PSERC 98-03

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MARKETS FOR ELECTRIC POWER:
EXPERIMENTAL RESULTS FOR ALTERNATIVE AUCTION INSTITUTIONS

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Abstract

The objective of this paper is to present experimental results for testing the performance of different auction mechanisms related to the introduction of competitive markets for the generation of electricity. The research is based on the concept of smart markets introduced by Vernon Smith and a simulation model (PowerWeb) of a realistic bulk power system. There are unique physical aspects associated with the supply of electricity (e.g. required instantaneous matching of supply and demand, unintended congestion of parallel transmission routes and maintenance of system stability in response to disturbances). As a result, traditional theories of efficient markets and auction structures developed for other commodities may not be efficient if applied without alteration to markets for electricity. Conversely, current utility rules of operation developed for a centrally-planned regime may not be appropriate in a competitive environment.

The research does not address the issues of multiperiod operations (unit commitment) and multidimensional markets (ancillary services), and considers only real power in a single time period. The main objective is to test three alternative auction mechanisms when market power is a potential problem. This situation occurs when limits on transmission lines are binding to form a load pocket in which demand is met by a few (in this case two) generators.

1. INTRODUCTION

The US electric power industry is taking major steps forward 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 1990 the United Kingdom restructured it's industry to form separate generation, transmission and distribution companies (see 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. 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). However, the electric utility industry presents unprecedented complications for restructuring. In particular, electric power networks offer multiple simultaneous commodities and there are a variety of externalities such as reliability concerns that imply a pure market solution is unlikely to be efficient. For this reason, Vernon Smith and his colleagues (McCabe, Rassenti, and Smith 1991) have proposed the notion of a smart market. The idea is that smart markets use a computer algorithm that interacts with buyers and sellers (using appropriate trading or activity rules) to provide feedback on physical constraints, such as congestion, which would not be attainable by the market alone. We agree with Smith on the need for such a market and evaluate an analytical framework that links power systems engineering with experimental economics. As a first step, alternative auction mechanisms are tested for real electric power for a market run by an Independent System Operator (ISO). As a result, the analysis will focus on the short-run economic efficiency of the market for a single time period. Future research will address the additional problems of unit commitment in multiperiod markets, and multidimensional markets for ancillary services.

Unfortunately, the move to competitive markets for electric power is advancing rapidly based on the notion that competition will generate cost savings. In our opinion, there is insufficient attention being paid to the type of smart market to be employed. The notion that any market is better than the existing structure is demonstrably false for a number of reasons (see Ethier 1997). Without careful attention to the design of these markets, the promise of restructuring power markets could easily be lost through new types of inefficiencies. For example, it has been shown in experimental economics that the specific auction institution (double auction, call auction, uniform price auction, English auction, etc.) can have dramatically different efficiencies. Some auctions are much more efficient in the face of market power than others. For example, Davis and Williams (1991) have shown that market power produces larger price increases in a posted offer market than in a double auction market. Efficiency differences of as much as 15% are commonly observed (see Bernard, Mount and Schulze 1997).

Although it has been shown by Smith in economics laboratory experiments that reasonable efficiencies can be achieved in smart markets for simple network situations, (see McCabe, Rassenti, and Smith 1991), no experiments have been conducted testing smart markets with complex networks. Testing markets for electric power requires collaboration between electrical engineering and experimental economics. We propose to use a realistically complex power system network as the basis for a series of laboratory experiments testing different aspects of a real-world implementation of the smart market concept. Simultaneously, observations about the nature and speed of response of market participants may suggest alterations in the operational rules for the electric system.

Experimental economics allows the experimenter to determine the actual achieved efficiency of a specified market structure (as compared to the theoretical ideal) using real economic decision makers who make or lose real money depending on their decisions in the laboratory. Subjects can be utility executives, financiers, practicing engineers or students. The existing literature suggests that subject type makes little difference. We conjecture that knowledge of how the power system works and new tools to help in the bidding process will be needed. Unfortunately, the approach proposed in many parts of the United States and around the world is to implement ad hoc solutions to a variety of problems using market structures that have never been tested. For example, the market implemented in England and Wales has lead to several difficulties in that system (Newbery 1995, Wolak and Patrick 1997). Furthermore it is very difficult to determine the achieved efficiencies of an established market since some of the information necessary to calculate efficiency may be privately held information.

The process of moving to competitive markets usually begins with a wholesale market where electric power is purchased from competitive generators by an ISO, (see Hogan 1992, Ring and Read 1994, Newbery and Green 1996, or alternatively Wu and Variaya 1995). Purchases of electricity are made to meet a forecast of the load using some type of single-sided auction. The objective of this paper is to present experimental results for the following three different auction mechanisms:

1) a uniform price auction using the last accepted offer to set the price,

2) a uniform price auction using the first rejected offer to set the price,
3) an "English" auction with a descending clock using the first (lowest cost) rejected offer to set the price.

For each of the three auctions, markets with six sellers and two sellers are evaluated first with no network constraints. Finally, a smart market for electric power with six generators is described using a network developed for Power Web (see Section 4). With high levels of load, the network effectively isolates one pair of generators in a "load pocket" to form an effective duopoly.

2. ECONOMIC ISSUES AND MARKET POWER

Economic researchers at the Economic Science Laboratory at the University of Arizona under Vernon Smith (Backerman, Rassenti, and Smith, Jan. 1997, and Feb. 1997) have investigated the performance of smart markets for electricity. Their experiments were conducted on a 3-node radial network, with power buyers located in the central node connected by a single transmission line to each of two generator nodes. The generator nodes were not connected. A two-sided market was implemented with pricing determined through use of a uniform price double auction. They have utilized this framework to test the effects on efficiency of a constrained transmission line, the experience of subjects and modifications in trading rules. More recently, they have used their radial configuration with base, intermediate, and peak demand cycles to examine pricing and efficiency under market power. Elsewhere, Plott (1997) has tested a market mechanism proposed by Wilson (1997). This experiment abstracts from an electric grid.

An auction must possess correct incentives for power producers to offer generating capacity at cost. Taking into account established economic theory, two strong candidate auctions exist: the simultaneous sealed-bid Uniform Price auction and the sequential English auction (Schulze and Mount 1996). While the pair are theoretically equivalent, experiments performed in a buyers' setting have shown superior performance for the "English" auction. Since an ISO must have offers from all participating generators to run a smart market, we are evaluating a new auction called the sealed bid "English" auction. The details of these auction mechanisms are presented in Section 5.

Market power is an important concern in the electric power industry. Potential for market power comes about from the multiple unit nature of the market and nature of the transmission system. In such cases, incentives may no longer yield true cost revealing behavior. We plan to investigate this danger experimentally.

First, it is well known that appreciable transportation costs in spatial markets can provide monopoly power to some suppliers in specific markets that are difficult or expensive to reach by others. Even when there is intense price competition, Holahan and Schuler (1988) have demonstrated that rational firms in spatial markets will never bid their prices down to marginal cost. Although by lowering its price a particular supplier anticipates gaining additional customers away from other suppliers, in doing so it also reduces its infra-marginal profits from existing customers. The stopping price can be shown to satisfy the properties of a Nash equilibrium. Therefore in this spatial context, it can be shown that different spatially separated firms can exist in equilibrium, each having different production costs and charging different prices at the generator, while earning substantial economic profits. To illustrate these findings, Hobbs and Schuler (1985) calibrated a spatial model of the transmission and electric supply and demand system in Upstate New York using 1978 data. Their estimates suggest that in the short run, if deregulation were initiated with existing generating capacity and costs, substantial economic profits would be earned in the short run and prices might rise ten to fifteen percent above existing regulated levels in the short run. However, subsequent entry of new gas turbine capacity is shown to be sufficient to drive that anticipated price increase down to less than five-percent.

More recently, simple examples in which a generator earns excess profits due to constrained transmission lines have been presented in the literature (Oren, Spiller, Variaya, and Wu 1996, Variaya and Wu 1996, Hogan 1993). A particularly striking real-world example which occurred in the United Kingdom is discussed in Newbery (1995). The generator in a "load pocket", in response to such knowledge, dramatically increased offer prices (by nearly 500%), minimum load, and payments received.

Using the Power Web platform, discussed in Section 4, line constraints can be induced and varied. The conditions under which market power can be expected to occur, and those under which market participants will be disciplined by competitors, can be explored. We hypothesize that under realistic transmission configurations, significant market power will be observed under certain configurations of load. We would also predict substantially worse performance for auctions where the last accepted offer determines price (as it does in the United Kingdom and Australian markets) than for the other auctions under conditions where load pockets are present. In an experimental setting, using Power Web will make it possible to compare the effects of alternative system configurations with or without load pockets.

3. ENGINEERING ISSUES AND OPERATIONAL PRACTICES

Comparing the efficiencies associated with moving to alternative market institutions requires knowing how the power system currently operates and being able to simulate operations with competitive markets. The unique aspects of an electric system that must be considered include: 1) the instantaneous system-wide matching of supply and demand; 2) the technical characteristics of many low-average-cost generating units that must operate continuously over a number of contiguous demand periods in order to achieve a reasonable operating efficiency (i.e., the unit commitment problem); 3) the economic burdens imposed on the system by reactive power needs to turn machinery simultaneously with meeting real power demands (i.e., multi-dimensional markets and ancillary services); 4) unintended congestion of parallel transmission links (i.e. transmission bottlenecks and load pockets); and 5) issues of system reliability and dynamic stability. While all five of these technical issues are to be incorporated into our simulation model, the results in this paper consider only real power and transmission bottlenecks. The issues of unit commitment and ancillary services will be addressed in future research.

The first generation of algorithms for dispatching generators employed heuristics, such as priority lists of generators based on some characteristic of their cost curves. Of course, heuristics do not guarantee any kind of closeness to the optimal solution. Subsequently, such techniques as Dynamic Programming (Pang and Chen 1976), Branch and Bound methods (Lauer, Sandell, Bertsekas, Posbergh 1982), Lagrangian Relaxation (Bertsekas, Lauer, Sandell, and Posbergh 1983) and Augmented Lagrangian (Cohen 1978, Cohen and Zhu 1994, Wang, Shahidehpour, Kirschen, Mokhtari, and Irisarri 1995) began to appear in the literature. Unfortunately, both Dynamic Programming and Branch and Bound methods suffer from Bellman's "curse of dimensionality" and become impractical when the number of generators is large. Lagrangian techniques have fared better in this respect. In Lagrange relaxation, the dual problem provides a lower bound to the optimal cost of the solution and the primal provides an upper bound. The difference between these costs is termed the "duality gap". When the problem at hand is non-smooth (like the unit commitment problem) it is possible that the duality gap at the optimal commitment is not zero. However, it was shown by Bertsekas, Lauer, Sandell and Posbergh (1983) that the expected relative duality gap is inversely proportional to the number of generators. Even though there may be many local minima, Lagrangian relaxation usually finds solutions with near-optimal cost, and the relative difference from the optimal cost becomes smaller as the number of generators increases. This, and the fact that the dual problem becomes separable when the constraints are linear (which allows each generator to be scheduled separately using a one-generator dynamic program, avoiding dimensionality) makes Lagrangian relaxation ideal for large scale problems. Finally, Augmented Lagrangian techniques make use of a modified Lagrangian to improve the convergence properties of the algorithm, as in Wang, Shahidehpour, Kirschen, Mokhtari, and Irisarri (1995).

It is worth noting that many constraints can be dealt with in the Lagrangian methods scheme. All restricted transition graphs can be directly cast in the dynamic programming part of the dual problem. Line constraints can easily be incorporated, at least in the linear case, which means that one assumes a direct current (DC) flow characterization of the network. This makes it feasible for the algorithm to shut down some inexpensive generators in favor of more costly units simply because the location of the former makes it impossible to transfer the power that they produce without overloading some lines. While this may not be an issue in regions where there is usually no congestion, this is expected to be important in regions like New York State where congestion is commonplace. Other security constraints based upon phase angle differences can be dealt with using the same DC flow model. Upper and lower limits on generation are simply bounds on the decision variables and can easily be added to the algorithm.

Once units are committed, a security constrained optimal power flow program is run to determine the specific operating point that meets load and satisfies generation, voltage, line and other constraints. The optimal power flow (OPF) problem, describes the objective of finding the least cost generation schedule (given a set of committed generation units) which can satisfy a given pattern of energy demand subject to the physical laws governing the flow of electricity, and subject to the operational restrictions on bus voltages, transmission line flows, generator limits, reserve margins, and stability criterion necessary for safe and reliable operation of the system. It can be stated mathematically as follows;

$$\begin{gathered}\min f(\mu)\\ \text{s.t.}\\ g(x,\mu) = 0\\ h(x,\mu) \le 0\end{gathered}$$

where μ contains the real power output of each generator, x contains the system state (node voltages), and $f(\mu)$ is the sum of the cost curves of all the generators. The equality constraint $g(x,\mu) = 0$, is a set of equations, one for each node in the system, which require that the net power received by the grid from that node (as determined by Kirchhoff's laws) is equal to the net power injection at the node (generation minus load). The inequality constraint, $h(x,\mu) \le 0$, contains all of the operational restrictions mentioned above.

VAr requirements are determined by the solution to the security constrained OPF as are spinning and supplemental reserves. Reserve requirements are then compared to agreed upon standards such as the NERC (N-1) criterion. Frequency regulation is assigned to units that have the control systems installed to accomplish it and the appropriate units are assigned standby status for unanticipated energy imbalance. All of this operational planning is currently done in a single place within the utility and the planners have access to any and all information needed to do the job. In the future these functions will be divided up between the ISO and the market.

4. THE EXPERIMENTAL PLATFORMS

Two new, separate experiment platforms were used in this research. The first of these, developed by Bernard based on an experimental platform from the University of Arizona, was used to test the performance of auction markets in the absence of the complexities of a true power system. This platform consisted of several individual programs, one for each auction to be tested. Each program can be configured to many possible situations, with up to 24 subjects participating in an experiment at once. Each subject can control up to three generators with varying costs and output capacities.

A different environment is required to test decision making by human subjects in a smart market that adequately represents the real complexities of power system operations. Power Web is a new Internet-based simulation environment for investigating the behavior of competitive electric power markets experimentally. It currently has the ability to model day-ahead markets for scheduling generation. A 6 generator, 30 bus bulk power system, as shown in Figure 1, is an example of the current system on which experiments can be performed. In such a market, participants may submit offers to sell power, and an ISO determines the dispatch schedule and prices based on some agreed upon auction mechanism. This platform can be used to investigate various characteristics of market behavior, such as the effects of transmission congestion using different types of human participants.

Since Power Web is based on the Internet, it is not necessary for participants to be in the same physical location to conduct an experiment. The web-based architecture enables a participant to access Power Web from anywhere Internet access is available. The only software necessary is a modern web browser, such as Netscape Navigator, which runs on the majority of computing platforms in common use today.

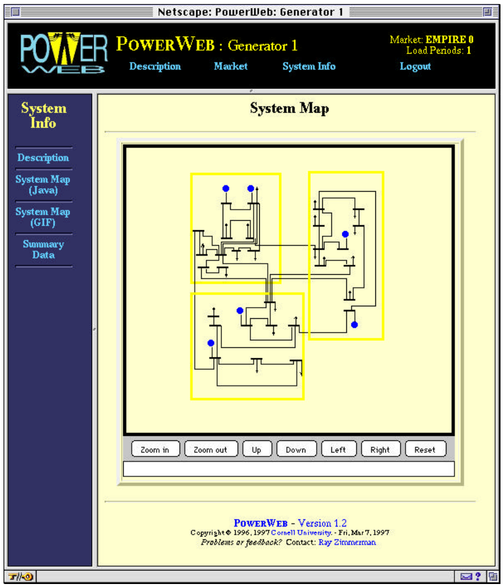

Figure 1. The one-line diagram of a 6-generator 30-bus bulk power system

There is a tremendous amount of data involved in supporting the types of experiments that Power Web is designed to test. The area of the database which stores power system data will contain all of the information needed for the ISO to solve the optimization problems. It will also be used to store the results of the ISO's optimal power flow computations and any system state which may change throughout the experiment, such as outages or changes in load patterns. Each session or experiment has its own set of data consisting of the power system being used for the test, the structure of the market, load forecasts, mappings of users to specific market agents, logging of offers and dispatch/price schedules. A more detailed account of Power Web is given in a companion paper.

5. SHORT RUN EFFICIENCY AND AUCTION MECHANISMS

The choice of market mechanism in a restructured electric power market can have profound efficiency consequences. An auction mechanism must provide incentives for power producers to offer generating capacity at actual cost so an ISO can accurately produce a merit order. Offers which do not reveal true cost not only transfer wealth, but also produce potentially large deadweight efficiency losses. A real concern is: does competition lower costs relative to those in a regulated industry? Poor auction design could make higher prices in a competitive market a real possibility (see Ethier 1997).

Testing known auction mechanisms in an electric power context is important. The existing market literature uses either a simplified, radial network (Backerman, Denton, Rassenti, and Smith 1997, Plott 1997) or presents a static, stylized or simulated version of the problem (*e.g.* Oren, Spiller, Varaiya, and Wu 1994, Johnson and Svoboda 1997, Hogan 1993). As discussed above, networks have unique externality characteristics, and auctions will need to be adjusted accordingly. One example is the adaptation of a uniform price auction to a network environment as described in Ethier, Zimmerman, Mount, Schulze, and Thomas (1997). Our proposed experiments utilize single-sided auctions, unlike Backerman, *et al.*, who use a double sided auction. While double-sided auctions generally perform better, single-sided auctions are used for two reasons: 1) there is a firm base of theory and 2) real world electricity markets are generally single-sided (as seen in the United Kingdom, Australia, and New Zealand).

Auction mechanisms will be judged by two criteria: economic efficiency and market price. Efficiency is a typical measure of auction performance and price is of obvious importance to all participants in the market. Two other concerns that could be used in deciding on an auction mechanism are speed of execution and speed of convergence. Speed of execution is important for electric power applications because they must be executed in real time and potentially many times per day, or even per hour. Of our auction mechanisms, speed of execution was a potential problem only for the sealed bid English. Speed of convergence is an issue with auctions involving multiple markets or multiple iterations. While the possible shortcomings can be seen in the auction rules tested by Plott (1997), convergence speed was not a factor in our single market, single iteration setup.

The list of single sided auctions tested will not be exhaustive. To narrow candidates, theoretical and experimental results are called upon. Theory allows us to initially select between two classes of auctions: those setting price at the last accepted offer versus those setting price at the first rejected offer. The simultaneous sealed bid uniform price auction can be run using either pricing rule while the sealed bid English auction has always used the first rejected price rule. In the single unit setting, last accepted offer (or first price) auctions provide strategic incentives, while first rejected offer (or second price) auctions have been shown to produce incentives favorable to efficient outcomes. Since electricity producers will wish to sell multiple units of electricity, multiple unit versions of these auctions must be utilized. Unfortunately, neither auction is likely to produce perfectly efficient outcomes in a multi-unit setting.

The multiple unit last accepted offer auction shares the strategic gaming incentives of the single unit first price auction. Interestingly, existing power markets in England and Australia utilize this auction (see Newbery and Green 1997, Bannister 1997). Data from the Australian spot market shows peak prices far above any conceivable production cost, demonstrating the presence of strategic offers. Ausabel and Crampton (1996) recently proved that the multiple unit first rejected offer uniform price (FRO) auction does not have the desirable properties of its single unit counterpart, the second price auction, for small numbers of participants.

As none of the available auction institutions is theoretically cost revealing in the multiple unit case, experimental testing is especially important. Both FRO and last accepted offer auctions (LAO) will be tested and compared using experimental data. We hypothesize that a FRO auction will be the better solution.

A third possible auction, the English auction, will also be tested. While theoretically isomorphic to the FRO auction, it is found to produce higher efficiencies in practice (Bernard, Mount and Schulze 1997). In the FRO auction, sellers submit a price and a maximum number of units they would be willing to sell at that price. Submitted offers are ranked lowest to highest, and the lowest priced units are purchased up to the point supply equals demand. The uniform price paid for purchased units is the price of the first rejected offer. In the English auction, each seller initially submits an offer indicating the maximum number of units they are willing to make available from each generating facility. The auctioneer begins the auction by starting a ‘clock’ which sweeps down from the reservation price. Suppliers withdraw facilities whenever they wish and the clock stops when supply falls to, or below, quantity demanded. If supply is less then demand, the clock is reset to the last price at which supply exceeded demand. If supply equals demand, the price is the current clock price. Either way, this price is paid as a uniform price to all remaining sellers.

A problem with the English auction in the electric power framework, though, is the need for costs of all participants to be known by the ISO. We are therefore proposing a new auction, called the sealed bid English auction, as a means to combine strengths of existing auctions. This auction retains the characteristic clock of the English auction, but does not stop until the clock price falls to zero, and does not reveal demand or supply during the auction. We hypothesize that the sealed bid English auction will be superior to both the FRO and LAO auctions. The real question is, ‘how much better?’

Laboratory experiments with identical generator cost characteristics will allow comparisons among all the auctions and a “regulated utility” OPF, where the ISO knows each generator’s true cost characteristics. These experiments will be performed both with and without an electricity grid, and with large and small groups of generators.

Our experiments will be conducted in two phases. First, experiments will be run to provide baseline results for alternative auction mechanisms without the complexity of an underlying network. This will be equivalent to having transmission unconstrained and costless. The Phase 1 experiments will examine the LAO auction, the

FRO auction, and the sealed bid English auction in competitive situations with six firms and with two firms where market power may affect results. Since the experiments in Phase 1 do not involve the complexity of a transmission grid, a traditional English auction is run as a fourth auction to provide a closer match to earlier experiments. The important difference from the sealed bid English auction is that the participants share the same clock and can see when other participants withdraw generators. It would not be possible for an ISO to provide this additional information about withdrawals in an electricity market.

Phase 2 will add a network with optimal nodal transmission charges, calculated by a smart market, for each of the three auctions. Different load conditions (high or low demand) over a large number of rounds will create different opportunities for monopoly behavior depending on network constraints and the creation of load pockets. Efficiencies will be compared with and without network constraints and at various load levels.

Subjects throughout the experiments were undergraduates in a Freshman business class at Cornell (future experiments may involve undergraduate engineering students and utility personnel). Experiments were run for relatively long periods to allow subjects time to learn in the auctions and to determine long run efficiencies. Efficiencies will be calculated as the ratio of lowest possible cost to meet demand to the actual cost to meet demand in an auction. Efficient prices in the least cost dispatch fall in the internal LAO to FRO.

For the four auctions tested in Phase 1, user interfaces have been constructed to be as consistent as possible to avoid performance differences due to "look and feel". Each subject controls three generators throughout and will always have their cost information visible. For each generator, costs will be the same throughout the experiment. Subjects will have no information on the costs of other generators or on the total supply offered. Demand will either be constant throughout or alternate between low and high periods. Parameter files for the first experiments were constructed so that each subject had an opportunity to earn approximately $5. Initially, Phase 1 experiments were run for 20 periods each. Since there were indicators that 20 periods were not enough to reach stable solutions, enough subjects where recruited from the respective subject pools to run extended tests of 50 periods in two cases. Payments in the this second stage of Phase 1 were increased greatly and designed to produce average earning potentials of around $25 to $30.

Phase 2 adds a realistic network representation. Auction interfaces, supply curves, demand, etc. will generally match those of Phase 1. Only groups of 6 will be tested. The plan for future research is that each experiment will cycle over many rounds through periods of low, and high demand so that efficiency differences can be examined across demand conditions for the three alternative auctions. At low demand, the transmission grid will be unconstrained, but transmission losses will still lead to locational prices. At high demand, a load pocket will be formed through network constraints in which load can only be met by two generators. Since each experiment will be conducted over many rounds and take longer than the Phase 1 experiments, subjects will earn about $40 for participating.

6. EXPERIMENTAL RESULTS

The four auction mechanisms discussed in Section 5 were tested in Phase 1 without a transmission network over twenty periods in both a two firm case and in the more competitive six firm case. In addition, two of the possible eight combinations were tested over fifty periods. Each firm had five units of generation with at least one unit each of low cost (roughly 0.1 per unit) and intermediate cost capacity (roughly 0.2 per unit), and two units of high cost capacity (roughly 0.4 per unit). Costs across firms were similar, but not identical, to limit the occurrence of tied offers. (Ties were broken by a random choice between two identical offers.) The load was specified to be exactly one half of the total capacity, and the participants knew this fact. In all cases, the efficient FRO price was 0.22. A reservation price of 0.60 was specified above which offers would not be accepted. An example of the typical instructions given to participants is shown in the Appendix.

Tables 1 to 4 present the results of the experiments conducted with the four auctions in Phase 1. These results proved counter to our initial expectations, especially with regard to the poor performance of the FRO auction. Looking first at the results for the groups of six experiments over 20 rounds, Table 1 shows that the overall average efficiencies of the three auctions that are applicable to electricity markets were less than 90 percent. Even the true English auction, which had earlier been shown to produce near perfect efficiencies for larger groups (with the notable design difference of a random, cost structure) by Bernard, Schulze, and Mount (1997) only achieved an overall average efficiency of 92 percent.

To investigate whether the efficiencies improved with experience, the averages were calculated for each interval of five periods through the experiment. In all cases, the first five periods had the lowest average efficiencies. The FRO and LAO auctions show an upward trend in average efficiency, but the sealed bid English and true English show little improvement beyond the first five periods.

Table 1: Auction Efficiencies in Group of Six Experiments

Twenty Periods	Last Accepted Offer	First Rejected Offer	Sealed Bid English	English
Observations	15	15	13	10
Average	0.8581	0.8494	0.8913	0.9206
Average 1-5	0.8310	0.7982	0.8602	0.8706
Average 6-10	0.8422	0.8322	0.8877	0.9404
Average 11-15	0.8658	0.8861	0.9191	0.9399
Average 16-20	0.8935	0.8812	0.8981	0.9315
Fifty Periods				
Observations	2			
Average	0.9506			
Average 1-10	0.8795			
Average 11-20	0.9675			
Average 21-30	0.9523			
Average 31-40	0.9752			
Average 41-50	0.9787			

Since the LAO auction showed the most improvement in efficiency with more experience, efficiency measures over a longer time frame of 50 periods were determined for this auction using experienced subjects. The results in Table 1 for 50 periods show a tremendous improvement in average efficiencies compared to the results for 20 periods. This suggests that, at least for the LOA auction, firms will in the long run offer power in an efficient manner which is consistent with cost minimization.

The other key area for evaluating the results is to compare the average market prices with the efficient price. The prices for the groups of six are presented in Table 2. In viewing the results, note that in all auctions the reservation price was .60 and the competitive price was .22. The overall average prices realized were essentially .30 in three auctions and .33 with the FRO which uses the auction expected to be closest to competitive. Dividing the results up into five period intervals, some trends can be seen. The LAO, in particular, showed an obvious decline in average prices throughout. In contrast, the price for the true English auction appeared to be rising.

The trend in prices for the LAO provided an additional reason for its selection as the first auction tested in longer trials. Given the limited time frame available for further experiments with the same subjects, tests of other auctions were not feasible at this time. These experienced subjects, produced substantially higher average efficiencies and drastically lower average prices in the 50 period experiments. Prices fell to the competitive level, and occasionally below. While admittedly based on only two observations, this suggests that the LAO may produce both efficient and competitively priced outcomes in market areas where a small number of different firms (six in the experiment) can offer electric power for sale. How robust this result would be to different cost structures, and the performance of other auctions over longer periods in a market with six participants are questions that still need to be answered.

Table 2: Auction Market Prices in Group of Six Experiments

Twenty Periods	Last Accepted Offer	First Rejected Offer	Sealed Bid English	English
Observations	15	15	13	10
Average	0.3017	0.3311	0.3011	0.3059
Average 1-5	0.3384	0.3551	0.3100	0.2968
Average 6-10	0.3044	0.3220	0.3152	0.2832
Average 11-15	0.2916	0.3220	0.2936	0.3196
Average 16-20	0.2724	0.3253	0.2856	0.3240
Fifty Periods				
Observations	2			
Average	0.2293			
Average 1-10	0.2605			
Average 11-20	0.2190			
Average 21-30	0.2315			
Average 31-40	0.2170			
Average 41-50	0.2185			

The next question addressed is the efficiency and price performance of the four auctions when there are only two competing participants. Looking at the efficiencies first, the results are summarized in Table 3. Interestingly, the efficiencies turned out to be worse than those experienced with the groups of six experiments, with efficiencies below 85 percent for three auctions. Only the sealed bid English, with an efficiency of 88 percent, had an efficiency that was close to the corresponding value for the groups of six experiments.

Table 3: Auction Efficiencies in Duopoly Experiments

Twenty Periods	Last Accepted Offer	First Rejected Offer	Sealed Bid English	English
Observations	9	9	5	5
Average	0.8106	0.8039	0.8830	0.8369
Average 1-5	0.7958	0.8075	0.8966	0.7995
Average 6-10	0.7977	0.8381	0.8808	0.8420
Average 11-15	0.8239	0.8130	0.8579	0.8415
Average 16-20	0.8249	0.7569	0.8969	0.8646
Fifty Periods				
Observations			3	
Average			0.9516	
Average 1-10			0.9143	
Average 11-20			0.9636	
Average 21-30			0.9616	
Average 31-40			0.9596	
Average 41-50			0.9588	

The most efficient performer in the duopoly experiments, the sealed bid English, was selected for an extended trial of 50 periods to see if efficiencies would improve with experience. As seen with the groups of six experiments, subjects do reach higher average efficiencies, of 95 percent over 50 periods. In this case, the overall average efficiency is basically identical to the level reached for the LAO auction run over 50 periods in the groups of six case.

Table 4: Auction Market Prices in Duopoly Experiments

Twenty Periods	Last Accepted Offer	First Rejected Offer	Sealed Bid English	English
Observations	9	9	5	5
Average	0.3999	0.4183	0.4086	0.4209
Average 1-5	0.3965	0.4245	0.3960	0.3748
Average 6-10	0.4181	0.4145	0.4037	0.4078
Average 11-15	0.3984	0.4231	0.4129	0.4480
Average 16-20	0.3864	0.4109	0.4217	0.4528
Fifty Periods				
Observations			3	
Average			0.5197	
Average 1-10			0.4343	
Average 11-20			0.4843	
Average 21-30			0.5290	
Average 31-40			0.5967	
Average 41-50			0.5540	

While efficiencies were lower with the duopoly experiments, Table 4 shows that average market prices were much higher. The range of prices was fairly close to the cost ranges of the most expensive plants. An obvious question is how much of the high price is a result of, or at least relates to, the lower efficiency. It appears that market power is playing a role to some degree and that experience will only make the potential for market power more evident to participants. This expectation is born out by the sealed bid English over 50 periods, the average market price was .52 and generally increased during the experiment. One of the three pairs of participants ended up getting the reservation price of .6 consistently. The limited evidence for the 50 period experiments shows that the groups of six get more competitive, with high efficiencies and competitive prices. In contrast, the duopolists are able to exploit market power effectively but they also achieve high efficiencies.

In the initial plan for Phase 1 and Phase 2, there was an expectation that the results for experiments over 20 periods in Phase 1 would be sufficient to identify which auctions worked well. When the results from the 20 period experiments were evaluated, it was clear that experiments over longer periods were needed. The need to set up another group of experiments delayed moving on to Phase 2. In addition most of the experiments over 50 rounds in Phase 1 still need to be completed.

Preliminary tests using Power Web have been completed. The configuration of the network and the specified pattern of loads imply that two of the six generators are effectively isolated by transmission constraints in a load pocket. In addition, one of the four generators outside the load pocket was found to be the only one that could keep one of the transmission lines into the load pocket at full capacity. Hence, three of the six generators determine the market prices for different regions of the grid. The unexpected ramifications of using a realistic transmission grid in a smart market pose exciting possibilities for future research. Full-scale testing of different auction institutions will be conducted using Power Web when the 50 round experiments are completed in Phase 1.

7. CONCLUSIONS

The plan for this research on the performance of different auction institutions for electricity markets consisted of two phases. In Phase 1, four auctions were to be tested over 20 periods with either six or two participants. The objective was to choose which auctions performed best in terms of cost efficiency and competitive pricing. In Phase 2, the selected auctions were to be tested in a smart market using Power Web to simulate the effects of line losses and congestion in a transmission grid for electric power. The four auctions tested in Phase 1, which are all uniform price auctions, were 1) Last Accepted Offer (LAO), 2) First Rejected Offer (FRO), 3) Sealed Bid English using FRO, in which participants respond to independent descending clocks, and 4) True English using FRO, in which participants use a common clock and see other participants withdraw units (this auction is not practical for an electricity market run by an ISO).

A distinguishing feature of this research is that the participants in each market can be viewed as “competing utilities” that control generators with different cost characteristics (high, intermediate and low). In many multiple-unit auctions, the units controlled by a given participant are all identical. Since all participants knew that the total load was going to be fixed at half of the total capacity (number of units) of all participants, it was conceptually easy for participants to conclude that their low cost generators should run, their high cost generators would not run and it was uncertain how many of the intermediate cost units would run. Offers for low cost generators were typically close to the true costs, but the offers for high cost generators were often much higher than the true costs. In other words, the cost structure of the generators made it quite natural for participants to exhibit some sort of strategic behavior.

Even though the market structure was relatively simple and total demand was the same in every period, a major surprise in Phase 1 was that running the experiments over 20 periods did not always lead to stable values of the efficiency or price by the end of the experiment. Efficiencies were generally low, particularly for the duopolies, and only the true English auction with six participants had an average efficiency above 90 percent. Prices were substantially greater than the competitive FRO price by roughly 30 percent with six participants, and by roughly 60 percent in the duopolies. In particular, the performance of the true English was much less efficient and less competitive in price than it had been in earlier experiments with around 20 participants.

The initial results from extending the experiments in Phase 1 to 50 rounds are very interesting. Using experienced participants from the experiments over 20 rounds, the performance of the LAO with six participants was excellent. Efficiencies reached 98 percent and the price ended up slightly below the competitive FRO. For the duopolies, the sealed bid English was also relatively efficient, reaching a level of 96 percent. For prices, however, the results were dramatically different, and the final prices were over twice as large as the competitive FRO. The conclusion is obvious, given some experience, duopolists were able to exploit market power and raise the price above the competitive level. This is a potential problem for transmission grids that are subject to the formation of load pockets, as they are in the northeastern region of the USA.

Additional experiments of 50 rounds will be completed in the near future for the other auctions using two and six participants. While additional auctions may match the competitive performance of the LAO with six participants, there seems no reason to expect that any of the auctions will work well under a duopoly. Hence, market power is expected to be a potential problem in electricity markets if load pockets are isolated from the rest of the transmission grid. It is possible, however, that a multi-unit Vickrey auction may perform better than the auctions tested so far, and a Vickrey auction will also be tested in Phase 1 over 50 rounds.

There is some evidence from Australia (Outhred 1997 and Bannister 1997) that market power is a problem in the Victorian market. Prices in the spot market are highly competitive for most of the time. However, when forced outages occur or the actual load is much higher than the forecasted load, price spikes are observed, with some prices over 100 times the average level. This happens even though the institutional structure of the market has been designed to limit the ownership of generators by making each major generator a separate company (Outhred 1997).

The formation of load pockets within the existing transmission grid is a distinct possibility in the northeastern states of the USA, particularly if ancillary services are considered. The existence of market power within a load pocket may explain why some buyers in the auctions used to sell utility generators are willing to bid high prices for “bundles” of generators that are strategically located. The new pattern of ownership of generators in New England after the sale of generators by members of the New England Power Pool may be an interesting example to examine. If the potential for market power exists, there is every reason to expect that brokers will find out how to exploit this potential because the auctions for electric power will be repeated so many times. In fact, it is possible that “competitive” markets with strategic patterns of ownership may not perform as well as the traditional regulated markets with a monopoly supplier in each service territory. Furthermore, major modifications to the existing transmission grid may be required to support a competitive market effectively.

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APPENDIX: INSTRUCTIONS FOR SEALED BID - LAST ACCEPTED OFFER AUCTION WITH TWO SELLERS, SINGLE BUYER

This is an experiment in the economics of decision making. Throughout the experiment, the decisions you make will determine your earnings in dollars and cents. Any money you earn will be yours to keep. Try and make as much money as you can. Please do not communicate with any of the other participants during the experiment.

In this experiment **you will be one of two sellers** of electricity in an auction market in which there is a single buyer with a fixed demand. You will be matched with the same person throughout the experiment, but you will not know who that person is. You will each be in control of an electric power company with three generators from which you can offer electricity into this market. The generators can be classified as low, medium, and high cost. While costs of other’s generators may or may not be the same as yours, you can be assured there is never more than a five cent difference per unit per period between the cheapest and most expensive generator in each category.

The maximum production of each of the generators will be either 1 or 2 units of electricity. The total amount of electricity that can be generated by each company is 5 units. Thus, everyone will have two generators that can produce 2 units and one generator which can produce only 1 unit. Again, different people may have different generators which are their low capacity producer.

The experiment will consist of three practice periods where your earnings will *not* count, followed by twenty actual periods where your earnings will count. At the beginning of each period you must decide on a quantity and price offer for electricity from each of your generators. Then an auction will be performed to determine the market price per unit of electricity and which units are sold. Units that are sold are paid the market price. You will never receive less than the price offer you submit. Making an offer and the auction are described below.

Making Your Offer

To aid you in making your decision, at the beginning of each period you will be able to see on your screen the maximum units of potential output (capacity) and the costs per unit for generating electricity for each of your three generators. These capacities and costs will be the same throughout the experiment.

Another important piece of information is the buyer’s "Reservation Price," which is the *maximum price per unit that the buyer would be willing to pay* for electricity. The reservation price will be 60 cents throughout the experiment. Price offers above 60 cents will not be accepted by the buyer.

The demand of the buyer will be 5 units of electricity every period. This represents half the total possible capacity in the market.

Using all the above pieces of information, you will need to **decide on the quantity from each generator that you wish to make available for sale and the price you’d want per unit from each generator**. The arrow keys move among the fields for your different generators. To change the number in a field, type in the number you want and press Enter (you need to press Enter before the arrow keys will allow you to move to a different field). In making your decision, note that the cost of producing a unit of electricity will only be charged to your firm if the unit is actually sold.

Once you have filled in your quantity and price offers for *all* of your generators, press the F10 key to submit these offers into the auction. ***It is important you enter offers from all of your generators that you wish to make an offer from before pressing F10 - there is no way to go back and it will be assumed you wanted zero in any remaining fields, including price!*** You will not be able to change your offered quantities or prices once you have submitted them. Note lastly that you do not have to offer the full capacity from any of your generators or even make an offer from all generators. When offers from all participants have been submitted, the auction will run.

The Auction

The auction determines the price at which the offered units of electricity will be sold to meet the buyer's quantity demanded. This price is called the "Reigning Price." All units included for sale are paid the Reigning Price.

The auction works as follows. Offered prices from all sellers are rank ordered from lowest to highest. Units with the lowest prices will be included for sale until the buyer’s demand is satisfied. Units above the quantity demanded with the highest offered prices will be excluded from sale. The reigning price is set equal to the offered price of the highest offer priced unit included in the sale, or to the reservation price if *not enough* units are offered in the market. Note that partial quantities may be sold. Partial offers are considered included; **final price is set to the highest priced offer for which *any* of the units were purchased.** Sellers receive this Reigning Price for all their included units.

At the end of the auction, your earnings will be calculated as the sum of the differences between the production cost and price for each of the units you sold. Earnings in subsequent periods will be added onto your prior earnings. After each period, the computer will give you your profits for that period as well as your overall total profits. The computer will also remind you when it is the end of the last practice period - it is only after this that your earnings actually count. Once you have reviewed your earnings, press a key so the next period can begin. **The exchange rate in this experiment will be one third a cent for each experimental cent you earn.**

It is important that you understand these instructions, please raise your hand if you have any questions.