(t) + f_i(t)x_i(t)$$

$$\begin{aligned} \text{subject to } \sum_{j=1}^{M} d_j(t) &= \sum_{i=1}^{N} q_i(t) && \forall t = 1,\ldots,T, \\ q_i(t) &\le x_i(t)k_i(t) && \forall i = 1,\ldots,N, \\ q_i(t) &\ge x_i(t)l_i(t) && \forall i = 1,\ldots,N, \\ x_i(t) &\in \ 0,1 && \forall i = 1,\ldots,N. \end{aligned}$$

As in the OCM auction, the selected sellers receive their individual start-up fees and the uniform MCPs for the supplied electricity.

In the experiment, both the OCM and the PCM auctions are designed to sell the maximum amount of units where buyers’ marginal willingness to pay is higher or equal to a buyer price. Tied offer combinations in the OCM auction are picked in a way that generates lower procurement cost. Tied offer combinations in the PCM auction are selected by giving priority to those sellers whose offer cost is lower. Such tie breaking mechanism gives the best performance chances to both COAs. To achieve similar tie breaking in real life applications would require additional costly computational power and time.

2.1.3 The Simple-Offer Auction

The sellers in the SOA can recover their production costs – both variable and avoidable fixed – only through a uniform MCP. Note that the SOA is a special case of the COAs, i.e. it is a COA where the start-up fees are constrained to be zero. The contract allocations in two COAs are identical when the start-up fees equal to zero. The offer cost minimization becomes equivalent to the payment cost minimization. Hence, either the OCM or the PCM algorithm could be used for the SOA by simply restricting all start-up fees to be zero, i.e. $f_i(t) = 0$ for $\forall i = 1,..., N$. The selected sellers receive the uniform MCPs for the supplied electricity.

In the complex-offer auctions, the suppliers are able to reveal their costs and be reimbursed in a way that the costs are incurred. In the SOA, the sellers have to think how to recover the fixed costs through the offered prices. See Appendix A for a simple numerical example that demonstrates the principles of offer-selection rules for all three considered auctions.

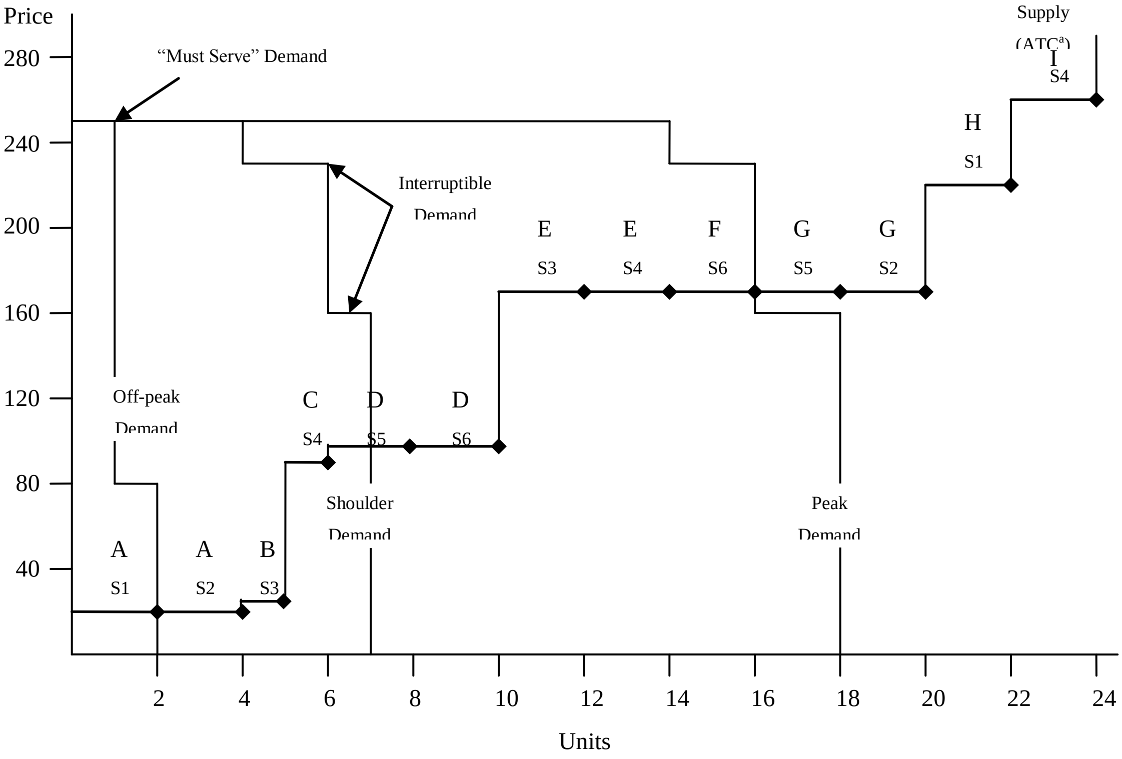
2.2 Environment

2.2.1 Supply & Demand

Each day in the experiment consists of four pricing periods: off peak period (low demand/night), shoulder period (medium demand/morning), peak period (high demand/ afternoon) and shoulder period (medium demand/ evening). Four pricing periods during the day are a simplification of the naturally occurring day-ahead electricity markets where separate prices are instituted hourly. Nevertheless, the cyclical dynamics of the demand are preserved.

Tables 1 and 2 as well as Fig. 1 depict aggregate supply and demand in the experimental environment. The second and third steps of the demand in Table 1 represent interruptible units of demand whereas the units on the first step at 250 are the “must serve” units. The level of “must serve” demand varied among three levels: 1 unit in off-peak periods, 4 units during shoulder periods, and 14 units during peak periods.

The market is comprised of six sellers denoted by an “*S*” and an identification number. The sellers own 13 plants of nine types. The technical characteristics of each plant are presented in Table 2. Fig. 1 presents the ownership of the plants. *S*1 and *S*2 own two low cost (type *A*) plants and two high cost plants (type *H* and *G* respectively). *S*3 and *S*4 own two high cost (type *E*) plants and respectively, one baseload (type *B*) plant and one intermediate cost (type *C*) plant. *S*4 also owns a very high cost (type *I*) peak capacity plant with average total cost (ATC) exceeding even the resale value at the “must serve” level. Each *S*5 and *S*6 own one intermediate cost (type *D*) plant and one high cost (type *G* and *F* respectively) peak capacity plant.



^{a}Average total costs at the maximum capacity of a plant.

Fig. 1 Market Structure and Design

Table 1 Demand Schedules

Demand	Quantity (demand values)		
	Step 1	Step 2	Step 3
Off-peak	1 (250)	1 (80)	N/A
Shoulder	4 (250)	2 (230)	1 (160)
Peak	14 (250)	2 (230)	2 (160)

The types and the distribution of ownership of the plants are designed to create a Bertrand-like competition between the marginal plants during each period of a day. In other words, at least two plants with identical production costs on the supply margins exist for each level of demand. In a competitive bidding process, *S*1's plant *A* can be easily replaced by *S*2's plant *A* during an off-peak period and *S*5's plant *D* can be easily replaced by *S*6's plant *D* during the shoulder periods. Five plants with 10 units of total capacity and identical ATC compete to supply six units of peak demand. Some plants have low start-up costs with high production costs per unit, while other plants have high start-up costs but lower production costs per unit. In a competitive equilibrium, the number of supplied units is 2 in off-peak periods, 7 in shoulder periods and 16 in peak periods. The lower quantities of supplied units would be the evidence of allocative inefficiencies. Note that an efficient allocation of production contracts would never include *S*4's plant *I* and *S*1's plant *H*.

Table 2 Average Total Costs (ATC) of Production at Maximum Capacity (Cap.) by Plant Type

Plant Type	Min Cap.	Max Cap.	Start-up Cost	Per Unit Cost	ATC at Max Cap.	Total Cap.
(Quantity)	Units	Units	$	$/Unit	$/Unit	Units
A (2)	0	2	0	20	20	4
B (1)	1	1	10	15	25	1
C (1)	0	1	20	70	90	1
D (2)	0	2	6	93	96	4
E (2)	0	2	120	112	172	4
F (1)	0	2	80	132	172	2
G (2)	0	2	40	152	172	4
H (1)	0	2	0	225	225	2
I (1)	0	2	0	255	255	2
					Total	24

2.2.2 Unilateral Market Power

In the experiment, a seller is said to be able to exert market power if, for a given distribution of capacity ownership, a seller profitably and unilaterally can submit an offer schedule above his plants' costs (or equivalently withdraw some generating capacity) such that the market price rises above the competitive level.

The costs for the units in the marginal plants are 20, 99, 172 and 93 per unit in the off-peak, shoulder 1, peak and shoulder 2 periods respectively. In the SOA, these costs translate into the competitive market prices at which the marginal plants earn zero economic profits. None of the six sellers can benefit from a unilateral attempt to raise the market prices above the competitive level. In doing so, the sellers of intermediate units would jeopardize their profits and the sellers of marginal units would simply lose the contract to his Bertrand-like competitor. The competitive prices correspond to a pure strategy Nash equilibrium in the SOA.

In the COAs, the marginal generators also have incentives to submit offers that are equal to the actual production costs of the marginal units but only if we look at an isolated period of the demand cycle. The asked fees do not necessarily need to be the actual start-up costs but then the offered seller prices need to add up to the actual production costs. Consider the OCM auction for an illustration. Take a shoulder 1 period. Each *S*5 and *S*6 owns a marginal intermediate cost plant that competes to supply the marginal seventh unit to the market. Either plant can generate this marginal unit at a cost of 99 [6+93]. If a seller offers to supply the unit at a cost higher than 99, the other seller would be able to undercut the offer by either lowering the fixed fee or lowering the offered seller price. Therefore, a start-up fee and a price per unit would have to add up to 99 in a competitive offer of *S*5 or *S*6.

Similarly, the competitive marginal offers [$\text{start-up fee} + \text{price per unit} \times 2 \div 2$] would have to be 20 during the off-peak periods, 172 during the peak periods and 93 during the shoulder 2 periods.

This illustration disregards the incentives to withhold a plant's capacity during the lower demand periods due to the opportunities to extract bigger start-up fees during the higher demand periods. For instance, *S*6 can decide to delay the start-up of his plant by placing a high offer for shoulder 1 period. Assume that *S*6's peak offer is 340 for the start-up fee and 1 for price. This offer is still cheaper than the competitive offers of the peak plants for 172 per unit $> \; 340+2\times 1 \;\; \div 2$. In this case, *S*6 makes a significant profit by abandoning competition in shoulder 1 period and by deliberately delaying the start-up of his plant *D* till the peak period. Consequently, *S*5 can now profitably raise her offer above her costs for shoulder 1 period as the competition from her Bertrand-like competitor *S*6 is absent. A competitive outcome becomes practically impossible. By allowing the sellers to submit complex-offers, the market mechanism automatically creates market power. This result holds for both the OCM and the PCM auctions. Note that the additional production capacity would not improve competitiveness in this environment because the suppliers of the additional capacity would have the same incentives to delay the start-ups.

The supply and demand are the same during the two shoulder periods of a day. However, since most plants are generating electricity during the peak period, they do not incur start-up costs and do not receive start-up fees to continue production during the shoulder 2 period, i.e. $f_i(\text{shoulder 2}) = 0 \quad \forall i$ such that $q_i(\text{peak}) > 0$. For this reason, all three examined auctions should perform similarly during the fourth period of a day. Theoretically, none of the six sellers can benefit from a unilateral attempt to raise the MCP above 93. The competitive price of shoulder 2 corresponds to a pure strategy Nash equilibrium in all three auctions.

3 Experimental Design and Procedures

To compare how the behavior and market performance differ in the complex- and simple-offer auctions, I conducted 12 experimental sessions using undergraduate students at George Mason University. The data from eight sessions of the OCM and the PCM treatments was previously presented by Baltaduonis (2007b). The reported data from four SOA sessions is new. Each session lasted 53 trading days. The dataset discussed in this paper includes a total of 636 trading days. Each session lasted approximately 90 minutes. The subjects in each market were provided with complete information about the market supply structure. Plants' minimum and maximum production capacity, start-up cost, cost per unit and the ownership of all plants were public information. Information about demand, however, was not available to the subjects. The situation was framed as a market for identical product to avoid the use of possibly intimidating or confusing electric power jargon. The instructions informed the subjects that the costs and production capacities for each seller would not change during the experiment, but that the purchased quantities of the product would vary over the course of a day. In particular, the instructions indicated that the computer will purchase "low" amounts of product for the first quarter of a day, "medium" amounts for the second quarter of a day, "high" amounts for the third quarter of a day and "medium" amounts for the fourth quarter of a day. The subjects did not know the number of trading days in advance. The instructions were read aloud in the beginning of each session.

A subject had 75 seconds to submit an offer for each day.[6] An exception was made for the first day offers. The sellers could take as much time as they needed to formalize their initial offers. Once the last seller submitted her offer for the first day, the following trading days were limited to 75 seconds. The offers were automatically filled in with the offer information from the previous trading day. However, a seller could revise her offer at any time within the 75 second period. An offer indicated the prices, start-up fees and quantities of the product that a seller was willing to supply from a particular plant over the course of the following day. The subjects could not alter the minimum and maximum quantities of the offer.[7] These quantities were set equal to the minimum and maximum capacities of a plant. The subjects could still effectively withdraw the capacity from the market by asking extremely high prices for those capacity units. Thus, in a COA, a seller had to decide on the price and the start-up fee for each plant and for each quarter of the upcoming day.[8] In the SOA, a seller had to decide only on the price for each plant for each quarter of the upcoming day, as all start-up fees were set equal to zero. The instructions pointed out that the actual market price may be higher than their offered price and that all sellers would receive the same market price if their offers were selected. The sellers received start-up fees only for the periods when their plant had to be started. In the beginning of each day all plants were idle.

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[6] The chosen time frame is similar to one-minute trading days of the RSW electric power experiments and 75 s trading days of DMORS experiment.

[7] ISOs usually demand an explanation if generators change their offered generation capacity or technical constraints. Thus strategic behavior is somewhat limited with regards to these parameters of an offer.

[8] I am aware that there are various initiatives to regulate start-up cost reimbursement (e.g. limiting the ability to change the start-up fees freely; and partial start-up cost reimbursement) for electric power generators in naturally occurring markets. However, the purpose of the study is to investigate the performance of the two auctions when such interventions into a deregulated market are absent.

At the end of the trading day, all offers were sent to the computerized market coordinator. A market-clearing algorithm was applied and the results of a sealed-offer auction were sent back to the sellers. Each seller could see how many units she sold, what the MCP for each period was and what profit/loss she earned on every owned capacity unit during each period of a day. The screens also displayed a history of the market prices from the past 10 days and the sold quantities during each quarter of the last day. The amount of paid fees was not public information.[9]

Subjects were paid $7 for showing up on time for the sessions. In addition to this show-up payment, the average earnings per subject for the data reported here was $21.55.

4 Results

The SOA, OCM and PCM auctions respectively extract on average 93, 92 and 94 percent of maximum total surplus. All three auctions sell on average 32 units a day. Thus, considering that the demand side of the market is perfectly revealed in the experiment, lower levels of allocative efficiency must be attributed to higher degrees of production inefficiency. To present how the captured total surplus is allocated among buyers and sellers and how volatile the allocation is, Fig. 2 depicts the buyer prices in each session of the three treatments. The last 17 days of the data are grouped by level of demand (quarter) then sequenced by how the demand varied over a market day: off-peak, shoulder 1, peak and shoulder 2.

I evaluate the results with respect to a benchmark of true cost revelation. The outcome of true cost revelation is particularly interesting in electricity markets because the design

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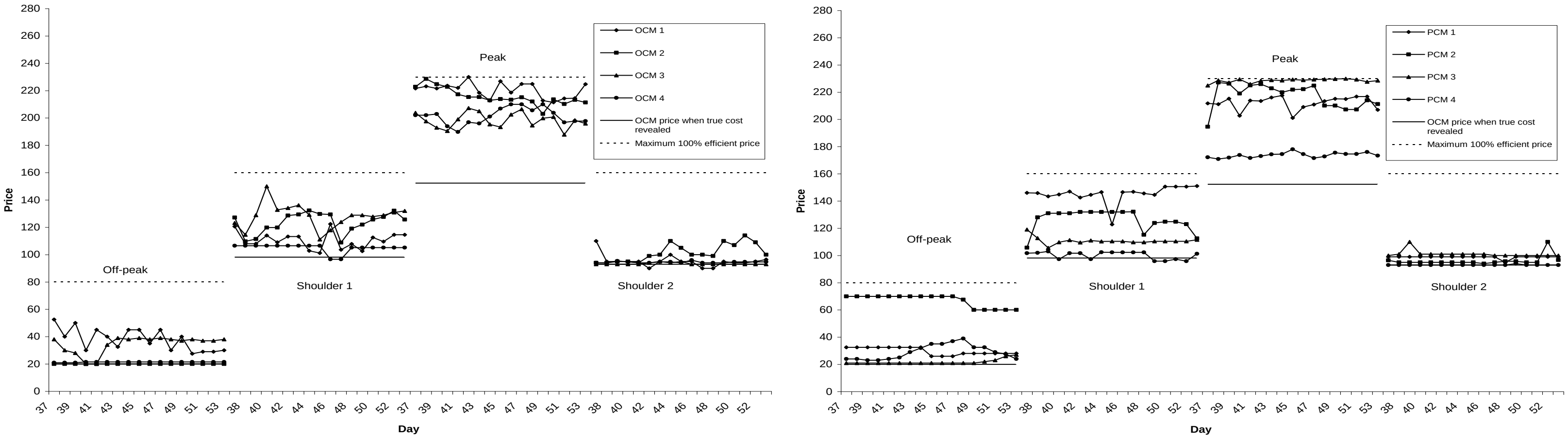
[9] See Appendix B for the experimental instructions and Appendix C for an example of a subject screen during the experiment.

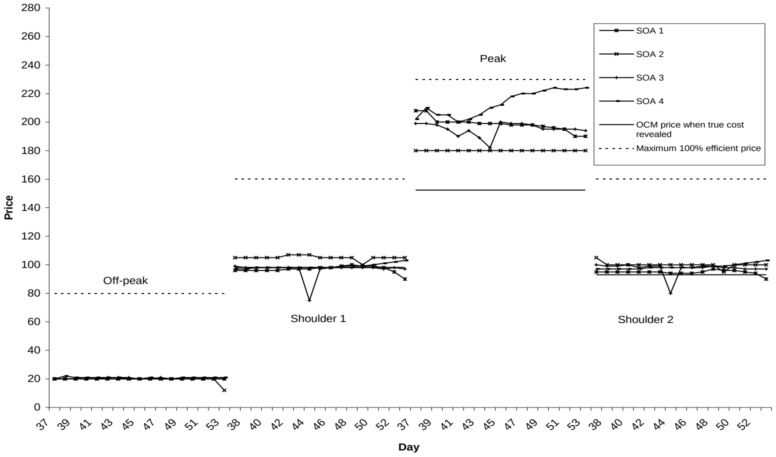
and the engineering of these complicated market systems often start with the assumption of the true cost revelation. In Fig. 2, the outcome of the perfectly revealed costs is shown as a solid line. The dotted line represents the value of the nearest unit of interruptible demand. The prices up to the dotted line are 100% efficient with respect to allocation. As an attempt to control for the convergence of the bidding behavior, I focus on the last 17 market days (1/3 of all days) in each session unless referred otherwise.

In Fig. 2, the SOA is more likely to approach the true cost revelation outcome than either of the two COAs. Both the OCM and the PCM auctions tend to deviate significantly from the outcome of perfectly revealed costs with shoulder 2 periods being an exception. In the SOA, the buyer prices substantially depart from the competitive outcome only during the peak periods. During shoulder 2 periods, all three auctions result in competitive outcomes. The conformity is not accidental since the fixed costs are absent in this period and, therefore, all three offer selection rules are identical as the start-up fees equal to zero.



(a) OCM

(b) PCM



(c) SOA

Fig. 2 Buyer Prices by Level of Demand for the Last 17 Market Days in Each Session

In what follows, the experimental results are summarized as a series of six findings. In addition to the qualitative results displayed in the figures, I analyze the data using a mixed-effects model for repeated measures on each of several sessions using different subjects. The results from estimating this model for the buyer prices by level of demand are given in Table 3. The dependent variable in this case is the difference between the observed buyer price (*Price*) and the buyer price from the OCM auction when production costs are perfectly revealed by the sellers, P^t. In the regressions, the SOA is used as a benchmark institution to allow for its straightforward comparison against the OCM and the PCM auctions. The treatment effects (*OCM* and *PCM*) are modeled as (zero-one) fixed effects, whereas the sessions are modeled as random effects, e_i. As mentioned above, the experimental days are divided into three equal groups to capture effects like learning over time. In the model, the data from the *First* and *Second* groups (days 1-18 and 19-36, respectively) are identified by (zero-one) dummy variables. Specifically, the estimated model is as follows:

$$Price_{ij}\text{-}P^t=\mu+e_i+\beta_1 OCM_i+\beta_2 PCM_i+\beta_3 First_i+\beta_4 Second_i+\beta_5 OCM_i\times First_i+$$

$$\beta_6 OCM_i\times Second_i+\beta_7 PCM_i\times First_i+\beta_8 PCM_i\times Second_i+\varepsilon_{ij};$$

where the sessions are indexed by i=1,…,12 and the repeated market days by j=1,…,53. $e_i \sim N(0,\sigma^2_1)$ and $\varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$.

Finding 1. *Ceteris paribus, the SOA institution significantly lowers buyer prices relative to the COAs in the periods when start-up costs are relevant. Buyer prices are not significantly different in shoulder 2 periods when no new plants need to be started and no start-up fees need to be paid.*

Support: Fig. 2 clearly illustrates that both the OCM and the PCM auctions can produce higher buyer prices than the SOA in all three periods where new plants need to be started, that is, in off-peak, shoulder 1 and peak periods. Except for peak periods, buyer prices in the SOA settle very close to the competitive equilibrium, i.e. 20, 99, 172 and 93, during the respective quarters of a day. SOA prices for peak periods do not come close to the expected competitive level of 172. My speculation is that the incentives to undercut the competitors' offers are weaker in the peak periods because winning a marginal contract and setting a lower uniform market price also means smaller profits for the low or/and intermediate cost plants that the seller owns. On the other hand, no discernible separation exists among three auctions in shoulder 2 prices. Since most of the plants are operating during the peak periods, no new plants need to be started when market demand falls. The absence of start-up fees makes the three offer selection rules identical which consequently should lead to similar outcomes.

These qualitative observations are supported by estimates from the mixed-effects model in Table 3. The SOA significantly reduces prices by 19.5 (*p-value*=0.0077) and 17 (*p-value*=0.0744) experimental dollars in the shoulder 1 and peak periods when compared to the OCM auction. The SOA significantly reduces prices by 18.2 (*p-value*=0.0417), 17.4 (*p-value*=0.0127) and 20 (*p-value*=0.0418) experimental dollars respectively in the off-peak, shoulder 1 and peak periods when compared to the PCM auction. The prices in shoulder 2 periods are not significantly different across all three auctions (*p-values*=0.1615, 0.4404 for OCM and PCM, respectively).■

Table 3 Estimates of the Linear Mixed Effects Model of Treatment Effects for the Buyer Prices

$$Price_{ij} - P^t = \mu + e_i + \beta_1 OCM_i + \beta_2 PCM_i + \beta_3 First_i + \beta_4 Second_i + \beta_5 OCM_i \times First_i + \beta_6 OCM_i \times Second_i + \beta_7 PCM_i \times First_i + \beta_8 PCM_i \times Second_i + \varepsilon_{ij},\ \ e_i \sim N(0,\sigma^2_1) \text{ and } \varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$$

	Estimate	Std. Error	Degrees of Freedom	H_a	t-statistic	p-value
Off-peak						
μ	**-1.21**	**5.41**	**618**	**$\mu>0$**	**-0.22**	**0.8227**
OCM	**8.58**	**7.70**	**9**	**$\beta_1 \neq 0$**	**1.12**	**0.2935**
PCM	**18.23**	**7.68**	**9**	**$\beta_2 \neq 0$**	**2.37**	**0.0417**
First	-1.66	0.40	618	$\beta_3 \neq 0$	-4.19	<.0001
Second	-0.36	0.40	618	$\beta_4 \neq 0$	-0.92	0.3584
OCM×First	-5.06	1.28	618	$\beta_5 \neq 0$	-3.95	0.0001
OCM×Second	-2.35	1.28	618	$\beta_6 \neq 0$	-1.84	0.0669
PCM×First	-0.81	0.89	618	$\beta_7 \neq 0$	-0.90	0.3664
PCM×Second	-1.31	0.89	618	$\beta_8 \neq 0$	-1.47	0.1434
Shoulder 1						
μ	**-1.13**	**3.99**	**618**	**$\mu>0$**	**-0.28**	**0.7771**
OCM	**19.53**	**5.71**	**9**	**$\beta_1 \neq 0$**	**3.42**	**0.0077**
PCM	**17.36**	**5.60**	**9**	**$\beta_2 \neq 0$**	**3.10**	**0.0127**
First	-9.02	1.80	618	$\beta_3 \neq 0$	-5.02	<.0001
Second	1.96	1.80	618	$\beta_4 \neq 0$	1.09	0.2760
OCM×First	1.05	2.82	618	$\beta_5 \neq 0$	0.37	0.7102
OCM×Second	-3.57	2.82	618	$\beta_6 \neq 0$	-1.27	0.2054
PCM×First	16.74	2.11	618	$\beta_7 \neq 0$	7.93	<.0001
PCM×Second	-0.31	2.11	618	$\beta_8 \neq 0$	-0.15	0.8832
Peak						
μ	**40.15**	**5.98**	**618**	**$\mu>0$**	**6.71**	**<.0001**
OCM	**17.02**	**8.44**	**9**	**$\beta_2 \neq 0$**	**2.02**	**0.0744**
PCM	**19.98**	**8.43**	**9**	**$\beta_2 \neq 0$**	**2.37**	**0.0418**
First	9.25	1.82	618	$\beta_3 \neq 0$	5.09	<.0001
Second	2.88	1.82	618	$\beta_4 \neq 0$	1.58	0.1137
OCM×First	-11.42	2.59	618	$\beta_7 \neq 0$	-4.41	<.0001
OCM×Second	1.47	2.59	618	$\beta_8 \neq 0$	0.57	0.5710
PCM×First	-17.87	2.48	618	$\beta_7 \neq 0$	-7.21	<.0001
PCM×Second	-6.24	2.48	618	$\beta_8 \neq 0$	-2.52	0.0121
Shoulder 2						
μ	**3.12**	**1.18**	**618**	**$\mu>0$**	**2.65**	**0.0083**
OCM	**-2.29**	**1.50**	**9**	**$\beta_2 \neq 0$**	**-1.53**	**0.1615**
PCM	**-1.31**	**1.62**	**9**	**$\beta_2 \neq 0$**	**-0.81**	**0.4404**
First	-0.44	1.12	618	$\beta_3 \neq 0$	-0.40	0.6924
Second	2.29	1.12	618	$\beta_4 \neq 0$	2.04	0.0415
OCM×First	-0.07	1.16	618	$\beta_7 \neq 0$	-0.06	0.9539
OCM×Second	-2.61	1.16	618	$\beta_8 \neq 0$	-2.25	0.0248
PCM×First	10.87	1.65	618	$\beta_7 \neq 0$	6.57	<.0001
PCM×Second	1.07	1.65	618	$\beta_8 \neq 0$	0.65	0.5191

Note. The linear mixed-effects model is fit by maximum likelihood with 636 original observations and 12 sessions. For purposes of the brevity the session random effects are not included in the table.

Finding 2: *Ceteris paribus, markets in the SOA treatment quickly stabilize at the competitive equilibrium quantity at all levels of demand, whereas the COAs continue to interrupt market demand throughout the experiment, especially during the peak periods.*

Support: On only 18 occasions (out of possible 848 = 53 days × 4 quarters × 4 sessions) the SOA exchanged an allocative inefficient quantity. 17 of these occasions happened during the peak periods. The last inefficient allocation was observed during the twelfth trading day in session 2. The OCM (PCM) auction experienced 55 (24) allocative inefficient exchanges, with the latest observation being during the 44th (53rd) trading day. 44 (19) or 80% (79%) of these inefficient exchanges happened during the peak periods. In Fig. 2, the last 17 days in all sessions resulted in 100% efficient buyer prices. However, this does not necessarily mean that all OCM sessions supplied the efficient quantity to the market during all those days. In fact, the demand had to be interrupted on five occasions (out of possible 272 = 17 days × 4 quarters × 4 sessions), because the price for the efficient amount exceeded buyers' maximum willingness to pay. Similarly, the demand was interrupted on four occasions in the PCM sessions.■

Failure to supply the efficient amount of units is not the only source of possible inefficiencies. The total surplus might also be reduced by production inefficiencies, i.e. the situations when higher cost plants produce while lower cost plants are idle.

Finding 3: *Ceteris paribus, the COA and SOA treatments exhibit similar degrees of production inefficiency.*

Support: Fig. 3, the estimates from the mixed-effects model in Table 4 and the statistics of the non-parametric Mann-Whitney U test in Table 5[10] report evidence that in all periods, the COA and SOA treatments are not significantly different from each other. The dependent variable in the mixed-effects model is the difference between the observed production cost (*ProdCost*) and the minimum production cost for the exchanged quantity, $ProdCost^*$.[11] The treatment effects are insignificant for all periods[12].

Some of the production inefficiencies in the COAs stem from frequent occasions when the very high cost generators of H and I types are called to produce. The owners of the most inefficient plants (type H and I) are able to win contracts and profitably supply to the market by offering low prices and recovering their variable costs through high start-up fees. During the last 17 days of the OCM sessions, these plants are selected and make positive profits during 42 days [out of possible 68 = 17days× 4sessions]. The same plants sell profitably during six days in the PCM sessions and never in the SOA.■

Since the deregulation of electricity markets, inflated and volatile wholesale electricity prices have been a concern.

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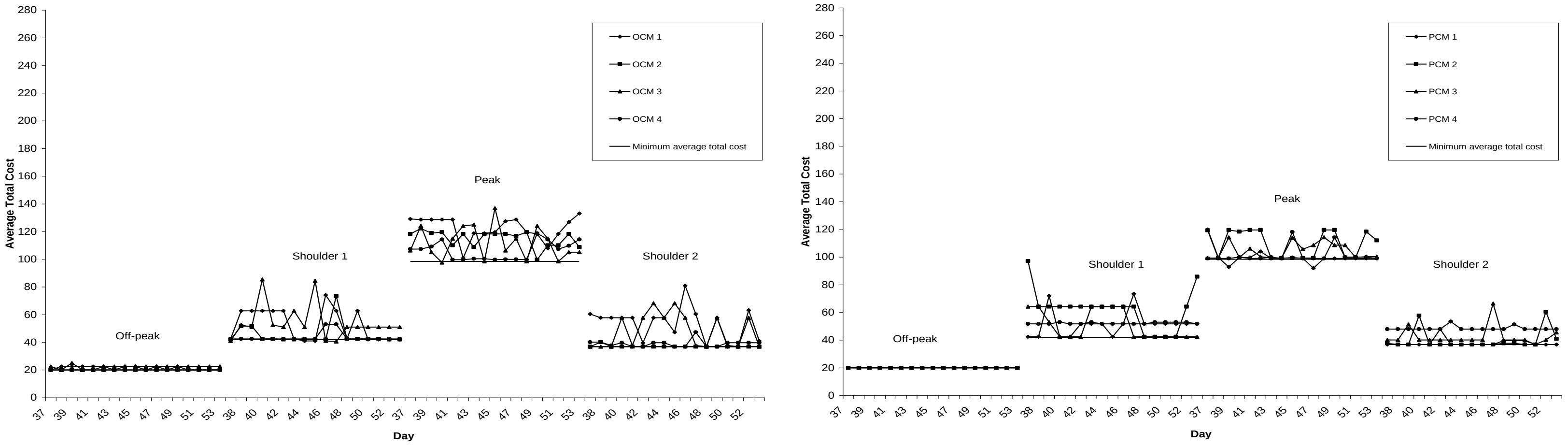
[10] Due to the lack of normality in the distribution of the estimated errors for the linear mixed effects model, I also applied the non-parametric Mann-Whitney U test to the average production costs for the last 17 market days.

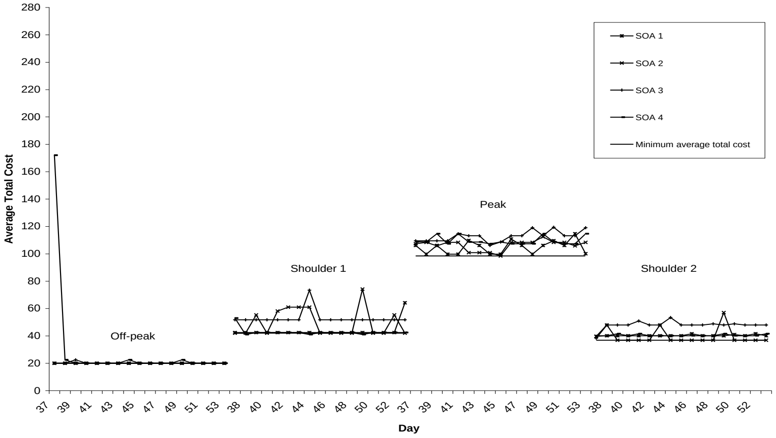
[11] An interpretation of the regression results might be problematic if the exchanged quantity fluctuates across the days. However, this problem does not arise here since during the last 17 days of the experiment, the demand had to be interrupted only on 5 occasions (out of possible 272 = 17 days × 4 quarters × 4 sessions) in the OCM treatment, and on 4 occasions in the PCM treatment.

[12] The estimated mixed-effects model suggests that in peak periods, the SOA treatment raises production costs above the PCM level by 83.3 experimental dollars (*p-value*=0.0298); on the other hand, the Mann-Whitney U test finds this difference in costs statistically insignificant (*p-value*=0.1143).



(a) OCM

(b) PCM



(c) SOA

Fig. 3 Average Total Costs by Level of Demand for the Last 17 Market Days in Each Session

Table 4 Estimates of the Linear Mixed Effects Model of Treatment Effects for the Production Costs

$$ProdCost_{ij} - ProdCost^{*} = \mu + e_i + \beta_1 OCM_i + \beta_2 PCM_i + \beta_3 First_i + \\ + \beta_4 Second_i + \beta_5 OCM_i \times First_i + \beta_6 OCM_i \times Second_i + \beta_7 PCM_i \times First_i + \beta_8 PCM_i \times Second_i + \varepsilon_{ij}, \\ e_i \sim N(0,\sigma^2_1) \text{ and } \varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$$

	Estimate	Std. Error	Degrees of Freedom	H_a	t-statistic	p-value
Off-peak						
Due to the lack of variability of the dependent variable, the model cannot be estimated for the off-peak periods. Treatment averages and standard deviations are presented instead.						
	Average	Std. Dev.				
SOA	**4.76**	**36.85**				
OCM	**1.69**	**2.38**				
PCM	**0.00**	**0.00**				
Shoulder 1						
μ	**47.96**	**17.63**	**618**	**$\mu>0$**	**2.72**	**0.0067**
OCM	**-10.94**	**24.92**	**9**	**$\beta_2 \neq 0$**	**-0.44**	**0.6711**
PCM	**31.44**	**24.92**	**9**	**$\beta_2 \neq 0$**	**1.26**	**0.2389**
First	120.28	14.75	618	$\beta_3 \neq 0$	8.15	<.0001
Second	5.71	14.75	618	$\beta_4 \neq 0$	0.39	0.6986
OCM×First	-6.28	21.04	618	$\beta_7 \neq 0$	-0.30	0.7653
OCM×Second	31.00	21.04	618	$\beta_8 \neq 0$	1.47	0.1412
PCM×First	-64.65	20.70	618	$\beta_7 \neq 0$	-3.12	0.0019
PCM×Second	18.45	20.70	618	$\beta_8 \neq 0$	0.89	0.3731
Peak						
μ	**165.52**	**21.61**	**618**	**$\mu>0$**	**7.66**	**<.0001**
OCM	**57.34**	**33.18**	**9**	**$\beta_2 \neq 0$**	**1.73**	**0.1180**
PCM	**-83.30**	**32.32**	**9**	**$\beta_2 \neq 0$**	**-2.58**	**0.0298**
First	-18.28	16.70	618	$\beta_3 \neq 0$	-1.09	0.2742
Second	-15.04	16.70	618	$\beta_4 \neq 0$	-0.90	0.3683
OCM×First	-47.65	29.11	618	$\beta_7 \neq 0$	-1.64	0.1022
OCM×Second	-35.60	29.11	618	$\beta_8 \neq 0$	-1.22	0.2218
PCM×First	72.55	27.92	618	$\beta_7 \neq 0$	2.60	0.0096
PCM×Second	61.60	27.92	618	$\beta_8 \neq 0$	2.21	0.0277
Shoulder 2						
μ	**58.95**	**18.92**	**618**	**$\mu>0$**	**3.11**	**0.0019**
OCM	**-13.81**	**26.98**	**9**	**$\beta_2 \neq 0$**	**-0.51**	**0.6208**
PCM	**-17.44**	**26.66**	**9**	**$\beta_2 \neq 0$**	**-0.65**	**0.5293**
First	65.63	10.53	618	$\beta_3 \neq 0$	6.23	<.0001
Second	7.68	10.53	618	$\beta_4 \neq 0$	0.73	0.4663
OCM×First	51.16	16.11	618	$\beta_7 \neq 0$	3.18	0.0016
OCM×Second	21.09	16.11	618	$\beta_8 \neq 0$	1.31	0.1912
PCM×First	-4.42	16.06	618	$\beta_7 \neq 0$	-0.28	0.7830
PCM×Second	6.40	16.06	618	$\beta_8 \neq 0$	0.40	0.6903

Note. The linear mixed-effects model is fit by maximum likelihood with 636 original observations and 12 sessions. For purposes of the brevity the session random effects are not included in the table.

Finding 4: *Ceteris paribus, the variance of buyer prices in the SOA is same or lower than in the COAs.*

Table 5 Mann-Whitney U test on the Average Total Production Costs for the Last 17 Market Days

	SOA vs. OCM		SOA vs. PCM	
Period	$U_{4,4}$	p (two-tailed)	$U_{4,4}$	p (two-tailed)
Off peak	8	1.0000	12	0.3429
Shoulder 1	10	0.6857	13	0.2000
Peak	12	0.3429	14	0.1143
Shoulder 2	8	1.0000	8	1.0000

Support: Fig. 2 presents the dynamics of buyer prices in the auctions. Fig. 4 provides averages of the price variances for the 12 sessions presented here. Table 6 summarizes the results of the Mann-Whitney U test comparing the variances of the COAs against the variances of the SOA. The evidence suggests that in all periods the SOA attains at least as low volatility of prices as the COAs. Price volatility is significantly higher in shoulder 1 periods of the OCM auction (*p-value*=0.0571) and off-peak periods of the PCM auction (*p-value*=0.0571).■

Table 6 Mann-Whitney U test on the Buyer Price Variances for the Last 17 Market Days

	SOA vs. OCM		SOA vs. PCM	
Period	$U_{4,4}$	p (two-tailed)	$U_{4,4}$	p (two-tailed)
Off peak	9.5	0.6857	15	0.0571
Shoulder 1	15	0.0571	14	0.1143
Peak	12	0.3429	9	0.8857
Shoulder 2	9	0.8857	10	0.6857

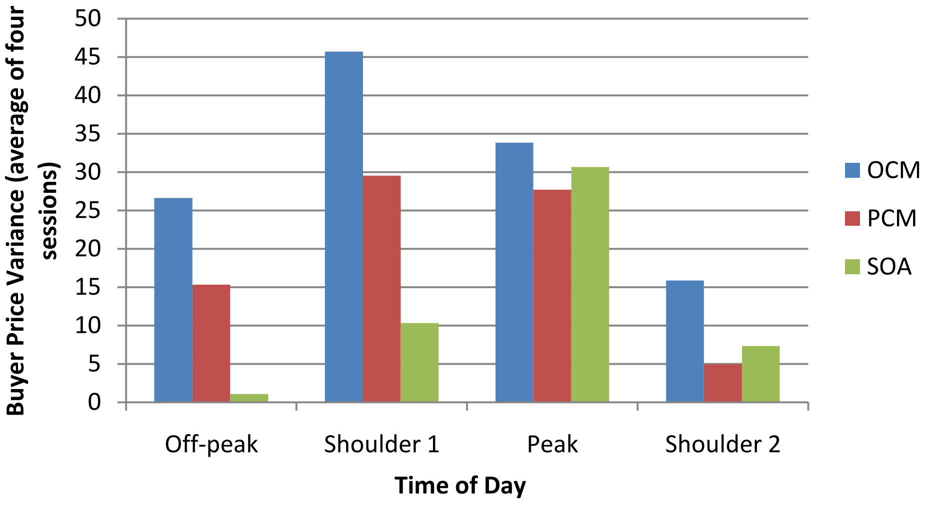


Fig. 4 Buyer Price Variances by Treatment for the Last 17 Market Days

The above findings implicate that the SOA outperforms the COAs with respect to allocative efficiency, buyer prices and price volatility. On the other hand, a concern was raised that the SOA might increase a risk of short-term losses to the sellers. Finding 5 addresses this issue.

Finding 5: *Ceteris paribus, plants experience more short-term losses in the SOA than in the COAs; however, the relative size of occasional losses compared to accumulated profits is small.*

Support: The total amounts of experienced losses in the OCM, PCM and SOA sessions are respectively 24346, 11679 and 38192 experimental dollars. The losses substantially decline towards the end of the sessions. The amounts of losses during the last 17 days of the experiment are respectively 562, 973 and 1966 experimental dollars. These losses represent 0.3, 0.6 and 1.3 percent of market profits. Fig. 5 summarizes the total amounts of experienced losses by quarter of the day. Table 7 presents the results of the Mann-Whitney U test comparing the losses of the SOA against the COAs. One-tailed tests suggests that the SOA accumulates significantly higher losses than the COAs during the off-peak and shoulder 1 periods (*p-values*=0.0571). The differences during the peak and shoulder 2 periods are statistically insignificant.[13]■

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[13] Interestingly, the amount of experienced losses in the SOA are almost perfectly correlated with the efficiency levels of the plants. The plants that are more costly are more likely to experience bigger short-term losses.

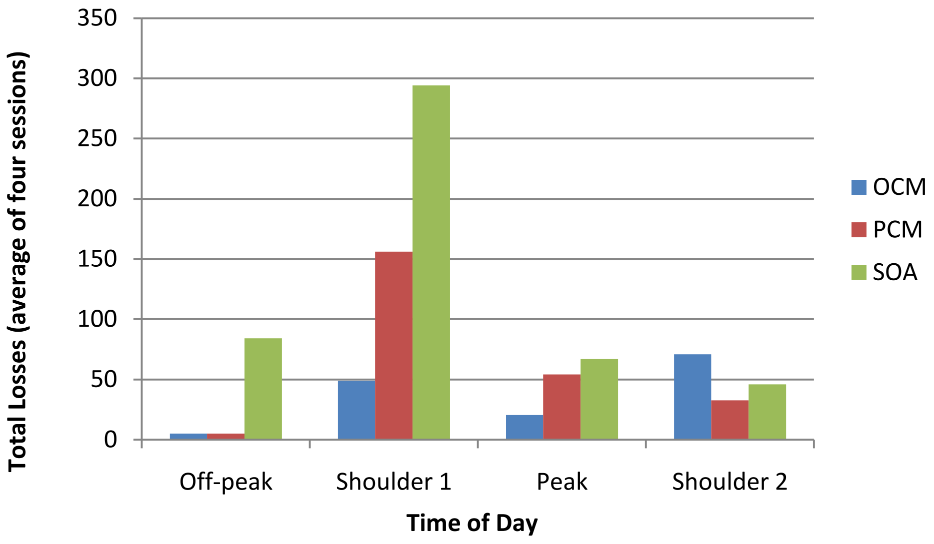

Fig. 5 Total Losses by Treatment for the Last 17 Market Days

Table 7 Mann-Whitney U test on the Total Experienced Losses for the Last 17 Market Days

	SOA vs. OCM		SOA vs. PCM	
Period	$U_{4,4}$	p (one-tailed)	$U_{4,4}$	p (one-tailed)
Off peak	14	0.0571	14	0.0571
Shoulder 1	14	0.0571	12	0.1714
Peak	10	0.3429	8	0.5571
Shoulder 2	9	0.4429	9	0.4429

Finding 6: *Ceteris paribus, outcomes in the SOA are more competitive than in the COAs during the periods when avoidable fixed costs are relevant.*

Support: The SOA always transacts competitive equilibrium amounts while as mentioned above, two COAs come short on number occasions especially during peak periods. Buyer prices in the SOA are significantly lower than the prices in two COAs (Finding 1). Average economic profits of the marginal plants are lower in the SOA than in two COAs during all but shoulder 2 periods (Fig. 6). The Mann-Whitney U test suggests that differences are significant during off-peak, shoulder 1 and peak periods (Table 8: one-tailed *p-values*=0.0571, 0.0286 and

0.0286 respectively for the OCM auction; *p-values*=0.0143 and 0.0571 for off-peak and peak periods in the PCM auction).■

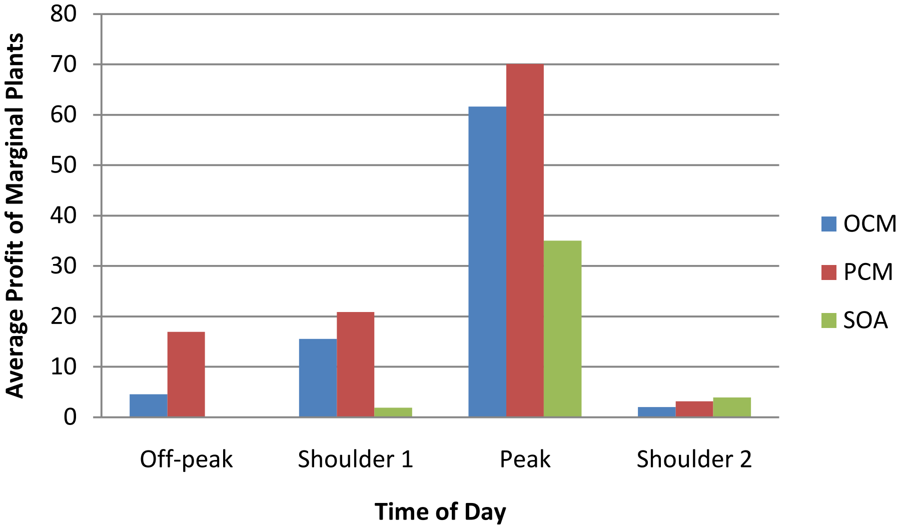

Fig. 6 Average Profits of Marginal Plants by Treatment for the Last 17 Market Days

Table 8 Mann-Whitney U test on Average Profits of Marginal Plants for the Last 17 Market Days

	SOA vs. OCM		SOA vs. PCM	
Period	$U_{4,4}$	p (one-tailed)	$U_{4,4}$	p (one-tailed)
Off peak	13.5	0.0571	16	0.0143
Shoulder 1	15	0.0286	12	0.1714
Peak	15	0.0286	14	0.0571
Shoulder 2	13	0.9000	10	0.6571

5 Conclusions

In a dynamic trading environment that models wholesale electric power markets, the SOA reduces prices to consumers, lowers price volatility and achieves allocative efficiency more quickly than either of two COAs. These gains come at the cost of higher risk of short term losses. The short term losses, however, are rather small relative to the accumulated profits in the described environment.

A frequent critique is if we can learn anything about complex electric power markets from the undergraduates submitting offers in a computer laboratory over the course of 90 minutes. As Fig. 2 shows, prices collapse to the competitive levels in the SOA. The so-called unprofessional undergraduates leave no room for professional commodity traders to be more competitive. On the other hand, the groups of random students in the COAs succeed in raising prices to levels observed in an environment with structural market power. Hence, undergraduates with no professional experience to a COA mechanism extract almost maximum profits during a 90 minute period of trading. The competitive forces are clearly weaker in two COAs relative to the SOA.

The SOA has less room for strategic behavior. Consequently, the SOA is able to mitigate anti-competitive effects that are present in the COAs, such as the incentive to withhold the lower cost production capacity for the higher demand periods and the ability to sell higher cost units by manipulating the combination of offered fees and prices. It seems that two noteworthy forces exist affecting the performance of COAs. First, the incentive to compete in a COA is weak. And second, a difficulty exists in identifying what offers could displace the offers of competitors since the information about relative structure of two-part priced offers is not public. Shoulder 2 periods are a good example how simpler and more transparent these markets could be if avoidable fixed costs did not exist. The outcomes are relatively competitive in all three auctions since most plants are not eligible for start-up fees in shoulder 2 periods. It is clear that allowing the sellers to recover their variable and avoidable fixed costs separately does not enhance the transparency and competition in the market.

These results implicate that auctions which adopt non-convex optimization mechanisms might be neither necessary nor constructive remedy dealing with non-convex production technologies. After all, many industries with fixed costs successfully operate in the competitive markets with price-per-quantity trades.

For policy makers the lesson is clear: keep market institutions simple. Allowing market participants to reveal more information and trying to make use of that information also creates more opportunities to act strategically. If a way to strike it rich exists within the institutional rules of trading, the market participants find it.

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Appendix A An Example of a Simple Wholesale Electricity Market

To highlight the differences of the market-clearing rules in question, consider a three-supplier market examined by Knoblauch (2005) and Baltaduonis (2007a). Say we have an electricity market for one hour. The demand is inelastic and equal to 2 units. Supplier 1 (*S*1) and Supplier 2 (*S*2) are identical. They incur 6 dollars of fixed costs to start up their plants and 93 dollars of variable costs to generate one unit of electricity. Each of them can supply 0, 1 or 2 units of electricity. Supplier 3 (*S*3) has start-up cost of 20 dollars and variable cost of 70 dollars per unit. She can supply 0 or 1 unit of electricity.

For the purpose of this example suppose that all suppliers submit offers that reflect their true production costs. Since the fees are constrained to be zero in the SOA, the suppliers would incur losses unless they recover their fixed costs through the prices. Therefore, in the SOA, the fixed cost can be evenly distributed over the variable cost at the full capacity level of a plant. In this case, *S*1 and *S*2 would submit offers of 96 (=93+6÷2) dollars per unit and *S*3 would submit an offer of 90 (=70+20) dollars per unit. Given these offers the three auctions would generate the following outcomes.

A.1 The OCM Auction

The OCM algorithm minimizes the total offered cost of electricity, as if all selected sellers would be paid their offered prices and fees. Given the offers, an ISO calculates the minimum offered cost in two cases: 1) buying two units from $S1(S2)$ or 2) buying one unit from $S3$ and one unit from $S1(S2)$:

$$\text{Min}\{Price_{1,2}\times 2+Fee_{1,2}\ , Price_3+Fee_3+Price_{1,2}+Fee_{1,2}\},$$

$$\text{Min}\{93\times 2+6,\ 70+20+93+6\}=70+20+93+6=189.$$

The auction chooses to buy 1 unit from $S3$ and 1 unit from $S1(S2)$. After the offers are selected, a uniform MCP is determined as the highest accepted price for that period; the MCP is 93 (=max{70, 93}). All selected sellers receive their individual start-up fees and the uniform MCP for the supplied electricity during that period; the total procurement cost of electricity is 212 (=93×2+20+6). The uniform market price that all buyers pay is 106 [=93+(20+6)÷2)]. Notice that this contract allocation is production efficient since no way exists to generate two units of electricity cheaper than the chosen suppliers do.

A.2 The PCM Auction

The PCM algorithm minimizes the actual procurement cost of electricity, simultaneously determining a MCP as the highest accepted price during that period. An ISO calculates the minimum procurement cost in two cases: 1) buying two units from $S1(S2)$ or 2) buying one unit from $S3$ and one unit from $S1(S2)$:

$$\text{Min}\{Price_{1,2}\times 2+Fee_{1,2}\ , \max\{Price_3\ , Price_{1,2}\}\times 2+Fee_3+Fee_{1,2}\},$$

$$\text{Min}\{93\times 2+6,\ \max\{70,\ 93\}\times 2+20+6\}=93\times 2+6=192.$$

The auction chooses to buy two units from *S*1(*S*2). The MCP is 93. As in the OCM auction, the selected sellers receive their individual start-up fees and the uniform MCP for the supplied electricity. Both the total procurement cost and the total production cost are equal to 192 (=93×2+6). The market price for buyers is 96 (=93+6÷2). This contract allocation is not production efficient since *S*3's plant with relatively lower average total cost is idle.

A.3 The Simple-Offer Auction

The sellers can recover their production costs – both variable and avoidable fixed – only through a uniform MCP in the SOA. Notice that the SOA is a COA where the start-up fees are constrained to be zero. The contract allocations in two COAs are identical when the start-up fees equal zero. Hence, either the OCM or the PCM algorithm could be used for the SOA by simply restricting all start-up fees to zero. In the discussed example, an ISO considers two options: 1) buying two units from *S*1(*S*2) or 2) buying one unit from *S*3 and one unit from *S*1(*S*2):

$$\mathrm{Min}\{Price_{1,2}\times 2\ ,\ Price_{3}+Price_{1,2}\},$$

$$\mathrm{Min}\{96\times 2,\ 90+96\}=90+96=186.$$

The auction chooses to buy 1 unit from *S*3 and 1 unit from *S*1(*S*2). The MCP is 96. The selected sellers receive the uniform MCP for the supplied electricity. The total procurement cost of electricity is equal to 192 (=96×2). This contract allocation is production efficient, since no way exists to generate two units of electricity cheaper than the chosen suppliers do. However, this outcome is problematic because *S*1(*S*2) is not able to recover all production costs and incurs a loss of -3 (=96-93-6). Since this outcome can not be sustained in the long run, $S1(S2)$ would be forced to increase the offer in order to recover the fixed cost even when she sells only one unit of energy. The minimum sustainable offer is 99 dollars per unit. In this case, the outcome is as follows:

$$\text{Min}\{99\times 2, 90+99\}=90+99=189.$$

The auction chooses to buy one unit from $S3$ and one unit from $S1(S2)$. The MCP for both buyers and sellers is 99. The total procurement cost of electricity is equal to 198 (=99×2). The contract allocation is production efficient.

In the presented example, given the assumption of truthful production cost revelation, the PCM auction produces the lowest procurement cost of electricity. It slightly outperforms the SOA and more significantly the OCM auction. On the other hand, the PCM auction is the only one to yield a production inefficient allocation. The SOA case shows that the sellers might face a risk of short-term losses.

Appendix B Experimental Instructions

<page 1>

Welcome

This is an experiment in the economics of decision-making. If you read the instructions carefully and make good decisions, you may earn a considerable amount of money that will be paid to you in CASH at the end of the experiment.

The experiment will take place through the computer terminals at which you are seated. If you have any questions at any time, please raise your hand and a monitor will come to assist you.

In this experiment, owners of plants sell an identical product to a computer buyer every day. Each day lasts 75 seconds. You are an **owner** of #yourNumberOfPlants# plants. There are #numberOfSellers# sellers and #numberOfPlants# plants including yours. Each seller owns between 1 and 4 plants.

<page 2>

Each day is divided into 4 quarters. Each quarter is represented by a line in the table at the top of your screen. The computer will purchase varying quantities of the product over the course of a day: Low, Medium, High and Medium amounts.

Sellers submit offers to sell. An offer indicates the prices and quantities of the product that you are willing to sell during the course of the following day. All quantities are measured in number of units.

<page 3 OCM and PCM>

You as a seller are able to decide:

Price/unit is the price per unit you are willing to sell at during that quarter from that plant. This is the minimum price at which you are willing to sell. The actual market price may be higher depending on the demand of the product. Each seller receives the same market price for sold units during the quarter. The market price is the highest accepted Price/unit among all of the sellers. If you sell the product you also incur a cost per unit sold. This cost is listed on the right side under the table and must be paid for each unit you sell.

Start-Up Fee is a fee that is paid to you for turning on your plant. The fee is paid to you only if the plant was not operating during the previous quarter. When your plant is turned on, you also must pay the start-up cost, which is listed on the right side under the table.

You will be able to make this decision for each quarter of the upcoming day for each plant that you have.

<page 3 SOA>

You as a seller are able to decide:

Price/unit is the price per unit you are willing to sell at during that quarter from that plant. This is the minimum price at which you are willing to sell. The actual market price may be higher depending on the demand of the product. Each seller receives the same market price for sold units during the quarter. The market price is the highest accepted Price/unit among all of the sellers. If you sell the product you also incur a cost per unit sold. This cost is listed on the right side under the table and must be paid for each unit you sell.

You will be able to make this decision for each quarter of the upcoming day for each plant that you have.

<page 4 OCM and PCM>

To switch between plants click on the tabs at the top of your screen. To enter the values select the appropriate cell in the table and double click.

Some offer values are automatically filled in for you:

Min Qty is the minimum number of units you are willing to sell during that quarter from that plant. Min Qty must be ≥ Minimum Capacity, which is specified under the table. This will be filled with that plant’s Minimum Capacity.

Max Qty is the maximum number of units you are willing to sell during that quarter from that plant. Max Qty must be ≤ Maximum Capacity, which is specified under the table. Max Qty must also be ≥ Min Qty. This will be filled with that plant’s Maximum Capacity.

<page 4 SOA>

To switch between plants click on the tabs at the top of your screen. To enter the values select the appropriate cell in the table and double click.

Some offer values are automatically filled in for you:

Min Qty is the minimum number of units you are willing to sell during that quarter from that plant. Min Qty must be ≥ Minimum Capacity, which is specified under the table. This will be filled with that plant’s Minimum Capacity.

Max Qty is the maximum number of units you are willing to sell during that quarter from that plant. Max Qty must be ≤ Maximum Capacity, which is specified under the table. Max Qty must also be ≥ Min Qty. This will be filled with that plant's Maximum Capacity.

When your plant is turned on, you also must pay the start-up cost, which is listed on the right side under the table. You will not receive the **Start-Up Fee** for turning on your plant.

<page 5 PCM>

Offers are sent to the computerized market coordinator when you click the Submit button or when the day is over. Your offer from the previous day will be automatically submitted for you if you choose not to make any changes during the course of a day.

The computerized market coordinator accepts those offers that satisfy the market demand during the day at the *lowest total procurement cost*, simultaneously determining the market price as the highest accepted Price/unit for that quarter.

If your offer has not been accepted, it means that other offers were able to satisfy the market demand at a lower or equal cost. The results are displayed on the right side of the table; you may need to scroll to the right to see them. Once you have reviewed the results of the previous day enter your offers for the next day for each plant and submit.

The right side of the table is filled in after everyone has submitted their offers. Your profit during each quarter of a day is:

(Units Sold × market price + Start-Up Fees collected) – (Units Sold × Cost/unit + Start-Up Costs incurred)

<page 5 OCM>

Offers are sent to the computerized market coordinator when you click the Submit button or when the day is over. Your offer from the previous day will be automatically submitted for you if you choose not to make any changes during the course of a day.

The computerized market coordinator accepts those offers that satisfy the market demand during the day at the *lowest total offered cost*. After the offers are selected, the market price is determined as the highest accepted Price/unit for that quarter.

If your offer has not been accepted, it means that other offers were able to satisfy the market demand at a lower or equal cost. The results are displayed on the right side of the table; you may need to scroll to the right to see them. Once you have reviewed the results of the previous day enter your offers for the next day for each plant and submit.

The right side of the table is filled in after everyone has submitted their offers.

Your profit during each quarter of a day is:

(Units Sold × market price + Start-Up Fees collected) – (Units Sold × Cost/unit + Start-Up Costs incurred)

<page 5 SOA>

Offers are sent to the computerized market coordinator when you click the Submit button or when the day is over. Your offer from the previous day will be automatically submitted for you if you choose not to make any changes during the course of a day.

The computerized market coordinator orders offered Prices/unit from lowest to highest for each quarter of the day. Market's bids to buy the product are ordered from highest to lowest. These two sorted lists will cross. The offered Price/unit where these lists cross becomes the market price during the quarter. The market coordinator accepts all offers with Prices/unit lower than the market price. If there is more than one offer exactly equal to the market price, then as many of those offers will be accepted as it is enough to satisfy the market demand during that quarter of the day.

If your offer has not been accepted, it means that other offers were able to satisfy the market demand at a lower or equal cost. The results are displayed on the right side of the table; you may need to scroll to the right to see them. Once you have reviewed the results of the previous day enter your offers for the next day for each plant and submit.

The right side of the table is filled in after everyone has submitted their offers.

Your profit during each quarter of a day is:

(Units Sold × market price) – (Units Sold × Cost/unit + Start-Up Costs incurred)

<page 6>

A history of the prices from the past 10 days and the sold quantities during each quarter of the last day are displayed in the bottom portion of your screen.

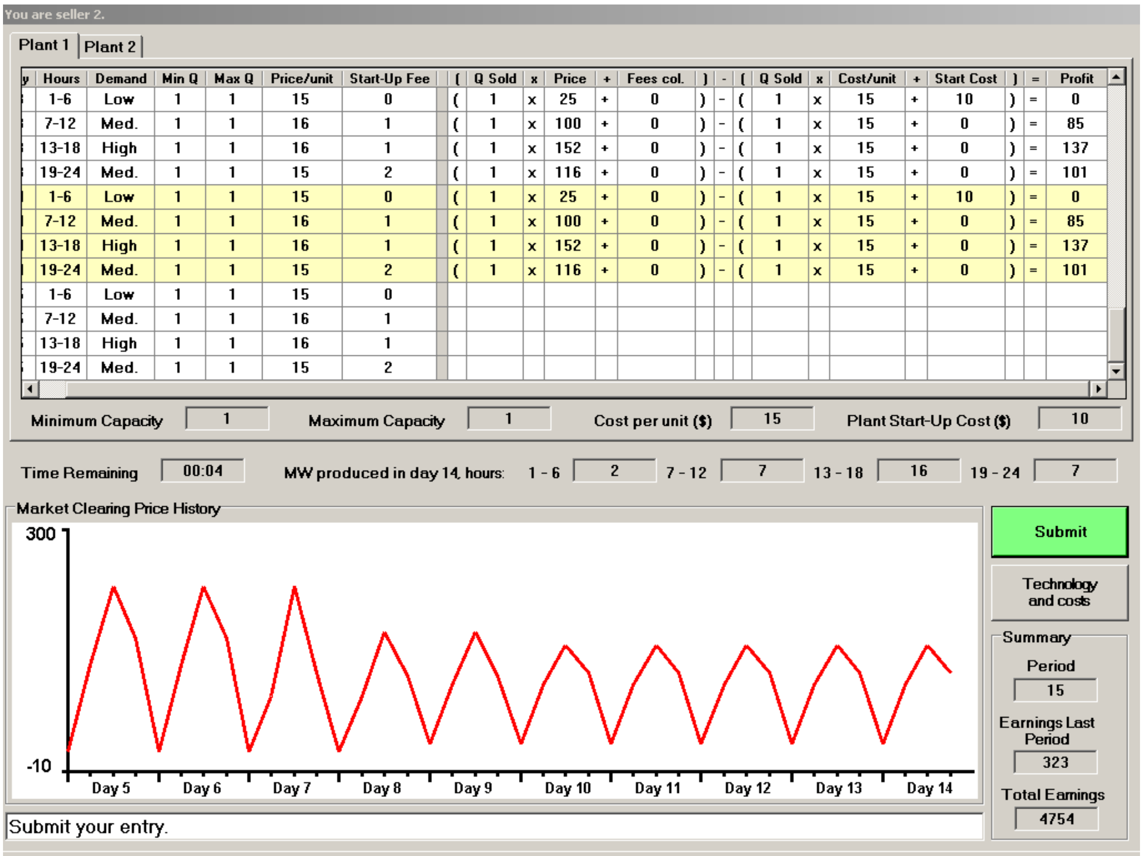
Information about all plants (including yours) is available to all sellers by clicking on the Technology and costs button.

Plants are restarted at the beginning of each day, meaning that during the first quarter of each day you receive your start-up fee and incur the start-up cost if you sell the product.

At the end of today's session, your 'computer dollars' will be converted into cash at a rate of #exchangeRate# computer dollars to US$1. If you have any questions please raise your hand. Press Start when you are ready to begin.

Even if you decide to keep your offer from the previous day, click the Submit button. The experiment will advance to the next day after everyone has clicked on the Submit button.

Appendix C Sample Screen Shot



You are seller 2.

y	Hours	Demand	Min Q	Max Q	Price/unit	Start-Up Fee	(	Q Sold	x	Price	+	Fees col.	)	-	(	Q Sold	x	Cost/unit	+	Start Cost	)	=	Profit
	1-6	Low	1	1	15	0	(	1	x	25	+	0	)	-	(	1	x	15	+	10	)	=	0
	7-12	Med.	1	1	16	1	(	1	x	100	+	0	)	-	(	1	x	15	+	0	)	=	85
	13-18	High	1	1	16	1	(	1	x	152	+	0	)	-	(	1	x	15	+	0	)	=	137
	19-24	Med.	1	1	15	2	(	1	x	116	+	0	)	-	(	1	x	15	+	0	)	=	101
	1-6	Low	1	1	15	0	(	1	x	25	+	0	)	-	(	1	x	15	+	10	)	=	0
	7-12	Med.	1	1	16	1	(	1	x	100	+	0	)	-	(	1	x	15	+	0	)	=	85
	13-18	High	1	1	16	1	(	1	x	152	+	0	)	-	(	1	x	15	+	0	)	=	137
	19-24	Med.	1	1	15	2	(	1	x	116	+	0	)	-	(	1	x	15	+	0	)	=	101
	1-6	Low	1	1	15	0																	
	7-12	Med.	1	1	16	1																	
	13-18	High	1	1	16	1																	
	19-24	Med.	1	1	15	2																	

Minimum Capacity: 1
Maximum Capacity: 1
Cost per unit ($): 15
Plant Start-Up Cost ($): 10

Time Remaining: 00:04
MW produced in day 14, hours: 1 - 6: 2; 7 - 12: 7; 13 - 18: 16; 19 - 24: 7

Period: 15
Earnings Last Period: 323
Total Earnings: 4754

Submit your entry.

Fig. 7 Sample Screen Shot.