CAN EXPERIMENTAL ECONOMICS HELP GUIDE RESTRUCTURING OF ELECTRIC POWER?

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Introduction

This paper attempts to show how experimental economics can be used to test alternative market designs for restructuring the electric power industry. The example experiments described here were funded by a grant from the National Science Foundation.

The US electric power industry, in particular California and the Northeastern United States, has taken major steps to restructure its institutional arrangements to support competition among energy suppliers. The US is not the first in the world to embark on this path, and to refer to the undertaking as deregulation would be a mistake. In early 1990s the United Kingdom restructured it's industry to form separate generation, transmission and distribution companies (Newbery and Green 1996). Today, this arrangement represents one of the most complex regulatory environments in the world due to efforts to ensure that the independent companies provide reliable electric power at "fair" prices. Indeed the England and Wales market will shortly undergo a transformation by abandoning the mandatory pool for a system of bilateral transactions and a voluntary power exchange, a system similar the Californian market which has recently come under intense criticism. Despite the experience in the UK, the historical experience with deregulation of other industries has been an unqualified success from the point of view of economic efficiency. For example, price decreases in the airline, natural gas, and long distance telephone industries have been well documented (Winston 1993; Crandall and Ellig 1997). Fortunately, restructuring of the electric power industry in Australia has resulted in price decreases that contrast sharply with the experiences to date in United Kingdom and the United States. What has become clear is that the electric utility industry presents unprecedented complications for restructuring.

Since electric power networks offer multiple simultaneous commodities and there are a variety of externalities in transmission, a pure market solution is unlikely to be efficient. For this reason, Vernon Smith and his colleagues (McCabe, Rassenti et al. 1991) proposed the notion of a "smart market." Smart markets use a computer optimization algorithm that interacts with buyers and sellers (using appropriate trading or activity rules) to provide feedback on physical constraints, such as line congestion, which would not be attainable by the market alone. In the United States, auctions for power have begun to replace centralized dispatch algorithms as a means to determine unit commitment (when to turn on or turn off generators with non-zero start up costs) and derive the local price of electricity including transmission charges that reflect line constraints.

This paper reports on two sets of experiments that address the market's ability to produce a cost efficient outcome in power generation. The first experiment examines the ability of generators to exact market power in the presence of line constraints. Under regulation, returns on generating assets could be considered guaranteed. Today, however, with those guarantees removed, power producers will be driven by the profit motive. There exists ample evidence from other industries that owners will seek to sustain higher than competitive prices when possible. The second experiment examines the efficiency of self-commitment in comparison to centralized unit commitment. The unit commitment problem is a complex mixed integer programming problem. Is it realistic to assume that it can be solved in a decentralized manner?

In both experiments, we implement a smart market to account for the operational constraints imposed by the physical transmission network. In this context, the sellers and the buyer's demands are connected by a transmission network which must be operated at all times in a manner consistent with the laws of physics governing the flow of electricity. The operation of the network is also constrained by the physical limitations of the equipment used to generate and transmit the power. This results in two phenomena which may affect the auction: (1) transmission losses and (2) congestion.

A small percentage of the energy produced by the generators is dissipated by the transmission lines. The amount of power lost depends on the flow in the line and the length of the line, among other things. Transmission loss implies that the total amount of power the buyer must purchase is slightly greater than the total demand and the exact amount is dependent on where the power is produced.

There are limits on the amount of electric power that can be transmitted from any given location to any other location. Some of the limits are simple line capacity limits and others are more subtle system constraints arising from voltage or stability limits. Congestion occurs when one or more of these network limits is reached. Congestion implies that some inexpensive generation may be unusable due to its location, making it necessary to utilize a more expensive unit in different location.

In our experiment platform, PowerWeb, the effects of losses and transmission system constraints are handled by adjusting all offers and prices by a location specific transmission charge that represents the shadow price of transporting the electricity. There is a two part transmission charge associated with each line which is divided up between the various generators based on their individual contributions to the flow in the line. The per-line transmission charges can be explained as follows. The value of the power dissipated by a transmission line is the loss component of the transmission charge for that line. The congestion component of the transmission charge is precisely the charge necessary to discourage overuse of the line. If there is no congestion, this component is zero. It is important to note that the transmission charges are dependent on the flow in each transmission line as well as each generator's contribution to that flow and therefore cannot be computed before performing the auction. In this context, each generator receives a price that is specific to its location.

Generator units are chosen so as to satisfy fixed location specific demand in the least expensive manner while satisfying the operational constraints of the transmission system. This is done by an optimal power flow program which computes the appropriate transmission charges for each generating station. The units selected by the optimization program are roughly those given by the following procedure. The appropriate transmission charge is added to the price of each offer, and the offers are ordered from lowest to highest adjusted offer price. Units are included for sale, starting from the low priced units and moving toward the higher priced units, until the supply reaches the total buyer's demand plus transmission losses. The remaining, higher priced, units are excluded from sale.

The reigning price is set to the adjusted offer price of the last (most expensive) unit chosen. The price paid for each unit produced by a given generator is the reigning price minus the corresponding transmission charge. In prior research, we have shown that this last accepted offer mechanism (LAO) performs as well, or better, than the Vickrey Multiple Unit Auction or alternative uniform price auctions that set the price equal to the first rejected offer when sellers have multiple units (Bernard et al., 1998).

Market Power

Market power increases as sellers own a larger fraction of the capacity available for serving demand (load). In an electric power grid, the supply and demand are dispersed throughout the system. Each generator and each load lie at a specific network location. Due to the constraints imposed by the transmission grid, it may not always be possible to transfer power from an arbitrary generating station to any given load. This implies that the capacity available to serve a specific load may be a subset of the total generation capacity in the system and that market power may be present if a small number of sellers own a large fraction of this subset of generation. The market is partitioned into smaller market islands by the limitations on transmission imposed by the network. If areas A and B of a transmission grid are isolated by transmission constraint, then generator A in area A cannot compete with generator B in area B to serve the load in area B. Likewise, generator B cannot compete with generator A to serve load in area A. The owner of a generation facility may have market power if they own a significant percentage of capacity in an isolated area even if they own only a small fraction of the total generation in the system.

These transmission limits may be simple and relatively constant thermal limits on the lines or they may arise indirectly from voltage or stability limits. In the latter case, the constraints may be very sensitive to VAr (reactive power) injections necessary to maintain voltage and other operating conditions. Therefore, market power could also arise from ones ability to manipulate the operating condition of the network in order to partition the markets to one's own advantage.

In summary, there are at least two ways in which the transmission network can create market power opportunities in load pockets. First, transmission constraints, arising from line limits, voltage limits, or stability limits, may partition the market into islands which may create the type of market power described above. Second, one may exploit one's position in the network to strategically partition the market to one's own advantage. Simple auctions that do not take into account transmission system constraints would often lead to infeasible operating conditions if employed in a constrained network (see for example, Hogan, 1992). The answer to this problem, of course, is use of a smart market which employs an auction where offers are adjusted for nodal pricing through transmission charges determined by an optimal power flow (McCabe, Rassenti et al. 1991).

The Experiment

We conducted three experiments with student subjects and one with electricity traders using our web-based experimental platform, PowerWeb, which implements the smart market described above using an OPF that models a full non-linear lossy AC transmission network. These experiments utilized the six generator, 30-node network model, shown as a simplified block diagram in Figure 1. The PowerWeb platform is described in detail in the Appendix.

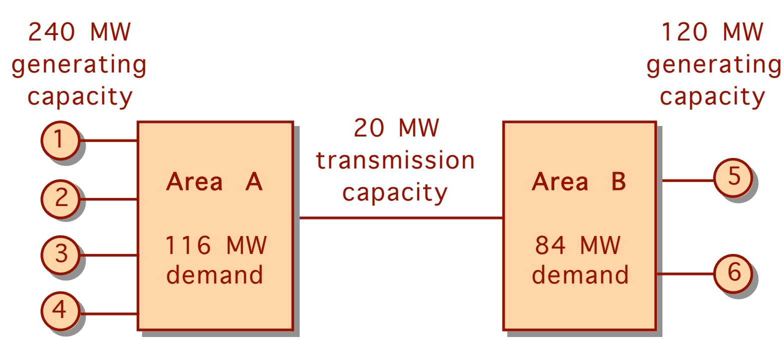

Figure 1: Transmission Network Block Diagram

Each of the six subjects in each experiment was one of six sellers in a market with a single buyer with a fixed demand. All generators had a capacity of 60 MW (megawatts) which was divided into 3 blocks, 12, 24, and 24 MW at marginal costs of $20, $40, and $50/MW-hr, respectively. All generators had identical capacity and cost structures. Each generator could generate between 12 and 60 MW of power, or could be shut down completely, in which case it incurred no costs. Given the inelastic demand, a limit price of $80/MW-hr was imposed.

The network was structured so as to create a load pocket in Area B, where generators 5 and 6 are located. The limitation on transmission capacity between areas A and B, can effectively separate the market into groups of four and two competitors, respectively. The demand levels and network constraints are such that neither generator 5 nor generator 6 can be shut down.

To see examples of the offer submission and auction result pages used by PowerWeb, please see Figures A1 and A2 in the Appendix.

Each of the three student sessions was run for 75 rounds, and each produced different results. Figure 2 shows the price results for a session that can be used to characterize all three sessions. In one session, the results for the prices received by the six generators remained similar to the price pattern shown in the figure prior to period 50. In other words, prices remained near the competitive level (shown by the heavy horizontal line in the figure) throughout the session. In a second session, prices were similar to those shown after trading period 50 in the figure, for the entire session. In other words, generators 5 and 6 were able to exploit their market power consistently from the initial trading periods through period 75. In the session shown in the figure, generators 5 and 6 were not able to coordinate their price offers to exploit the market power opportunities offered by the network until period 50. It appears that generator 5 (dashed/dotted line, 2nd from top) was not responsive to generator 6 (solid line, top) who attempted to raise prices earlier.

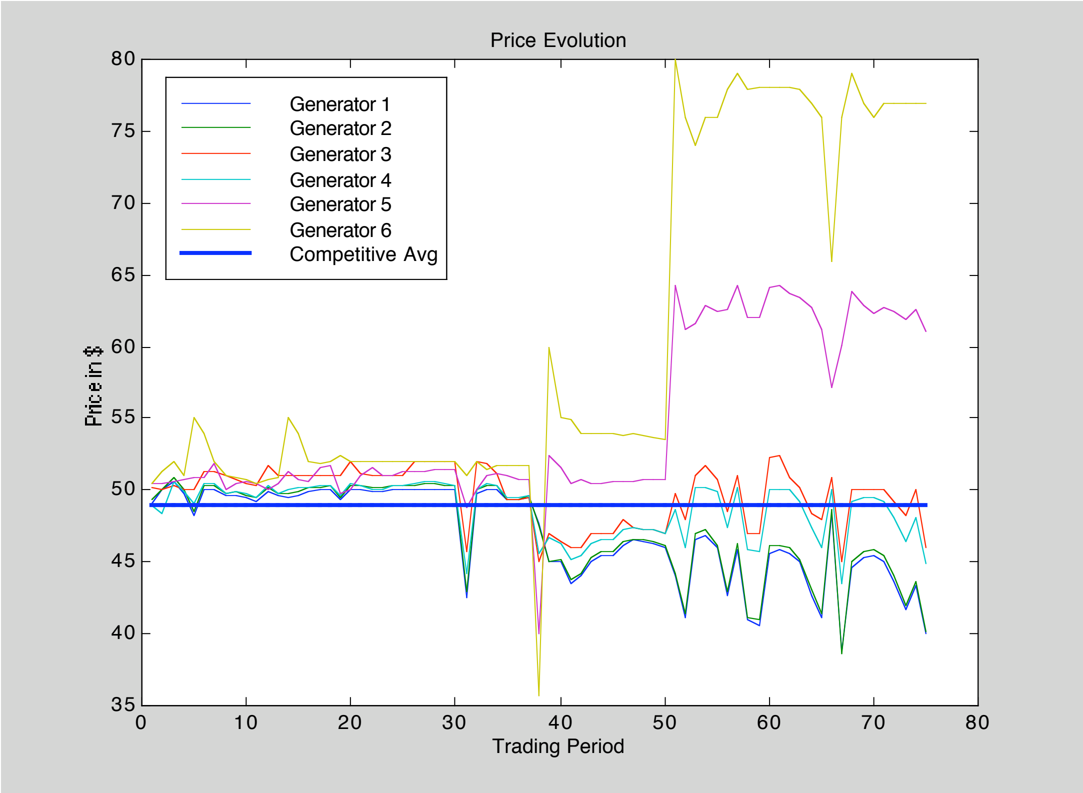

Figure 2: Nodal Prices, Undergraduate Session

We draw two conclusions from these results. First, in two of the three sessions generators 5 and 6 were able to exploit the opportunity to use market power. It should be noted that the 75 trading periods used provides far less experience than actual generators will accumulate over a summer season during peak load periods when networks are likely to be constrained. Thus, it is reasonable to conclude that market power will be exercised. Second, if generators exploit market power, prices will not only be higher in load pockets, but also price volatility will increase. This implies the possibility that network stability and reliability may be jeopardized since relays have been set on the basis of stable generation patterns throughout the networks.

An identical experiment, except for the use of larger incentives and 65 trading periods, was later performed using electricity traders as subjects at a utility headquarters. Figure 3, below, shows the results for the session with the traders. As can be seen, the market power opportunities were quickly recognized and exploited. Prices well above competitive levels were observed at generators 5 and 6 as early as the second trading period, and remained consistently high after about 25 periods. This result supports the conjecture that the behavior of expert subjects does not differ significantly from that of the more accessible student subjects.

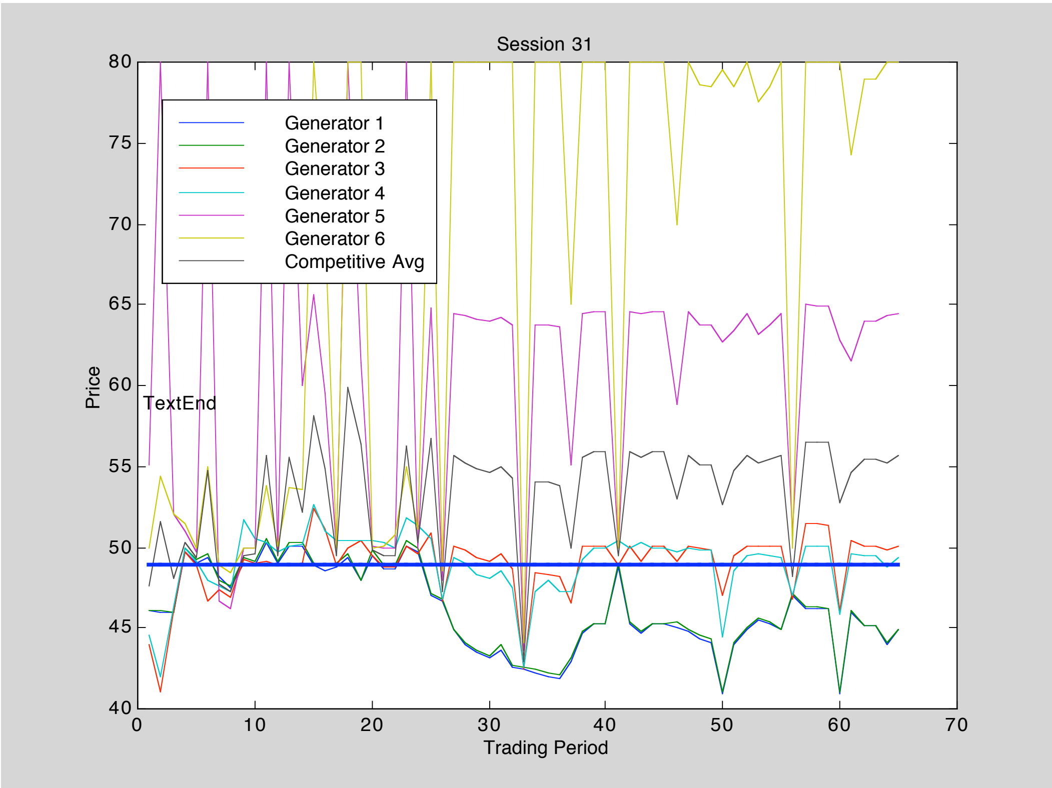

Figure 3: Nodal Prices, Electricity Traders

Unit Commitment

Given the load profile of most electricity markets and the capacities of the generators supplying power to markets, it is likely that only a subset of the total number of generators will be required to satisfy the load during periods of low demand. One of the most important roles for a system operator, whether it is a utility with a portfolio of generating assets, a state controlled government agency, or an independent system operator, is to determine which generators should be running and for how long. This is frequently called the "unit commitment problem". While the task has to be solved, the method can dramatically vary in different markets. For example, the system operator in the United Kingdom solves both the unit commitment and dispatch problems in a day-ahead market. In contrast, the markets in Australia and California are based on self-commitment by generators and the system operator determines dispatch only. The emerging markets in the eastern United States are closer to the United Kingdom model than to the simpler markets with self-commitment. The basic question posed by these different markets is which approach is the best?

In the case of self-commitment, the inter-temporal dependencies caused by start-up costs provide an incentive to accept losses or reduced profits in some periods in order to increase profits overall. This may cause generators to offer blocks of capacity at below marginal cost in order to avoid a greater start-up cost in a future period. Every generator must determine whether this increases profitability or whether its cost structure is such that it should cycle on and off with the variations in demand. In an intensely competitive market, the optimal strategy should be one that leaves the generator at worst indifferent between the cycling and continual operation. In such a case, the losses incurred would exactly equal the start-up costs avoided. For that reason, this strategy would appear consistent with aims of profit maximization and lead to an efficient solution. It is this hypothesis that has been tested in our research.

The Experiments

We conducted eight experiments to test this hypothesis with our web-based PowerWeb platform, which implements the smart market, described previously, using an OPF that models a full non-linear lossy AC transmission network. These experiments used a six generator, 30 node network model. Each of the six subjects in each of the experiments was one of six sellers in a market with a single buyer with demand that alternated between 100 MW and 200 MW. All generators had a capacity of 60MW that was divided into three blocks, the size of which varied between generators. The costs for each block of capacity varied between generators too. Subjects knew their own capacities and costs but not those of their competitors. Table 1. below shows the capacity and cost structure of each of the competitors:

	Variable Costs					
	Block 1		*Block 2*		*Block 3*	
Generator	**MW**	**Cost ($)**	**MW**	**Cost ($)**	**MW**	**Cost ($)**
1	10	23	25	30	25	35
2	10	23	25	30	25	35
3	20	18	30	18	10	40
4	20	20	20	30	20	40
5	20	20	20	30	20	40
6	20	15	30	15	10	40

Table 1: Generator Capacities and Variable Costs

Each generator was required to sell at least its first block of capacity in its entirety. If this did not happen, the generator was shut down for that period. In the event of being shut down, a start-up cost was incurred when the generator again was selected to operate. Table 2. shows the start-up costs for each of the generators:

Generator	*Type*	*Start-Up Cost ($)*
1	Peaking	50
2	Peaking	50
3	Base-load	500
4	Mid-Level	150
5	Mid-Level	150
6	Base-load	500

Table 2: Start-Up Costs

The network was structured to eliminate any network constraints. Losses in the system still occurred but were too insignificant to affect the optimal offer strategy of each generator.

Six sessions were run with undergraduate business and economics students at Cornell University. The majority of students were sophomores and juniors taking an intermediate microeconomics class and/or a class in price analysis. One experiment was run with Graduate students in economics and a final experiment was run using larger payoffs with power industry professionals. The six undergraduate sessions and one professional session were run for 60 rounds alternating between a total demand of 100MW and 200MW. The graduate experiment ran for 40 rounds, being also evenly split between high and low demand periods.

A uniform price auction was held in advance of each of the trading periods. Subjects were informed of the demand for that period and asked to submit offers for each of their blocks of capacity. Units were chosen based of their offers into the auction so as to satisfy demand in the least cost manner while satisfying the constraints of the transmission system (in this experiment to include losses only). Upon submission of offers and completion of the OPF, students were presented the results and profits (based on the reported clearing price and the quantity of electricity sold in the auction) from the previous trading period before submitting offers for the next period. Subjects were paid based on their performance in experimental dollars. An exchange rate was applied to this and students were shown their earnings in actual dollars at each stage. Each subject received an initial "show-up" fee, which was used as an incentive to encourage people to attend the experiment. It was then considered as a starting balance in the experiment. It was possible for subjects to lose money as well as make profits. Losses were capped at $0 (after application of the show-up fee). There was no cap on the profits that could be made.

Our hypothesis has been that some generators would find it profitable to offer sufficient capacity so as to be dispatched at below marginal cost in order to avoid start-up costs in the next period as required for efficiency. Invariably, given the demand and supply structure in these experiments, everyone sold something in high demand periods. The low demand periods are, therefore, of most interest. Table 3 below shows the appropriate offer strategy for each generator. The offer strategy is calculated using the following formula, applicable to two period games[1]:

On capacity < minimum capacity,

offer = average cost of block[2] - start-up cost/ size of first block

On capacity > minimum capacity,

offer = marginal cost

	Block 1		*Block 2*		*Block 3*	
	Cost ($)	**Offer ($)**	**Cost ($)**	**Offer ($)**	**Cost ($)**	**Offer ($)**
1	23	18	30	30	35	35
2	23	18	30	30	35	35
3	18	-7	18	18	40	40
4	20	12.5	30	30	40	40
5	20	12.5	30	30	40	40
6	15	-10	15	15	40	40

Table 3: Optimal Offers

The Results

The experiments validated the hypothesis that last accepted offer auctions can produce cost efficient dispatch. The graphs in Figure 4 show the offer strategy of each of the six generators averaged over all of the undergraduate sessions in low demand periods. The upper boundary straight line is the offer expected if the generator submitted only marginal cost offers. The lower boundary represents the offer predicted which would leave the generator indifferent between being on in both periods or being on only in high demand periods. In reality the cost structures of the generators in the experiments meant that different generators faced different degrees of competition. The baseload generators faced the least competition while competition was fiercest between generators 1,2 (ordinarily cycling) and generators 4,5 (ordinarily dispatched). We believe that an offer pattern between marginal cost and lowest possible offer can be considered (close to) optimal.

As to be expected, generators 1,2 and 4,5 all converge on the predicted offer. The base-load generators were under less competitive pressure. Nonetheless, their offers also sank below cost in

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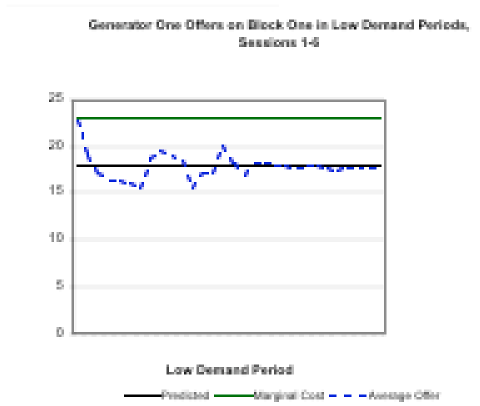
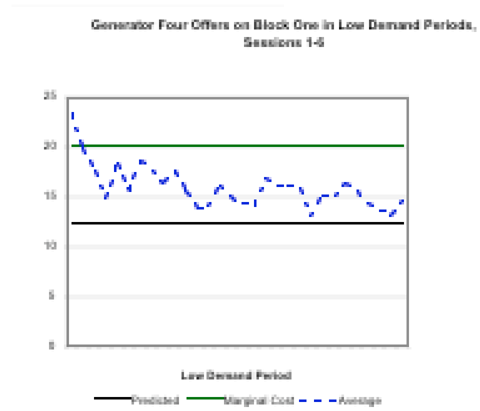
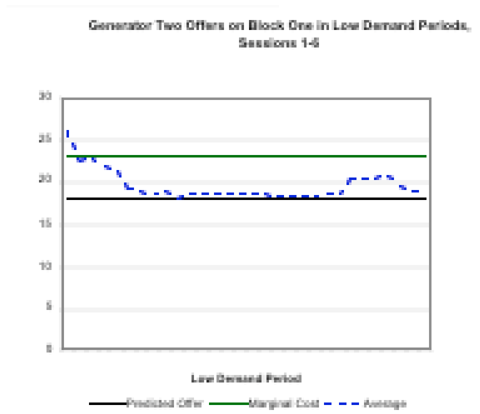
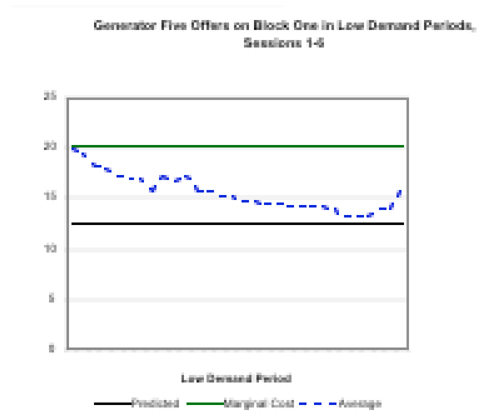
[1] If all generators followed this strategy, optimal dispatch of generators would occur.

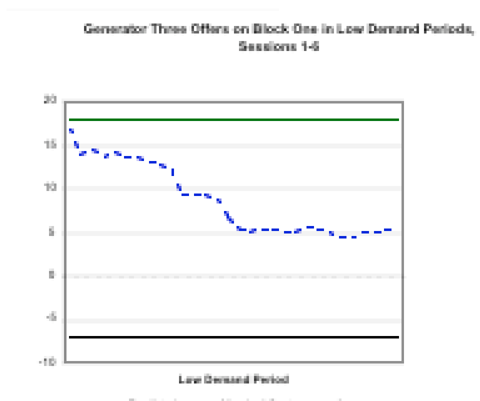
low demand periods, though to a lesser extent. This merely reflects the fact that it is only rational to lower the offer until dispatch is secured. For the base-load generators in this experiment, that was significantly higher than the minimum offer suggested in this paper. These results were also replicated in the graduate and professional experiments.

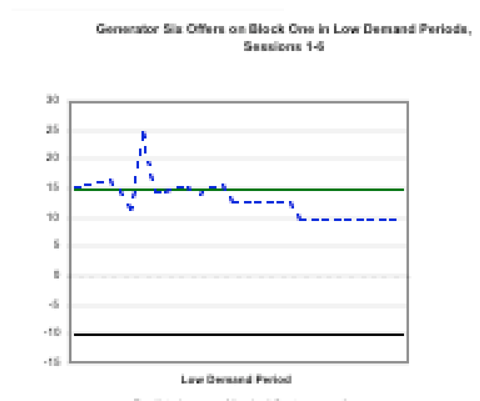












[2] Because each MW in a block is the same price, average cost equals marginal cost. It is appropriate, however, to think in average cost terms because in the US power auctions often restrict the number of segments in a price/offer schedule.

Figure 4: Low Demand Period Offers in Undergraduate Sessions

Figure 5. shows the cost efficiencies of the experiments over cycles of one high and low periods. It's a messy picture but one which conveys the convergence of each of the experiments to close to 100%. Efficiency in these experiments is defined as optimal system cost divided by realized system cost. By means of comparison, had generators submitted marginal cost offers, the efficiency would have been just over 96%. The results show that self-commitment using a uniform price auction converged to a higher efficiency than this.

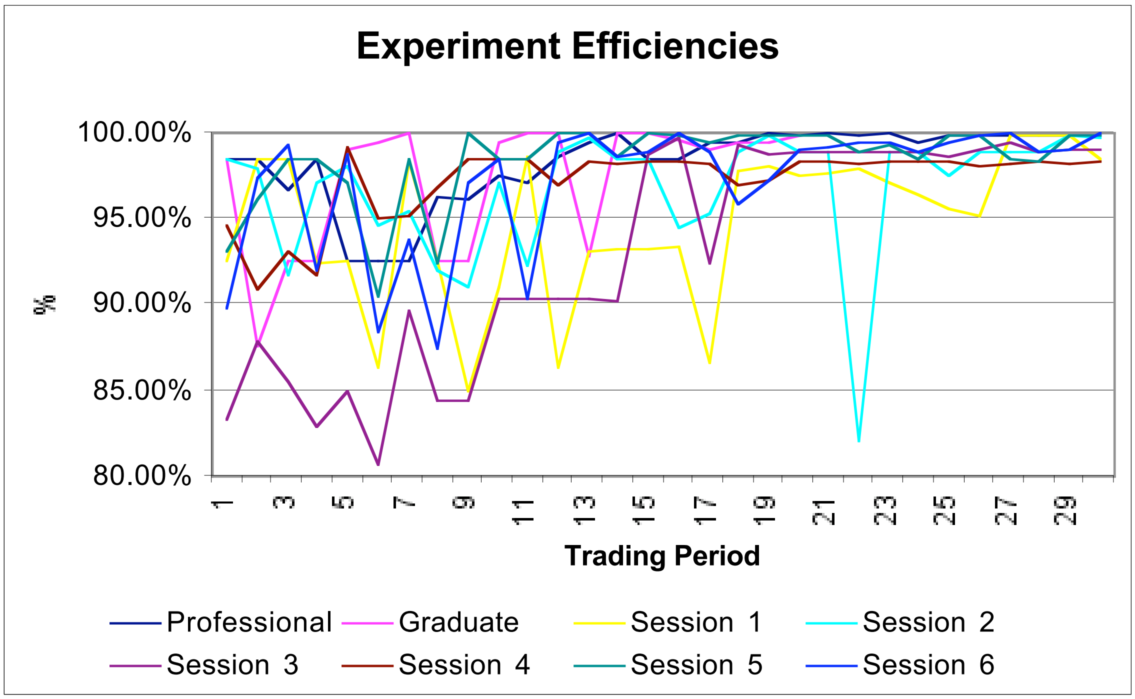


Figure 5: Experiment Efficiencies

Figure 6 shows the average efficiency of the undergraduate experiments compared to the efficiency of the graduate and the professional experiments. The only difference that can be seen between the three groups is the speed with which optimal dispatch was achieved. This again

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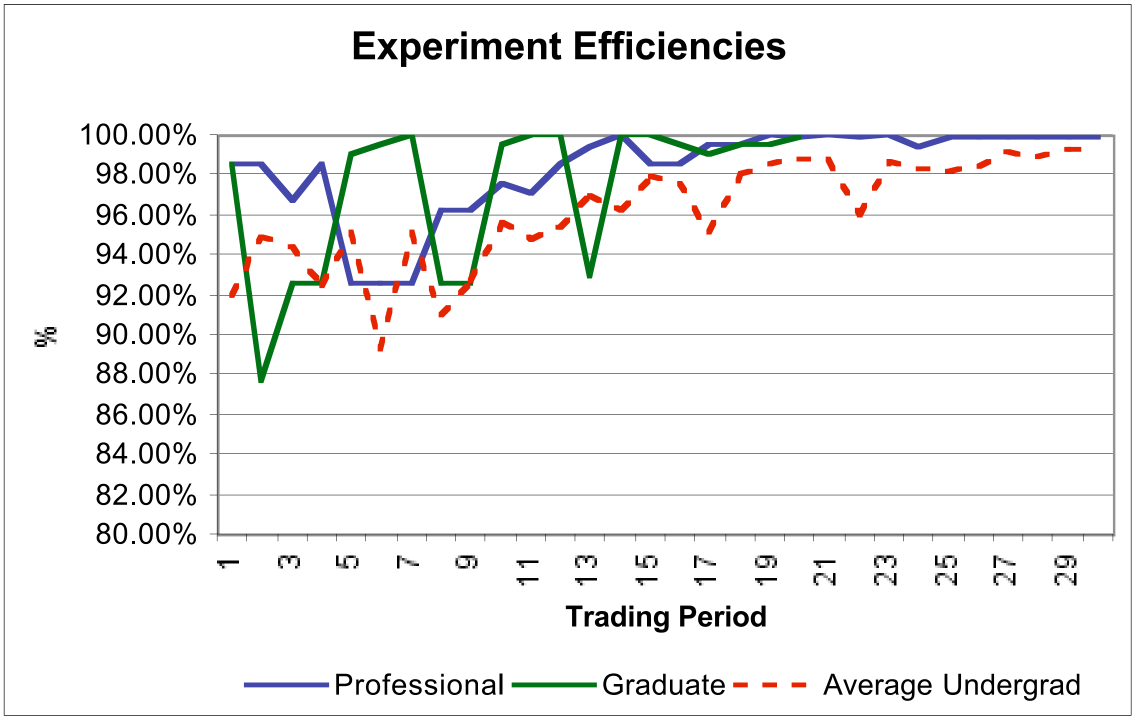
This forces generators to offer blocks of capacity at the same price.

supports the conjecture that behavior of expert subjects does not differ greatly from more accessible



student subjects.

Figure 6: Comparison of Efficiencies

Our experiments show, in a simplified situation, self-commitment can produce a cost efficient dispatch of thermal units. Further complexity needs to be added to the model in the form of ramping constraint and minimum up and down times before it is possible to conclusively say that self-commitment is feasible. Nonetheless, the success of the uniform price auction in this instance is encouraging, given its position as auction-of-choice in electricity markets. Had it failed this simple test, severe doubt would be cast upon its ability to handle more complicated scenarios.

Conclusions

Efforts to restructure the electric power industry in the United States have failed to pay very much attention to market power. In fact, unlike Australia where power plant owners were limited in the number of generators that they could control, auctions to sell generators encouraged the purchase of multiple plants by allowing bids for combinations of plants and allocating sales to the combination of bidders that produced the greatest revenue. This procedure, while helping with the problem of stranded assets, encouraged the establishment of market power since buyers would pay more for a package of power plants gave them the opportunity to charge higher prices. Both our own early work with alternative auction institutions as shown in Figure 7 (Bernard et al., 1998), and the work of others (see for example, Backerman, Denton, Rassenti and Smith, 1998)) suggested that market power could be a serious problem, especially under high load conditions where constrained lines lead to load pockets.

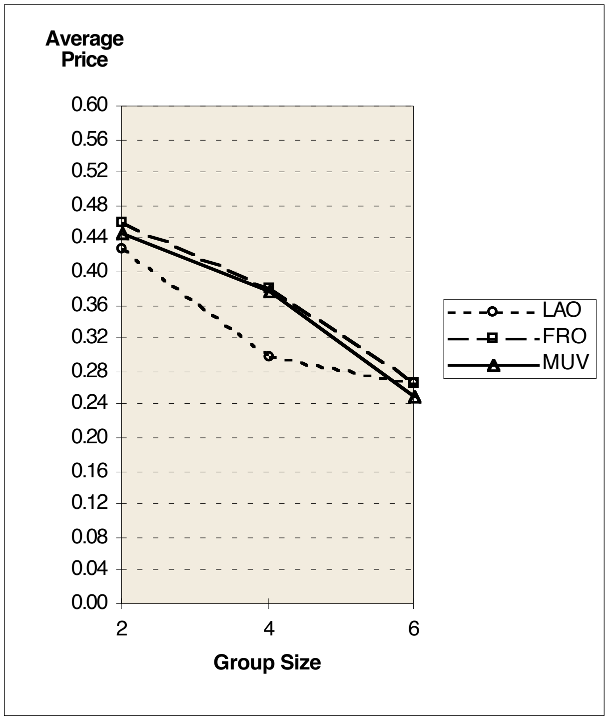


Figure 7 Auction Comparison: Price vs. Number of Sellers (LAO, FRO, and MUV denote Last Accepted Offer, First Rejected Offer, and Multiple Unit Vickrey auctions, respectively).

Similarly, many problems have been experienced in the United Kingdom and the United States with attempts to establish mechanisms to solicit information on startup costs to allow central control of unit commitment. Because, from a theoretical economic perspective, such attempts to solicit offers to start up are both unnecessary and likely to lead to strategic behavior, we felt it important to test whether markets could efficiently handle the unit commitment problem. Consistent with the experience in Australia, where markets seem able to handle unit commitment, our results suggest that markets can not only handle the unit commitment problem, but are also likely to do so efficiently.

Many obvious problems remain unexplored. For example, although Charles Plott at Cal Tech has explored the stability of multiple interacting markets, no detailed investigation of markets for ancillary services with network constraints has been conducted. How should the markets for reserves and voltage control be structured? Similarly, no experimental investigation has been conducted of the optimal structure of the timing of power markets: Are day ahead combined with hour ahead markets run each hour the optimum configuration? Finally, demand side bidding and load reduction have only been explored in a limited way in the laboratory and never in actual applications. However, the potential to reduce price spikes is very real. In terms of the optimal power flow and resulting prices, each block of load that can be eliminated at high prices at a particular location is equivalent to the addition of the same amount of generating capacity at that demand location. It is remarkable to us that, rather than running "cheap" experiments in the laboratory to explore these issues, experiments involving billions of dollars are being run in States like New York and California. Further, ad hoc repairs to the design of restructured systems have been repeatedly introduced without laboratory testing.

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APPENDIX

The PowerWeb Platform

Ray Zimmerman

1 The POWERWEB Platform

POWERWEB is designed to be a flexible platform experimentally examining the behavior of various proposed electricity markets using realistic modeling of the physical network and real human decision-makers. As an Internet-based, network-centered computing environment, POWERWEB makes use of a wide variety of technologies in its implementation. The user interface is web-based, all data are handled by a relational database and market computations are performed by a Matlab-based optimal power flow (OPF) program.

1.1 Overview

Because of operational constraints on a power system, it is necessary to have a central agent acting as an independent system operator (ISO). In the current implementation of POWERWEB, the ISO receives offers to sell power from independently owned generation facilities. Based on a forecasted demand profile for the next day and the information gathered from the generator's offers, the ISO computes the optimal generator set points along with a corresponding price schedule which will allow the system to meet changing demand while satisfying all operational constraints.

As a web-based tool, POWERWEB may be used in several capacities. It can be utilized in a tightly controlled setting where a well-defined group of subjects are used for a very specific set of market experiments. It can also be used in a more open environment in which anyone on the web can log in and "play" as a generator competing against other generators, controlled by other humans or computer algorithms (agents), to generate power profitably. In either case, since POWERWEB is web-based it is accessible at all times to anyone with proper authorization, as long as the servers are up and running.

1.2 A Typical Session

To eliminate the need to coordinate accesses (via phone, e-mail, etc.) and to prevent one user's actions from interfering with another's, all accesses occur in the context of a given "session". The session specifies which power system is being simulated, who "owns" which system resources (generators, etc.), and what market mechanism is in use. Multiple sessions can be active at any given time and activity in each is completely independent of the others. Typically, a user in a session will "own" one or more generating plants.

After logging in as a generator in a simple auction session, for instance, the user is taken to the *Offer Submission* page shown in

Figure **A1**, which displays the cost and capacity information for their generator. Here they can enter offers to sell power to the ISO.

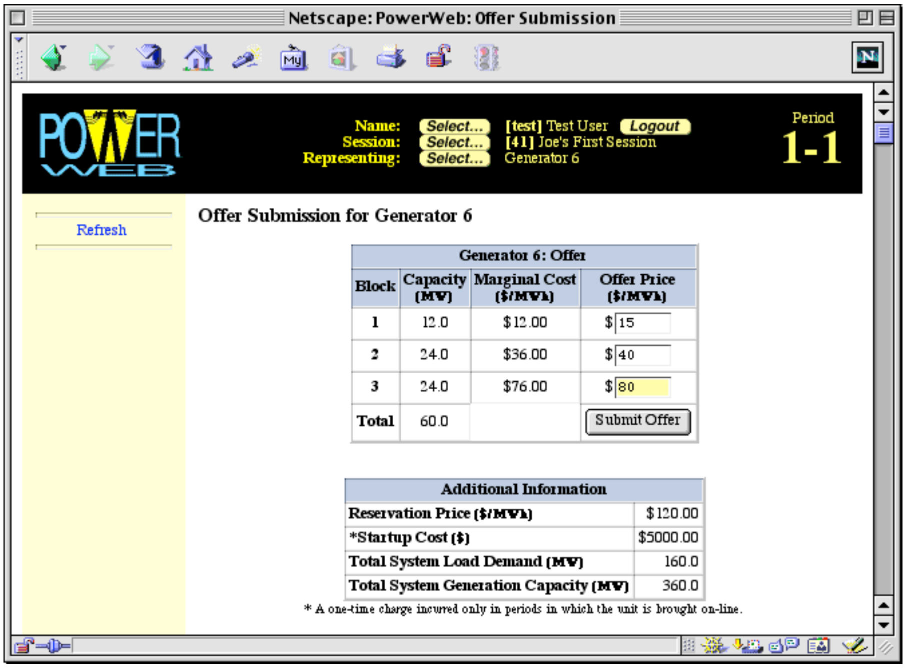

Figure A1 ***Offer Submission*** **Page**

When all participants have submitted their offers, POWERWEB's computational engine runs the auction according to the rules specified and reports back the results to the user. The *Auction Results* page is shown in Figure A2.

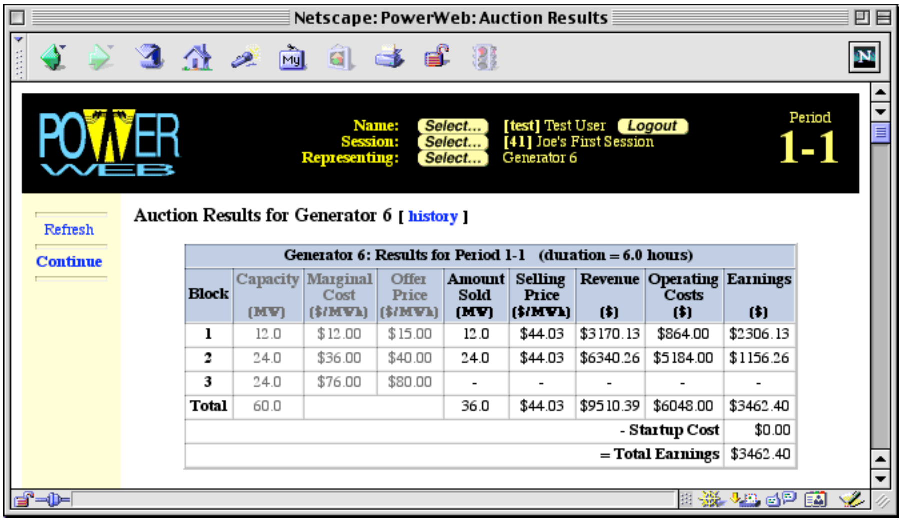

Figure A2 *Auction Results* Page

POWERWEB also has the capability to provide differing levels of information to the players, as specified by the experimenters. In a full information setting, each user would have access to the system information area, which gives tabular summaries of the system operation conditions as well as a "live" one-line diagram of the power system.

Figure A3 shows the one-line diagram of a 6 generator, 30 bus system in POWERWEB's database. This diagram is generated dynamically by a Java applet from information retrieved from a relational database server. The diagram can be panned and zoomed and it is interactive in that clicking on an object such as a line, bus, generator, or load will query the database for information about the object. For example, selecting a bus will display the current information about real and reactive flows into and out of the bus as well as information about the current voltage level of the bus.

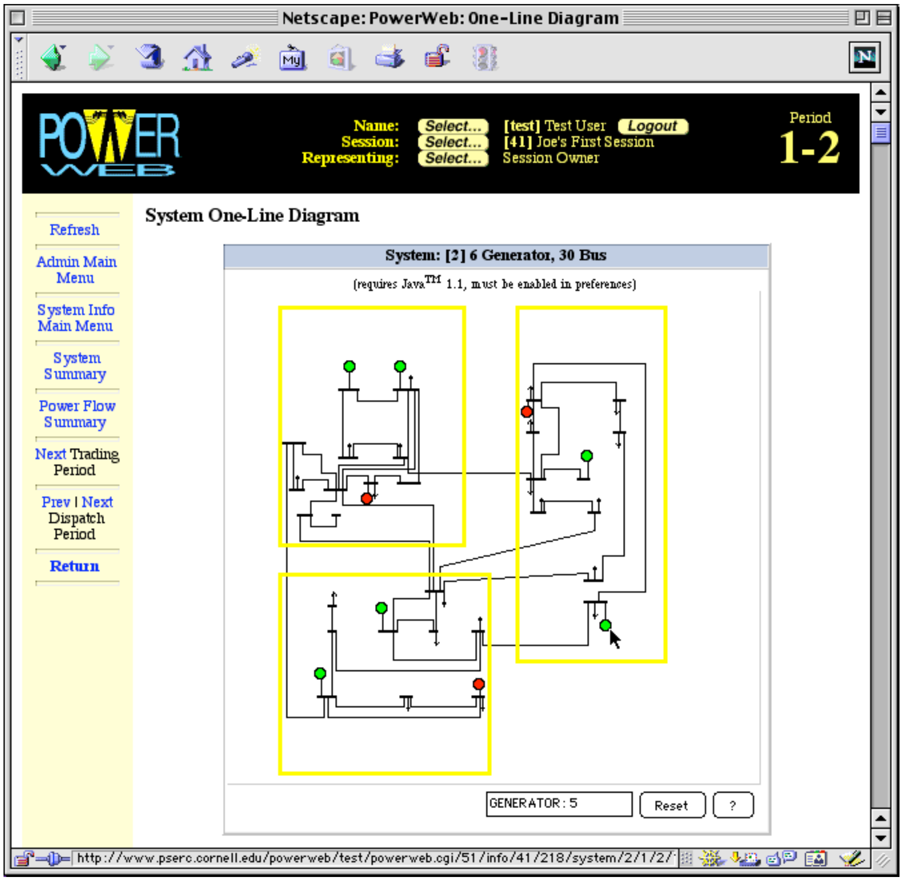

Figure A3: POWERWEB one-line diagram display, showing 30-bus system

The POWERWEB User's Manual, available from the POWERWEB home page at <http://www.pserc.cornell.edu/powerweb/> has more details regarding POWERWEB's functionality.