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Rimvydas Baltaduonis
University of Connecticut and George Mason University

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Rimvydas Baltaduonis
University of Connecticut and George Mason University

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341 Mansfield Road, Unit 1063
Storrs, CT 06269–1063
Phone: (860) 486–3022
Fax: (860) 486–4463
http://www.econ.uconn.edu/

Abstract

A Payment Cost Minimization (PCM) auction has been proposed as an alternative to the Offer Cost Minimization (OCM) auction to be used in wholesale electric power markets with the intention to lower the procurement cost of electricity. Efficiency concerns about this proposal have relied on the assumption of true production cost revelation. Using an experimental approach, I compare the two auctions, strictly controlling for the level of unilateral market power. A specific feature of these complex-offer auctions is that the sellers submit not only the quantities and the minimum prices at which they are willing to sell, but also the start-up fees that are designed to reimburse the fixed start-up costs of the generation plants. I find that both auctions result in start-up fees that are significantly higher than the start-up costs. Overall, the two auctions perform similarly in terms of procurement cost and efficiency. Surprisingly, I do not find a substantial difference between less market power and more market power designs. Both designs result in similar inefficiencies and equally higher procurement costs over the competitive prediction. The PCM auction tends to have lower price volatility than the OCM auction when the market power is minimal but this property vanishes in the designs with market power. These findings lead me to conclude that both the PCM and the OCM auctions do not belong to the class of truth revealing mechanisms and do not easily elicit competitive behavior.

Journal of Economic Literature Classification: C72, D4, D61, L94

Keywords: strategic behavior, sealed-bid auction, complex offer auction, electricity, efficiency

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1. Introduction

Many wholesale electric power markets employ auctions that differ in their offer complexity from other common quantity-price offer auctions. Besides the quantities and the minimum offer prices, the sellers may also declare their technical constraints and start-up fees that are designed to reimburse the fixed start-up costs of the plants. The generation contracts are generally allocated 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 period. In this paper, I compare the performance of two such algorithms by using laboratory experiments. An offer cost minimization (OCM) algorithm is currently used by independent system operators (ISOs) in the United States. It relies on the traditional unit commitment approach.[2] A payment cost minimization (PCM) algorithm, designed to lower the procurement cost of electricity, is proposed as an alternative to the existing mechanism.[3] With the exception of a few game theoretic studies (Knoblauch 2005, Shunda 2005, Baltaduonis 2006), comparisons of these auction mechanisms rely on the assumption of true production cost revelation (Alonso et al. 1999, Arroyo & Conejo 2002, Yan & Stern 2002, Luh et al. 2005a, 2005b). In this paper, I test the claim that the PCM auction could lead to significant savings to consumers and that those savings might be at the expense of efficiency. Allowing for strategic behavior, the experimental study, similarly to Rassenti, Smith & Wilson (2003a, 2003b), hereafter, RSW, strictly controls for the level of unilateral market power and simulates trading environments with minimal demand

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

[3] For the mathematical formulation of the proposed algorithm see Luh et al. (2005a).

elasticity, cyclical demand uncertainties and an absence of significant excess generation capacity.

The paper is organized as follows. *Market Institution, Structure, and Environment* defines market power in a sealed complex-offer market. It outlines the market structure and design for the experiment. This section provides an example that highlights the major differences of the OCM and the PCM auctions. *Experimental Design and Procedures* discusses the procedures of the experiment, and *Results* presents the findings. *Conclusions* summarizes the analysis and suggests the direction of future research.

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 the day-ahead wholesale markets of observed power systems. Hour-ahead and real time power markets are organized in a similar fashion, but they also more often employ locational marginal pricing instead of having one uniform price for the whole energy pool region. The performance of the PCM auction is measured against the OCM auction in a stationary supply and cyclic demand environment with varying levels of unilateral market power.

2.1. Auction Institution

The objective of this paper is to compare the performance of two complex-offer auction rules (OCM and PCM) while holding constant all other characteristics of the system – the costs and structure of supply, the resale values and structure of demand. The criteria for evaluation are allocation efficiency, procurement cost of the commodity to the buyers, production efficiency, and volatility of prices. Since demand-side bidding is often absent in the naturally occurring spot markets for electricity, similarly to RSW, a computer is used to submit bids that perfectly reveal the demand at any point in time in all experiments. The sellers privately submit a schedule of offers, i.e. plant start-up fees and prices, for their production capacity for each pricing period. The offers and the computerized bids are then sent to an optimization algorithm to allocate the production contracts for the next day. Each day includes four pricing periods: night (low demand/off peak period), morning (medium demand/shoulder period), afternoon (high demand/peak period) and evening (medium demand/shoulder period). 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.

Currently, the dominant practice in electricity spot markets is to employ uniform price auctions where each seller receives the same market price for megawatts sold. The market price is usually the highest accepted price per megawatt among all of the sellers. I retain these institutional features and leave aside the discussion of "pay-as-offered" discriminatory price auctions.[4] In both the OCM and the PCM experimental treatments,

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

the sellers get paid the uniform prices and their individual start-up fees. The difference in the treatments lies in the optimization objective of a market-clearing algorithm.

In the case of a uniform-price auction, where sellers also request fixed start-up fees, the mechanism of distributing these fees across the 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 required. The markup on 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.

The following numerical example demonstrates the principles of the offer-selection rules for both auctions.

Example 1: A Simple Wholesale Electricity Market

To highlight the major differences in the above-mentioned market-clearing rules I use a three-supplier market described by Knoblauch (2005). Consider an electricity market for one hour. The demand is inelastic and equal to 2 units. Supplier 1 ($S1$) and Supplier 2 ($S2$) 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 energy. Supplier 3 ($S3$) has start-up cost of 20 dollars and energy cost of 70 dollars per unit. She can supply 0 or 1 unit of energy.

For the purpose of this example suppose that all suppliers submit offers that reflect their true production costs. Given these offers the two auctions would generate the following outcomes.

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 from two cases: (1) buying 2 units from either $S1$ or $S2$, OR (2) buying 1 unit from $S3$ and 1 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 market-clearing price is determined as the highest accepted price for that period; the market price is 93 (=max{70, 93}). All selected sellers receive their individual start-up fees and the uniform market price 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 there is no way to generate 2 units of electricity cheaper than the chosen suppliers do.

The PCM Auction

The PCM algorithm minimizes the actual procurement cost of electricity, *simultaneously* determining a market-clearing price as the highest accepted price during that period. An ISO calculates the minimum procurement cost in two cases: 1) buying 2 units from either *S*1 or *S*2, OR 2) buying 1 unit from *S*3 and 1 unit from *S*1(*S*2):

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

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

The auction chooses to buy 2 units from *S*1(*S*2). The market-clearing price is 93. As in the OCM auction, the selected sellers receive their individual start-up fees and the uniform market-clearing price for the supplied electricity. Both the total procurement cost and the total generation 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.

In the preceding example, given the assumption of truthful production cost revelation, the PCM auction produces the lowest procurement cost of electricity. On the other hand, the PCM auction yields a production inefficient allocation. Intuitively then, one could think that in a competitive environment, the PCM auction should result in contract allocations that are cheaper to the buyers and the OCM auction should result in allocations that cost less to produce. After all, that is exactly what these optimization algorithms were designed to minimize. The example also suggests that there might be a trade off between lower electricity cost to the buyers and production efficiency.

Both the OCM and the PCM auctions are designed to sell the maximum amount of electricity where buyers' marginal willingness to pay is no less than the average procurement cost. Tied offer combinations in the OCM auction are chosen in a way that generates lower procurement cost. Tied offer combinations in the PCM auction are selected by giving priority to those sellers whose offered cost is lower. Such a tie-breaking mechanism gives the best performance chances to both complex-offer auctions, though to achieve similar tie-breaking in real life applications would require additional costly computational power and time.

2.2. Unilateral Market Power

Concerns for market power abound in the electric power industry. A comparison of the OCM and the PCM auctions would not be adequate without an investigation of the relationship between the degree of market competitiveness and an auction's performance. In the experiment, I develop a market environment that strictly controls for structural features of market power. Given the inelastic nature of the market demand for electricity, 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. Davis and Holt (1994), and RSW (2003) create market-power incentives in the simple-offer laboratory markets by reallocating production capacities in the market while keeping the market supply unchanged. My study uses a similar approach. Recall the three-supplier market described in example 1. Transferring two of $S2$'s capacity units to $S1$ would undoubtedly create unilateral market power in an effective duopoly. $S1$ would be guaranteed to supply at least one unit to the market. She could unilaterally bid up the price for her unit and earn a significant profit as long as the market demand is perfectly inelastic. If *S*1 submitted a low offer with the hope to supply two units to the market, she would risk losing her guaranteed profit. In this case, offering the capacity at high prices and/or start-up fees is a dominant strategy for *S*1.

2.2.1. No Power Treatment

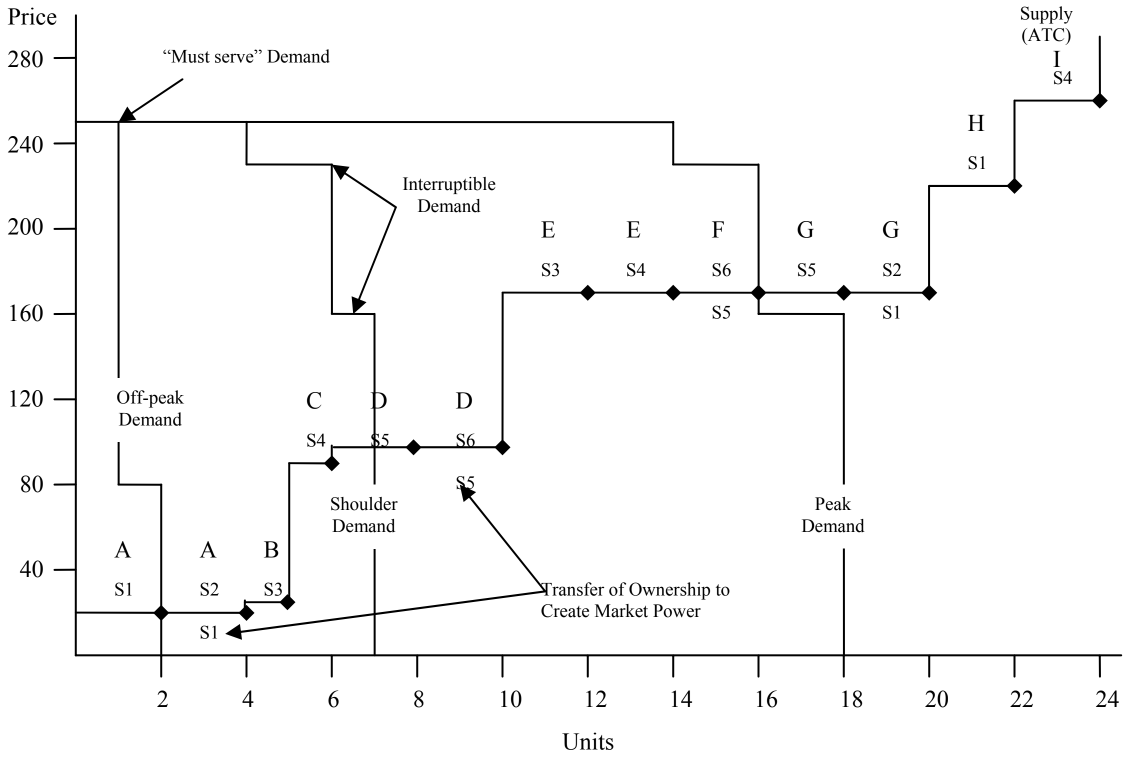

Figure 1. Market Structure and Design

Tables 1 and 2, as well as Figure 1, depict aggregate supply and demand in the experimental environment. Following RSW, I implement the condition that the buyers perfectly reveal their willingness to pay. The second and third steps of the demand in

Table 1 represent interruptible units of demand, whereas the units on the first step at 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. Recent spikes in energy prices prompted various attempts to increase the responsiveness of retail demand to wholesale energy prices. The idea is to promote the management of electricity consumption, especially when the wholesale prices exceed some critical levels.

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)

Table 2. Minimum Average Total Costs (ATC) of Generation by Generator Type

Generator Type (Quantity)	Min Load	Max Load	Start-up Cost	Energy Cost	ATC at Max Load	Total Load
	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

In the designed market, there are thirteen plants of nine types. The technical characteristics of each plant are presented in Table 2. Some of them have low start-up costs with high production costs per unit, while other plants have high start-up costs but lower production costs. In the *No Power* treatment, all plants are owned by six firms (or sellers) denoted by an "*S*" and an identification number. *S*1 and *S*2 own two low cost (Type *A*) generation plants and two high cost generation plants (Type *H* and *G* respectively). *S*3 and *S*4 own two high cost (Type *E*) plants and, respectively, one baseload (Type *B*) generation plant and one intermediate cost (Type *C*) plant where generation capacity is one unit. *S*4 also owns a very high cost (Type *I*) peak capacity plant with average total cost 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 generation plant.

These pairs are designed to be Bertrand-like competitors that share an identical structure of generation costs at the certain demand level. In off-peak periods, the baseload plants owned by *S*1, *S*2 and *S*3 depict the three-competitor market structure described by Knoblauch (2005) and later analyzed by Baltaduonis (2006). During shoulder periods, the intermediate cost plants owned by *S*4, *S*5 and *S*6 resemble a similar market but with different cost distribution. When start-up cost bidding is limited, Knoblauch shows that a Bertrand competition game in these markets results in a competitive outcome. The market during peak periods is designed to be competitive as well. Five sellers with ten units of similar cost capacity are competing to supply at least six units of peak demand.

In the presence of complex-offers, where a seller receives not only a price for each sold unit but also a fixed fee, the notion of a competitive outcome can not be summarized by a market-clearing price that all sellers receive. A seller asking a price equal to marginal cost can still exercise her market power by charging a higher fee than the actual start-up cost and possibly causing a deadweight loss if this action reduces the number of units traded. In the *No Power* treatments of my experiments, I design the market structure such that, at a given period of the demand cycle, the non-cooperating marginal generators would have incentives to submit offers that request payments that do not exceed the actual production costs of the marginal units. However, the requested fees do not necessarily need to be the actual start-up costs if the asked seller prices are adjusted accordingly. Consider the OCM auction for an illustration.

Take the shoulder demand period following the off-peak. 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, in the OCM auction, the other seller would be able to undercut the offer by either lowering the fixed fee or offered price. Therefore, a competitive price that all sellers receive should not exceed 99 during the shoulder periods. On the other hand, the price that all buyers pay in this case can be as high as 155. This would happen if other low cost generators (Type *A*, *B* and *C*) decided to recover their costs exclusively through fixed fees, i.e. submitting offers with prices equal to zero and start-up fees equal to 98 (<99) for one-unit capacity generators and equal to 196 (=2×98) for two-unit capacity generators. The OCM auction would select these offers before the marginal offers of 99. As discussed above, the amount of fees would be used to mark-up the buyer price during the shoulder period [99 + (98 × 4 ÷ 7) = 155]. In this case, the buyer price of 155 would correspond to a competitive outcome in the OCM auction.

If we apply a similar analysis to other periods of the demand cycle, we find that the price (both for sellers and buyers) should not exceed 20 during the off-peak periods. The maximum price during the peak periods should be 172 and 230 for sellers and buyers respectively. And the price (both for sellers and buyers) should not exceed 93 during the shoulder periods following the peak demand. Notice that the shoulder periods before and after the peak demand have the same demand and supply structures. However, most of the plants are not idle after the peak period. Therefore, they do not incur start-up costs and do not receive start-up fees to continue generation during the second shoulder period of a day. For this reason, the competition during this period can be modeled as a standard Bertrand-competition game, where the competitive price equals the marginal cost. The comparison of the two shoulder periods should provide some insights on competition with complex offers versus simple offers.

The PCM auction results in the same upper bounds for the competitive buyer and seller prices as in the OCM auction. The result follows from the identical structure of an offer in both auctions and from the presence of marginal "twin" competitors at every level of the market demand. There are many pure strategy Nash equilibria that correspond to a competitive outcome in these auctions. However, one could expect that in a competitive environment, the PCM auction should result in contract allocations that are at least as cheap to the buyers as in the OCM auction. After all, the PCM algorithm was designed for this objective.

Similarly, one could expect that in a competitive environment, the OCM auction should result in contract allocations that are at least as cheap to produce as in the PCM auction. There are pure strategy Nash equilibria that achieve 100% production efficiency in both auctions.

The experiment could shed some light as to whether some equilibria are more likely to dominate in the OCM and the PCM auctions. The *No Power* treatment is my attempt to design a market structure that would contain minimal market power in a complex-offer auction.

2.2.2. Power Treatment

Market power can be raised merely by transferring the ownership of *S*2's and *S*6's plants to *S*1 and *S*5, respectively. The reallocation of plant ownership gives the power to *S*1 and *S*5 to charge more for the marginal units. In the *Power* treatments, *S*1 and *S*5 can unilaterally increase their profits by raising the offers for the off-peak and shoulder periods regardless of the auction.

For example, during an off-peak period, *S*1 is basically guaranteed to sell at least one unit as long as the buyer price does not exceed the second step of the demand curve (80). Instead of competing with *S*3's and her own plants, *S*1 can profitably withdraw three units of generation capacity (or equivalently raise the offers for those units). Depending on *S*3's offer, there are many stable pure strategy Nash equilibria with different profit shares. Notice that by withdrawing relatively cheaper capacity from the market, *S*1 also causes production inefficiency.

Similarly, during a shoulder period, *S*5 can profitably increase the offer for her marginal unit. As long as the buyer price does not exceed the third shoulder demand step (160), *S*5 should be able to earn a positive profit. In equilibrium, the size of the profit would depend on the offers of S1, S3 and S4. However, during the second shoulder period of a day, when most plants are not eligible for fixed fees, *S*5 should set the price at exactly 160 and earn profit of 67. In shoulder periods, the production efficiency should be preserved even when market power is exercised.

Notice that during the peak demand, all unilateral deviations from the competitive outcome are unprofitable in both *No Power* and *Power* treatments. This should serve as a common control across sessions in both treatments.

The structural features of market power in my experiment suggest similar incentives in both the OCM and the PCM auctions. Holt (1989) points out that the notion of unilateral market power can be sensitive to the distinguishing characteristics of market institutions. He notes that the effects of institutions often seem to dominate the effects of structural characteristics of the market. The experiment could show whether such institutional effects exist.

The purpose of this experiment is to compare the performance of the OCM and the PCM auctions, holding the production capabilities, demand levels and competitive predictions constant. In fact, if all sellers would truthfully submit their actual generation cost, in both the OCM and the PCM auction, the amount of exchanged units during each period of a day would be the same, the total procurement cost of electricity during the day would be the same, and the total generation cost of electricity would be barely one percent higher under the PCM auction.

Providing rather equal grounds for both auctions to perform, I intend to use the experimental data to test the theoretical results developed by Knoblauch (2005) and Baltaduonis (2006). Their game theoretic models predict that at a given period of the demand cycle of a *No Power* treatment, the marginal generators will submit the offers that are equal to the actual production costs of the marginal units. Consequently, in the constructed environment both auctions should perform the same with regards to the efficiency and the procurement cost in the off-peak periods. But in the shoulder 1 periods, the PCM auction should result in cheaper allocations to buyers, whereas the OCM auction should produce more efficient allocations. The same comparative statics hold for the *Power* treatments with the difference being that procurement cost of the commodity rises from a competitive level to a supra-competitive level. The suggested tradeoff between lower electricity cost and production efficiency is considered as well.

The degree of susceptibility to the exercise of market power over the course of a day and the propensity to reveal the true generation costs in these auctions are other questions of interest in this paper.

3. Experimental Design and Procedures

3.1. Experimental Design

Table 3 summarizes the balanced 2 × 2 experimental design with four replications in each cell. Each session lasted 53 trading days.[5] The experimental dataset contains data from 848 trading days.

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[5] I originally planed to have 60 trading days per session. However, the first conducted session was interrupted by the computer network failure after the 53rd day. Since the data from that first session suggested that the bidding behavior in the market stabilized around the 35th day, I decided to shorten the rest of the sessions to 53 days as well.

Table 3. Experimental Design (No. of Sessions; No. of Trading Days per Session)

	OCM	*PCM*	Total
No Power	(4; 53)	(4; 53)	(8; 53)
Power	(4; 53)	(4; 53)	(8; 53)
Total	(8; 53)	(8; 53)	(16; 53)

3.2. Procedures

To compare how the behavior and market performance differ in the OCM and the PCM auctions, I conducted 16 market experiments using undergraduate students at George Mason University. Four sessions for each cell in Table 3 were conducted using the experimental software that we developed at the Interdisciplinary Center for Economic Science at George Mason University. Each session lasted approximately 90 minutes.

The subjects in each market were provided with complete information on the market supply structure; i.e. every plant's minimum and maximum production capacity, start-up cost, cost per unit and the ownership of all plants were public information. Information on 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 generation jargon. An experimenter informed the subjects that the costs and production capacities for each seller would not change during the experiment, but that the quantities of the product that the computer buyer will purchase 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. Each day consisted of a four period cycle: off-peak, shoulder 1, peak and shoulder 2 periods. The subjects did not know the total number of trading days in advance.

A subject had 75 seconds to submit an offer for each day.[6] 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. However, the subjects could still effectively withdraw the capacity from the market by asking extremely high prices for those capacity units. Thus, 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] 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 offer was 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. An experimenter also explained a rule of offer selection. A subject could at any time within the 75 seconds period revise her offer.

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 market price for each period was and what profit/loss she earned on every owned

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[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 his/her offer for the first day, the following trading days were limited to 75 seconds. The chosen time frame is similar to one-minute trading days of the RSW electric power experiments.

[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; partial start-up cost reimbursement) for electric power generators in real life. However, the purpose of the study is to investigate the performance of the two auctions when such regulations are absent.

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 $21.47.

4. Results

The OCM and the PCM auctions on average extract respectively 92 and 94 percent of maximum social surplus in the *No Power* treatments. In *Power* treatments, both auctions capture 90 percent of the maximum possible surplus. Both auctions on average sell 32 and 31 units a day in *No Power* and *Power* treatments respectively. Thus, considering that the demand side of the market is perfectly revealed in the experiment, the drop in allocative efficiency in *Power* treatments can be at least partially attributed to output reduction. On the other hand, the difference in allocative efficiency between two auctions in *No Power* treatments must arise due to the different levels of production inefficiency. To have an idea how the captured social surplus is allocated among buyers and sellers, and how volatile the allocation is, Figure 2 depicts the buyer prices in each session of the four conducted treatments. The last seventeen days of the data are grouped by level of demand (quarter) and 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 true cost revelation. The outcome of true cost revelation is particularly interesting in the electricity markets because the design and the

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

engineering of these complicated market systems often start with the assumption of true cost revelation. In Figure 2, the outcome of 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.

From Figure 2, it is evident that the outcome of perfectly revealed costs does not dominate in the markets with the exception of shoulder 2 periods. In shoulder 2 periods, when most of the plants are already operating and, therefore, not eligible for the start-up fees, the sellers compete purely on prices and apparently are more likely to approach the true cost revelation outcome. The absence of fixed costs in this period leads to relatively competitive outcomes in both *No Power* and *Power* treatments regardless of the auction. Shoulder 2 gets closer to the true cost revelation than any other quarter of a day. A relatively competitive performance of the auctions in shoulder 2 periods of the *Power* treatments, however, is unexpected. From the figure, the differences between *No Power* and *Power* treatments are not obvious, especially for the OCM auction. It is apparent, however, that the *Power* sessions of the PCM auction are likely to experience inefficient prices causing allocative inefficiencies, while the prices of the OCM auction fluctuate within the efficient price range.

In what follows, the experimental results are summarized as a series of five 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.[10] The results from estimating this model for the buyer prices by level of demand are given in Table 4. The dependent variable in this case is the difference between the observed buyer price (*Price*) and the buyer price when generation costs are perfectly revealed by the sellers, P^t. The treatment effects (*Power* 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 the 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:

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

$$+\beta_6 PCM_i\times First_i+\beta_7 PCM_i\times Second_i+\beta_8 Power_i\times First_i+\beta_9 Power_i\times Second_i+$$

$$\beta_{10} PCM_i\times Power_i\times First_i+\beta_{11} PCM_i\times Power_i\times Second_i+\varepsilon_{ij};$$

where the sessions are indexed by i=1,…,16 and the repeated market days by j=1,…,53.[11] $e_i \sim N(0,\sigma^2_1)$ and $\varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$. I begin with the findings related to the procurement cost first and then follow with the results regarding the efficiency of the auctions.

Finding 1: *Both the OCM and the PCM auctions do not elicit true cost telling in the periods when start-up costs are relevant, i.e. off-peak, shoulder 1 and peak periods. The departure from the true cost revealing outcome is greater in the PCM/Power than in the*

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[10] See e.g. Longford 1993.

[11] Similar mixed-effects models were used in other experimental studies of electricity markets (Rassenti, Smith and Wilson, 2003a and 2003b; Kiesling and Wilson, 2007).

PCM/No Power treatment, whereas the OCM/Power and the OCM/No Power treatments do not exhibit such a difference.

Support: Figure 2 clearly shows that both auctions can produce buyer prices that are much higher than the prices corresponding to the revealed true costs. In all three periods where new plants need to be started, i.e. in off-peak, shoulder 1 and peak periods, the prices are higher even in the *No Power* treatments. On the other hand, shoulder 2 prices are much closer to the "truth" outcome. These qualitative observations are supported by estimates from the mixed-effects model in Table 4. In the shoulder 1 (peak, off-peak) periods, the *OCM/No Power* treatment significantly raises buyer prices above the prices of "truth" revelation [*p-value*=0.0108 (<.0001, 0.1092)]. The *PCM/No Power* treatment mirrors these results [*p-value*=0.0184 (<.0001, 0.0022)].[12] There is no significant difference between the prices in the *OCM/Power* and the *OCM/No Power* treatments during all periods of a day (*p-values*=0.1112, 0.5482, 0.8272, 0.2828 for off-peak, shoulder 1, peak and shoulder 2 periods respectively). The *PCM/Power* treatment, on the other hand, significantly raises prices above the *PCM/No Power* level by 26.9 experimental dollars in off-peak periods (*p-value*=0.0043) and insignificantly by 12.2 experimental dollars in shoulder 1 periods (*p-value*=0.1529). In peak (shoulder 2) periods of the *PCM/Power* treatment, the prices are not significantly greater than the *PCM/No Power* prices [*p-value*=0.8799 (0.1732)]. However, the prices in shoulder 2 periods are not significantly higher than the "truth" telling outcome, i.e. the *Bertrandesqe*

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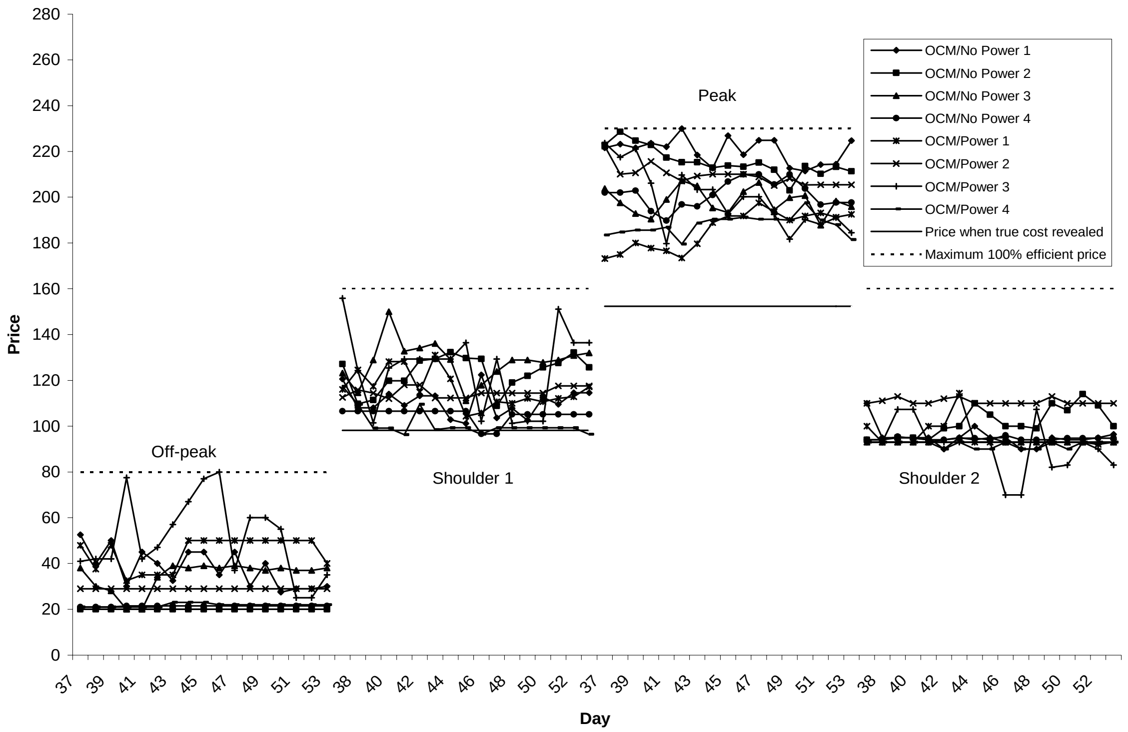
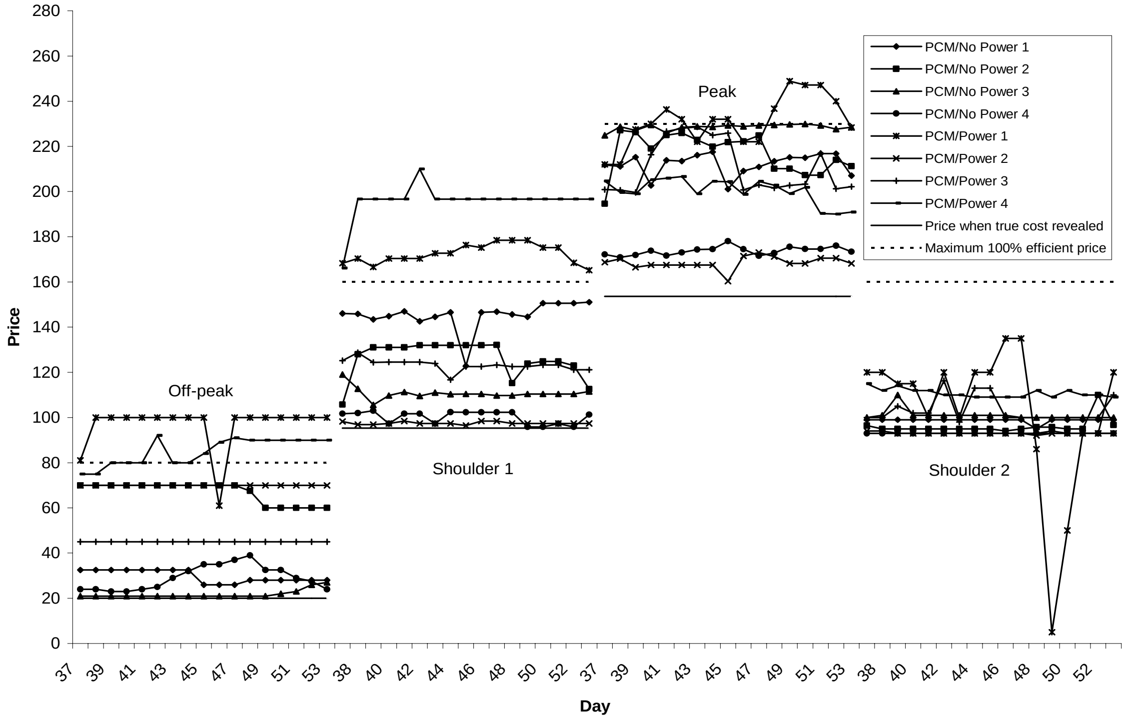
[12] The p-values for the *PCM/No Power* treatment are based on the linear mixed-effects model where the benchmark treatment is *PCM/No Power*. These estimates parallel the estimates reported in table 4.



(a) OCM/No Power vs. OCM/Power



(b) PCM/No Power vs. PCM/Power

Figure 2. Buyer Prices 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 Buyer Prices

$Price_{ij} - P^t = \mu + e_i + \beta_1 PCM_i + \beta_2 Power_i + \beta_3 PCM_i \times Power_i + \beta_4 First_i + \beta_5 Second_i + \beta_6 PCM_i \times First_i + \beta_7 PCM_i \times Second_i + \beta_8 Power_i \times First_i + \beta_9 Power_i \times Second_i + \beta_{10} PCM_i \times Power_i \times First_i + \beta_{11} PCM_i \times Power_i \times Second_i + \varepsilon_{ij},\ e_i \sim N(0,\sigma^2_1)$ 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	**7.38**	**5.99**	**824**	**$\mu>0$**	**1.23**	**0.1092**
PCM	**9.70**	**8.46**	**12**	**$\beta_1\neq0$**	**1.15**	**0.2736**
Power	**10.98**	**8.53**	**12**	**$\beta_2>0$**	**1.29**	**0.1112**
PCM×Power	**15.88**	**12.07**	**12**	**$\beta_3\neq0$**	**1.32**	**0.2131**
First	-6.71	1.22	824	$\beta_4\neq0$	-5.51	<.0001
Second	-2.72	1.22	824	$\beta_5\neq0$	-2.23	0.0262
PCM×First	4.25	1.46	824	$\beta_6\neq0$	2.91	0.0037
PCM×Second	1.04	1.46	824	$\beta_7\neq0$	0.72	0.4748
Power×First	6.39	1.97	824	$\beta_8\neq0$	3.24	0.0012
Power×Second	3.29	1.97	824	$\beta_9\neq0$	1.67	0.0952
PCM×Power×First	-7.41	2.62	824	$\beta_{10}\neq0$	-2.83	0.0047
PCM×Power×Second	2.62	2.62	824	$\beta_{11}\neq0$	1.00	0.3166
Shoulder 1						
μ	**18.53**	**8.05**	**824**	**$\mu>0$**	**2.30**	**0.0108**
PCM	**-1.86**	**11.33**	**12**	**$\beta_1\neq0$**	**-0.16**	**0.8724**
Power	**-1.42**	**11.45**	**12**	**$\beta_2>0$**	**-0.12**	**0.5482**
PCM×Power	**13.58**	**16.14**	**12**	**$\beta_3\neq0$**	**0.84**	**0.4164**
First	-7.98	2.17	824	$\beta_4\neq0$	-3.68	0.0003
Second	-1.61	2.17	824	$\beta_5\neq0$	-0.74	0.4595
PCM×First	15.69	2.44	824	$\beta_6\neq0$	6.44	<.0001
PCM×Second	3.26	2.44	824	$\beta_7\neq0$	1.34	0.1818
Power×First	0.26	3.33	824	$\beta_8\neq0$	0.08	0.9375
Power×Second	8.65	3.33	824	$\beta_9\neq0$	2.59	0.0096
PCM×Power×First	-5.68	3.55	824	$\beta_{10}\neq0$	-1.60	0.1099
PCM×Power×Second	-9.11	3.55	824	$\beta_{11}\neq0$	-2.57	0.0105
Peak						
μ	**57.17**	**7.67**	**824**	**$\mu>0$**	**7.45**	**<.0001**
PCM	**2.87**	**10.84**	**12**	**$\beta_1\neq0$**	**0.26**	**0.7957**
Power	**-10.66**	**10.86**	**12**	**$\beta_2>0$**	**-0.98**	**0.8272**
PCM×Power	**-2.84**	**15.41**	**12**	**$\beta_3\neq0$**	**-0.18**	**0.8567**
First	-2.09	1.85	824	$\beta_4\neq0$	-1.14	0.2565
Second	4.37	1.85	824	$\beta_5\neq0$	2.36	0.0183
PCM×First	-6.54	2.50	824	$\beta_6\neq0$	-2.62	0.0090
PCM×Second	-7.72	2.50	824	$\beta_7\neq0$	-3.09	0.0021
Power×First	-8.37	2.75	824	$\beta_8\neq0$	-3.05	0.0024
Power×Second	-4.00	2.75	824	$\beta_9\neq0$	-1.46	0.1453
PCM×Power×First	11.00	4.10	824	$\beta_{10}\neq0$	2.68	0.0074
PCM×Power×Second	6.56	4.10	824	$\beta_{11}\neq0$	1.60	0.1099
Shoulder 2						
μ	**0.66**	**4.00**	**824**	**$\mu>0$**	**0.17**	**0.4345**
PCM	**1.22**	**5.67**	**12**	**$\beta_1\neq0$**	**0.21**	**0.8338**
Power	**3.45**	**5.84**	**12**	**$\beta_2>0$**	**0.59**	**0.2828**
PCM×Power	**2.14**	**8.16**	**12**	**$\beta_3\neq0$**	**0.26**	**0.7975**
First	-0.51	0.28	824	$\beta_4\neq0$	-1.79	0.0733
Second	-0.31	0.28	824	$\beta_5\neq0$	-1.10	0.2723
PCM×First	10.88	1.25	824	$\beta_6\neq0$	8.72	<.0001
PCM×Second	3.67	1.25	824	$\beta_7\neq0$	2.94	0.0034
Power×First	-3.22	2.15	824	$\beta_8\neq0$	-1.50	0.1342
Power×Second	0.24	2.15	824	$\beta_9\neq0$	0.11	0.9102
PCM×Power×First	-5.25	2.53	824	$\beta_{10}\neq0$	-2.08	0.0383
PCM×Power×Second	-3.67	2.53	824	$\beta_{11}\neq0$	-1.45	0.1468

Note. The linear mixed-effects model is fit by maximum likelihood with 848 original observations and 16 sessions. For purposes of the brevity the session random effects are not included in the table.

competitive equilibrium, in both *OCM/No Power* and *PCM/No Power* treatments (*p-values*=0.4345, 0.3204).■

Finding 1 raises the question as to whether a complex offer nature brings any value to wholesale electricity markets. The opportunity to recover fixed and variable costs at exact proportions is not used even during the most competitive periods of the experiment.

Finding 2: *The supracompetitive buyer prices in the OCM and the PCM auctions are due to the heightened offers on both start-up fee and seller price dimensions. All treatments result in similar aggregate daily amounts paid to sellers in terms of fees and seller prices.*

Support: Table 5 presents the mixed-effects models of treatment effects for the income from fees and for the income from seller prices. The dependent variable in this case is the difference between the observed income from fees (seller prices), *FeeInc* (*PriceInc*), and the income from fees (seller prices) when generation costs are perfectly revealed by the sellers, $FeeInc^t$ ($PriceInc^t$). The estimates from the models point out that the sellers receive significantly higher incomes than in the "truth" outcome by increasing both fees and seller prices. In the *OCM/No Power* treatment, the daily amount of fees exceeds the true start-up costs by 171.9 experimental dollars (*p-value*=0.0474) and the price income surpasses the variable production costs by 871.9 experimental dollars (*p-value*=0.0001). The estimates for the *PCM/No Power* (*PCM/Power, OCM/Power*) treatment do not significantly differ from the *OCM/No Power* treatment estimates [fee income *p-values*=0.8297 (0.1066, 0.7223); price income *p-values*=0.8180 (0.1830, 0.6423)].

Table 5. Estimates of the Linear Mixed Effects Model of Treatment Effects for the Income from Fees and Seller Prices

$$FeeInc_{ij} - FeeInc^{t} = \mu + e_i + \beta_1 PCM_i + \beta_2 Power_i + \beta_3 PCM_i \times Power_i + \beta_4 First_i + \beta_5 Second_i + \beta_6 PCM_i \times First_i + \beta_7 PCM_i \times Second_i + \beta_8 Power_i \times First_i + \beta_9 Power_i \times Second_i + \beta_{10} PCM_i \times Power_i \times First_i + \beta_{11} PCM_i \times Power_i \times Second_i + \varepsilon_{ij},\ e_i \sim N(0,\sigma^2_1) \text{ and } \varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$$

	Estimate	Std. Error	Degrees of Freedom	H_a	t-statistic	p-value
Whole Day						
μ	**171.93**	**86.58**	**824**	**$\mu \neq 0$**	**1.99**	**0.0474**
PCM	**26.94**	**122.56**	**12**	**$\beta_1 \neq 0$**	**0.22**	**0.8297**
Power	**-44.60**	**122.58**	**12**	**$\beta_2 \neq 0$**	**-0.36**	**0.7223**
PCM×Power	**304.94**	**174.79**	**12**	**$\beta_3 \neq 0$**	**1.74**	**0.1066**
First	-229.16	15.72	824	$\beta_4 \neq 0$	-14.58	<.0001
Second	-83.79	15.72	824	$\beta_5 \neq 0$	-5.33	<.0001
PCM×First	168.75	21.27	824	$\beta_6 \neq 0$	7.93	<.0001
PCM×Second	78.82	21.27	824	$\beta_7 \neq 0$	3.71	0.0002
Power×First	146.35	23.20	824	$\beta_8 \neq 0$	6.31	<.0001
Power×Second	85.44	23.20	824	$\beta_9 \neq 0$	3.68	0.0002
PCM×Power×First	-350.28	39.14	824	$\beta_{10} \neq 0$	-8.95	<.0001
PCM×Power×Second	-124.61	39.14	824	$\beta_{11} \neq 0$	-318	0.0015

$$PriceInc_{ij} - PriceInc^{t} = \mu + e_i + \beta_1 PCM_i + \beta_2 Power_i + \beta_3 PCM_i \times Power_i + \beta_4 First_i + \beta_5 Second_i + \beta_6 PCM_i \times First_i + \beta_7 PCM_i \times Second_i + \beta_8 Power_i \times First_i + \beta_9 Power_i \times Second_i + \beta_{10} PCM_i \times Power_i \times First_i + \beta_{11} PCM_i \times Power_i \times Second_i + \varepsilon_{ij},\ e_i \sim N(0,\sigma^2_1) \text{ and } \varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$$

Whole Day						
μ	**871.79**	**132.26**	**824**	**$\mu \neq 0$**	**6.59**	**0.0001**
PCM	**44.12**	**187.51**	**12**	**$\beta_1 \neq 0$**	**0.24**	**0.8180**
Power	**-89.36**	**187.56**	**12**	**$\beta_2 \neq 0$**	**-0.48**	**0.6423**
PCM×Power	**-376.89**	**266.66**	**12**	**$\beta_3 \neq 0$**	**-1.41**	**0.1830**
First	-82.44	36.28	824	$\beta_4 \neq 0$	-2.27	0.0233
Second	113.41	36.28	824	$\beta_5 \neq 0$	3.13	0.0018
PCM×First	65.34	56.83	824	$\beta_6 \neq 0$	1.15	0.2506
PCM×Second	-121.53	56.83	824	$\beta_7 \neq 0$	-2.14	0.0328
Power×First	-255.34	55.26	824	$\beta_8 \neq 0$	-4.62	<.0001
Power×Second	-108.16	55.26	824	$\beta_9 \neq 0$	-1.96	0.0506
PCM×Power×First	317.92	87.31	824	$\beta_{10} \neq 0$	3.64	0.0003
PCM×Power×Second	123.33	87.31	824	$\beta_{11} \neq 0$	1.41	0.1582

Note. The linear mixed-effects model is fit by maximum likelihood with 848 original observations and 16 sessions. For purposes of the brevity the session random effects are not included in the table.

The low and intermediate cost plants that did not sell during the off-peak and shoulder 1 periods are namely responsible for the inflated fees. Since they need to be started for higher demand periods, they can offer high start-up fees for those periods and still undercut the higher cost generation plants. For instance, in session 2 of the *OCM/No Power* treatment, *S*3 is able to charge as much as 80 (true start-up cost=10) experimental dollars to start his low cost one-unit plant during the intermediate demand periods. Similarly, during the intermediate demand periods of session 1 of the *PCM/No Power* treatment, *S*1 is able to charge 195 (true start-up cost=0) experimental dollars to start her low cost two-unit plant. These big payoffs from fees do not leave many incentives to compete for the contracts during the lower demand periods. Indeed, such withholding of capacity for higher demand periods explains why competition is so weak even in the "*No Power"* treatments. The *Power* treatments exhibit similar offer strategies as well. In session 1 of the *PCM/Power* treatment, *S*4 is constantly able to charge 500 (true start-up cost=6) experimental dollars to start an intermediate cost plant during the peak periods.■

In Table 5, the significant coefficients for early periods (e.g. *First*, *Second* etc.) also show that the sellers are actively adjusting their offer strategies for both fees and prices over time. Interestingly, the OCM auction starts with low fees in the beginning of the experiment and increases them as the time goes on, whereas the PCM auction starts with high fees and lowers them over time.

Finding 2 highlights two important points with respect to the total procurement cost of a commodity. First, there are no special institutional effects on offer strategies towards the end of the experiment. Second, the sellers in a more competitive environment (*No Power* treatment) are able to extract the same amount of wealth as in an environment with structural market power (*Power* treatment). Finding 2 might be an explanation why there are some attempts from the ISOs' side to limit frequent offer changes for start-up fees, while remaining faithful to the unregulated nature of the seller prices. The effects of such restrictions are still to be evaluated.

Finding 3: *In all treatments with an exception of PCM/No Power, sellers supply the efficient amount of the product to the market during all periods of a day.*

Support: It is easy to see from Figure 2 that fourteen out of sixteen sessions resulted in 100% efficient buyer prices and only two *PCM/Power* sessions clearly failed to supply the efficient quantity to the market. However, this does not necessarily mean that all OCM sessions succeeded to do that during all days. In fact, the demand had to be interrupted on 19 occasions (out of possible $544 = 17\text{days}\times 4\text{quarters}\times 8$ sessions) in the OCM sessions, because the buyer price for the efficient amount exceeded buyers' maximum willingness to pay. Besides the two *PCM/Power* sessions, the demand was interrupted on 5 occasions in other PCM sessions. Interestingly, there is not a single occasion when the demand had to be interrupted during the shoulder 2 periods regardless of the auction.■

Failure to supply the efficient amount of product to the market is not the only source of possible inefficiencies. The social surplus might also be reduced by production inefficiencies, i.e. the situations when the higher-cost plants produce the product instead of the lower-cost plants.

Finding 4: *All OCM and PCM treatments exhibit similar degrees of production inefficiency with an exception of peak periods. In peak periods, the PCM/Power and OCM/No Power treatments generate significantly higher production costs than the PCM/No Power and OCM/Power treatments.*

Support: Figure 3 and the estimates from the mixed-effects model in Table 6 report evidence that in all but peak periods, the treatments are not significantly different from each other. The dependent variable in this case is the difference between the observed production cost (*ProdCost*) and the production cost when all sellers perfectly reveal their private generation costs, $ProdCost^t$. All estimates for the last 17 days in the experiment are insignificant for both shoulder 1 and shoulder 2 periods. Note that if the true costs were revealed, in the shoulder 1 periods, the OCM auction would have produced a more efficient allocation of contracts than in the PCM auction. In off-peak periods, the *Power* treatments result in higher production costs than *No Power* treatments, but the differences are insignificant. As hypothesized in the beginning of the paper, production inefficiencies are expected in the off-peak periods of the *Power* treatments, because it is more profitable for *S*1 to supply half of the market demand and ask for a high pay rather than to compete with *S*3 for the whole market demand and receive a competitive return.

In peak periods, the estimates from the mixed-effects models suggest that the production costs in the *PCM/Power* treatment are not significantly different from the *OCM/No Power* treatment. Similarly, the production costs in the *PCM/No Power* treatment are not significantly different from the *OCM/Power* treatment. But the *PCM/Power* and *OCM/No Power* treatments attain significantly higher production costs than the *PCM/No Power* and *OCM/Power* treatments (*p-value*=0.0898 and 0.0462).[13] These empirical differences in peak periods are surprising since all unilateral deviations from the competitive outcome are unprofitable in all treatments. Another indicator of

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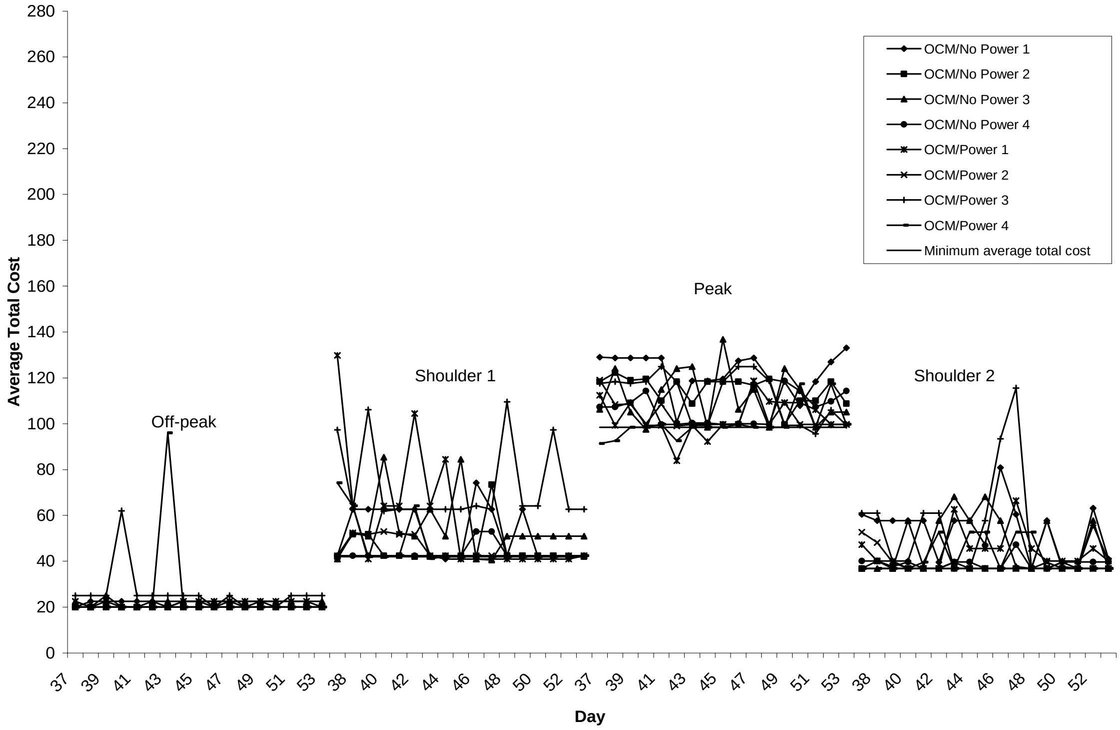
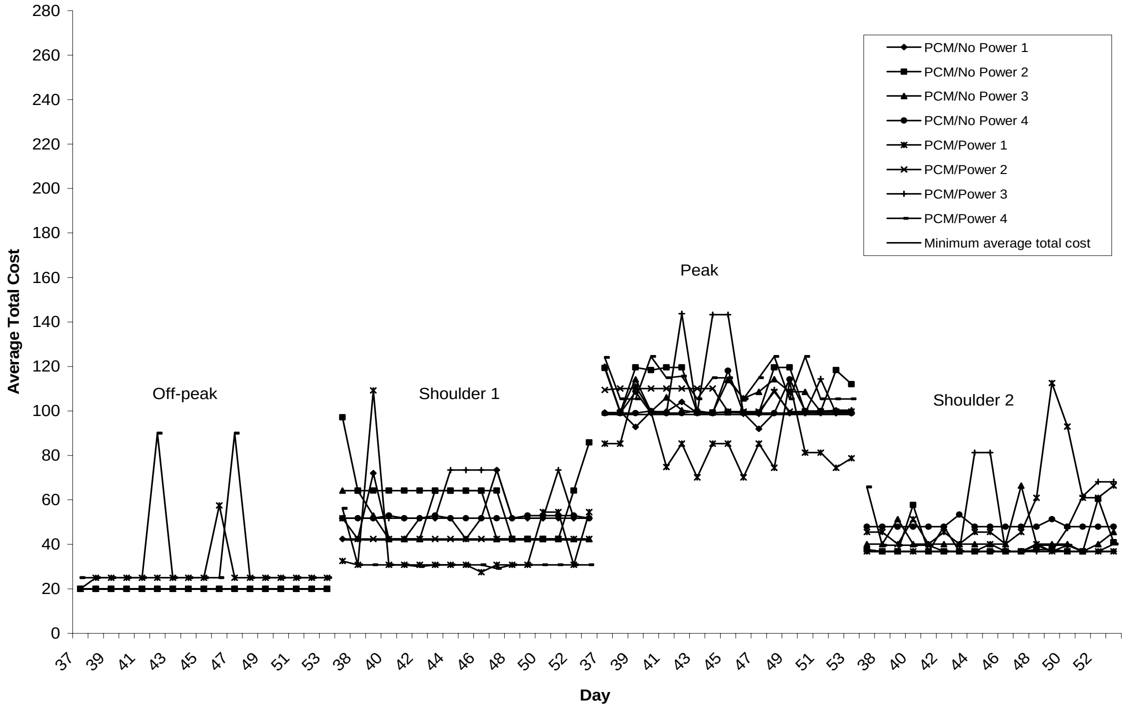
[13] The p-values for the *PCM* treatment are based on the linear mixed-effects model where the benchmark treatment is *PCM/No Power*. These estimates parallel the estimates reported in table 6.



(a) OCM/No Power vs. OCM/Power



(b) PCM/No Power vs. PCM/Power

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

Table 6. Estimates of the Linear Mixed Effects Model of Treatment Effects for the Production Costs

$$ProdCost_{ij} - ProdCost^{t} = \mu + e_i + \beta_1 PCM_i + \beta_2 Power_i + \beta_3 PCM_i \times Power_i + \beta_4 First_i + \beta_5 Second_i + \beta_6 PCM_i \times First_i + \beta_7 PCM_i \times Second_i + \beta_8 Power_i \times First_i + \beta_9 Power_i \times Second_i + \beta_{10} PCM_i \times Power_i \times First_i + \beta_{11} PCM_i \times Power \times Second_i + \varepsilon_{ij},\ e_i \sim N(0,\sigma^2_1) \text{ and } \varepsilon_{ij} \sim N(0,\sigma^2_{2,i})$$

	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.				
OCM/No Power	**1.69**	**2.38**				
PCM/No Power	**0.00**	**0.00**				
OCM/Power	**5.16**	**20.78**				
PCM/Power	**5.37**	**14.57**				
Shoulder 1						
μ	**36.98**	**31.10**	**824**	**$\mu\neq0$**	**1.19**	**0.2347**
PCM	**43.39**	**43.97**	**12**	**$\beta_1\neq0$**	**0.99**	**0.3434**
Power	**53.90**	**45.47**	**12**	**$\beta_2\neq0$**	**1.19**	**0.2588**
PCM×Power	**-54.62**	**63.51**	**12**	**$\beta_3\neq0$**	**-0.86**	**0.4067**
First	114.04	15.02	824	$\beta_4\neq0$	7.59	<.0001
Second	36.72	15.02	824	$\beta_5\neq0$	2.45	0.0147
PCM×First	-58.45	20.89	824	$\beta_6\neq0$	-2.80	0.0053
PCM×Second	-12.55	20.89	824	$\beta_7\neq0$	-0.60	0.5483
Power×First	-8.82	26.48	824	$\beta_8\neq0$	-0.33	0.7391
Power×Second	83.57	26.48	824	$\beta_9\neq0$	3.16	0.0017
PCM×Power×First	28.90	32.61	824	$\beta_{10}\neq0$	0.89	0.3757
PCM×Power×Second	-96.43	32.61	824	$\beta_{11}\neq0$	-2.96	0.0032
Peak						
μ	**230.13**	**38.04**	**824**	**$\mu\neq0$**	**6.05**	**<.0001**
PCM	**-146.37**	**53.21**	**12**	**$\beta_1\neq0$**	**-2.75**	**0.0176**
Power	**-120.62**	**54.26**	**12**	**$\beta_2\neq0$**	**-2.22**	**0.0462**
PCM×Power	**217.83**	**75.63**	**12**	**$\beta_3\neq0$**	**2.88**	**0.0138**
First	-62.30	23.78	824	$\beta_4\neq0$	-2.62	0.0090
Second	-51.04	23.78	824	$\beta_5\neq0$	-2.15	0.0322
PCM×First	116.18	32.71	824	$\beta_6\neq0$	3.55	0.0004
PCM×Second	97.35	32.71	824	$\beta_7\neq0$	2.98	0.0030
Power×First	100.62	34.95	824	$\beta_8\neq0$	2.88	0.0041
Power×Second	88.91	34.95	824	$\beta_9\neq0$	2.54	0.0112
PCM×Power×First	-204.19	46.85	824	$\beta_{10}\neq0$	-4.36	<.0001
PCM×Power×Second	-153.55	46.85	824	$\beta_{11}\neq0$	-3.28	0.0011
Shoulder 2						
μ	**46.98**	**29.24**	**824**	**$\mu\neq0$**	**1.61**	**0.1086**
PCM	**-5.45**	**41.13**	**12**	**$\beta_1\neq0$**	**-0.13**	**0.8967**
Power	**-1.71**	**43.31**	**12**	**$\beta_2\neq0$**	**-0.04**	**0.9691**
PCM×Power	**32.37**	**59.90**	**12**	**$\beta_3\neq0$**	**0.54**	**0.5988**
First	116.74	12.19	824	$\beta_4\neq0$	9.58	<.0001
Second	28.77	12.19	824	$\beta_5\neq0$	2.36	0.0185
PCM×First	-55.55	17.19	824	$\beta_6\neq0$	-3.23	0.0013
PCM×Second	-14.68	17.19	824	$\beta_7\neq0$	-0.85	0.3934
Power×First	32.06	25.39	824	$\beta_8\neq0$	1.26	0.2072
Power×Second	80.53	25.39	824	$\beta_9\neq0$	3.17	0.0016
PCM×Power×First	-41.96	30.28	824	$\beta_{10}\neq0$	-1.39	0.1663
PCM×Power×Second	-104.42	30.28	824	$\beta_{11}\neq0$	-3.45	0.0006

Note. The linear mixed-effects model is fit by maximum likelihood with 848 original observations and 16 sessions. For purposes of the brevity the session random effects are not included in the table.

production efficiency could be the frequency of how often the very high cost generators of H and I types are called to produce. During the last 17 days in the experiment, these generators are selected in peak periods and make positive profits for 42 (4) times [out of possible 68 = 17days× 4sessions] in the *OCM/No Power* (*/Power*) treatment and for 6 (28) times in the *PCM/No Power* (*/Power*) treatment. The most inefficient plants (type I) make significant profits by offering low prices and recovering their variable costs through high start-up fees. Note that these plants would never sell profitably if they had to recover their costs only through prices.■

One might wonder why the more efficient plants are unsuccessful in competing with the high cost plants since all sellers could use similar strategies. My guess is that this outcome reflects incomplete information about the returns in the market. While the seller prices are publicly announced in the market, the collected individual start-up fees are not known to other sellers. Possibly, it is the lack of transparency in earnings (rather than production costs) that weakens the performance of these auctions with regards to the production efficiency.

Finding 5: *The variance of buyer prices from day to day for the same level of demand is lower with the PCM auction than with the OCM auction, holding the No Power design constant. The Power treatments result in higher variances than the No Power treatments.*

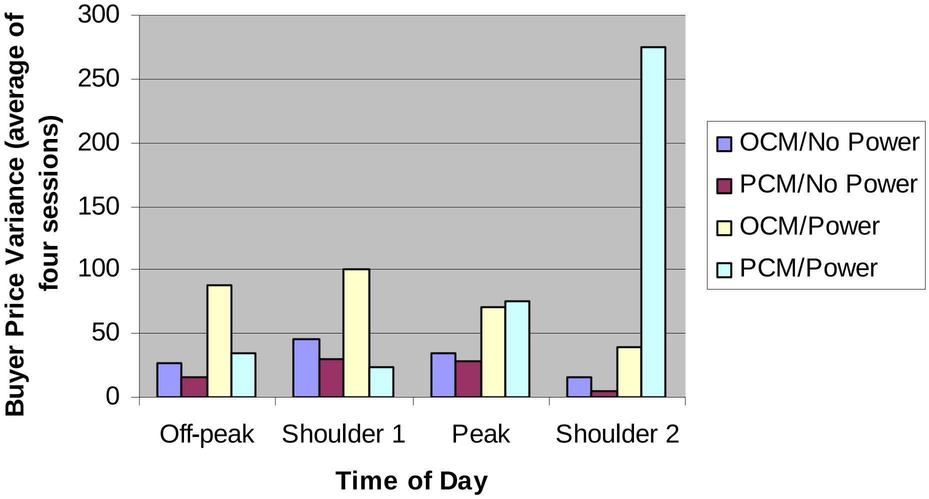


Figure 4. Buyer Price Variances by Treatment for the Last 17 Market Days

Support: Figure 4 summarizes the price variances for the sixteen sessions presented here. The statistics use the last 17 days of each session to allow for the convergence of the observed prices evident in Table 4. Individual session variances are averaged across each treatment. From Figure 4, it is clear that the PCM auction reduces the volatility of prices compared to the OCM auction in all periods. It is also evident that the *Power* design raises the volatility of prices compared to the corresponding *No Power* treatments. Also note that, with the exception of the *PCM/Power* treatment, the buyer price volatility substantially drops in shoulder 2 periods when most of the plants are not eligible to receive start-up fees.■

Overall, both the OCM and the PCM auctions do not exhibit major differences with regards to buyer prices, allocative or production efficiency. The expected institutional effects with regards to these criteria are greatly dominated by the effects of strategic behavior that arises due to the offer structure in these auctions. Incentives to start-up the plants during the higher demand periods and the ability to sell higher cost units by manipulating the combination of offered fees and prices have strong anti-competitive effects. The outcomes of the *No Power* treatments approach the outcomes of the *Power* design.

5. Conclusions

This paper compares the performance of the OCM and the PCM sealed complex-offer auctions in a dynamic trading environment that models wholesale electricity markets. Game theory predicts that in a competitive environment, marginal generators will submit offers that are equal to the actual production costs of the marginal units. This leads to low prices of electricity to the buyers. However, if a market is concentrated, the theory suggests that the sellers can profitably increase the prices to the buyers regardless of the auction. Specifically, in the discussed environment, both the OCM and the PCM auction should perform similarly in the off-peak periods, while in the shoulder 1 periods, the PCM auction should result in lower procurement cost and the OCM auction should lead to more efficient contract allocations.

The results of the experiment indicate that in a competitive environment the marginal generators do not reveal their actual production costs in both auctions. In fact, the sellers are able to increase the buyer prices to the level of a concentrated market even in an environment with no structural market power. Both auctions do not exhibit strong differences in overall performance.

While theoretical analyses model the market demand as static, the experimental environment simulates a cyclical nature of the market demand. It appears that in the experiment, the intertemporal strategic behavior dominates the expected institutional effects of the two auctions. Market participants use fixed start-up fees very strategically in these complex-offer auctions. The incentives to start-up the plants during the higher demand periods practically extinguish competition. Furthermore, given the offer complexity and the cyclical nature of market demand, it becomes impossible to design a competitive environment during the lower demand periods. Even if new cheap-capacity plants entered the market, they would have the same incentives to withhold their start-ups for the periods with a higher market demand.

The outcomes for shoulder 2 periods, however, are noticeably more competitive and predictable. Since the start-up costs are basically absent in the shoulder 2 periods, and therefore, most plants are not eligible to receive the start-up fees, one might ponder how simpler and more transparent these markets could be if these fixed costs did not exist. But they do. And it is clear that allowing the sellers to recover their fixed and variable costs separately does not enhance the transparency in the market.

To sum it up, the OCM and the PCM auctions are not truth revealing mechanisms and do not elicit competitive behavior in an unregulated market. These findings beg the question as to whether a simple-offer auction could mitigate the anti-competitive behavior in the described trading environment.

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Appendix A: 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.

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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>

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.

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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 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)

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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.

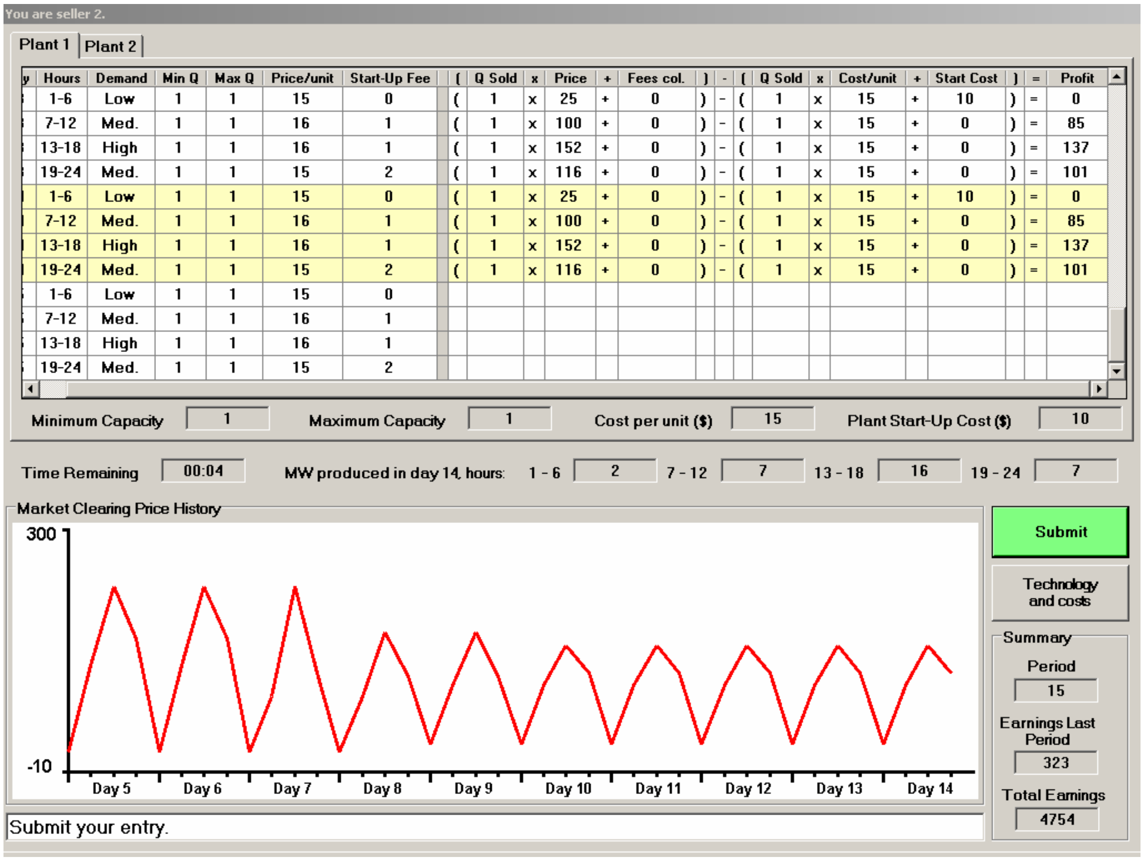
Information about all plants (including yours) is available to all sellers by clicking on the Technology and costs button.

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 B: 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

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

Submit your entry.

Figure B1. Sample Screen Shot.