EXPERIMENTAL RESULTS FOR SINGLE PERIOD AUCTIONS

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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.

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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 evaluated 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.

While recognizing the importance of the work of Smith and others, we believe the specifics of their implementations do not reflect realistic problems that may arise in full-scale power systems. The key fact is simply that the full effect of restructuring on the delivery and pricing of electric power can not be determined without the incorporation of the intricacies of a realistic electric power grid and the interactions with complex market mechanisms.

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 occured 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 PowerWeb 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;

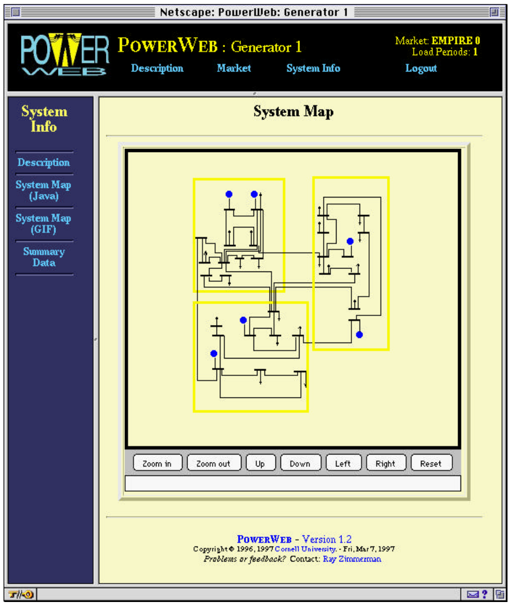
$$\begin{aligned} &\min f(\mu) \\ &\quad \text{s.t.} \\ &g(x,\mu) = 0 \\ &h(x,\mu) \leq 0 \end{aligned}$$

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, $h(x,\mu) \leq 0$, 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 EXPERIMENTATION PLATFORM: POWERWEB.

A unique environment is required to test decision making by human subjects in a smart market that adequately represents the real complexities of power system operations. PowerWeb is a new Internet-based simulation environment for investigating the behavior of competitive electric power markets experimentally. It has been under development since the beginning of 1996. It currently has the ability to model day-ahead markets for generation scheduling. A 6 generator 30 bus bulk power system, as shown in Figure 1, is an example of a system on which experiments could be performed. For example, market participants may submit offers such as those shown in Figure 2 to sell power, and an ISO could determine the dispatch schedule and prices based on some agreed upon auction mechanism. This platform can be used to investigate various characteristics of market behavior based on experiments conducted using appropriate human participants.



POWERWEB - Version 1.2
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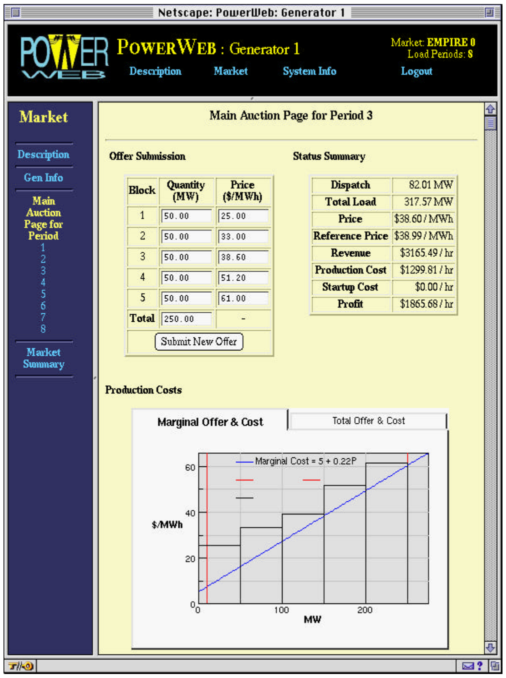
Problems or feedback? Contact: Ray Zimmerman

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

Since PowerWeb 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 PowerWeb 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.



Main Auction Page for Period 3

Offer Submission

Block	Quantity (MW)	Price ($/MWh)
1	50.00	25.00
2	50.00	33.00
3	50.00	38.60
4	50.00	51.20
5	50.00	61.00
Total	250.00	-

Status Summary

Dispatch	82.01 MW
Total Load	317.57 MW
Price	$38.60 / MWh
Reference Price	$38.99 / MWh
Revenue	$3165.49 / hr
Production Cost	$1299.81 / hr
Startup Cost	$0.00 / hr
Profit	$1865.68 / hr

Production Costs

Figure 2. The offer submission page

At the current stage of development, PowerWeb is capable of hosting experiments with participants accessing the site remotely via the Internet. There is a tremendous amount of data involved in supporting the types of experiments that PowerWeb is designed to test. A relational database is used to maintain three primary types of data.

- user administration data
- power system data
- session data

The user administration data are used to track the use of PowerWeb (since it will be openly accessible via the web), and to control who has access to information. 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 PowerWeb 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 the speed of execution. Efficiency is a typical measure of auction performance. Speed of execution/convergence is important for electric power applications because they must be executed in real time and potentially many times per day, or even per hour. Speed of convergence is one of the possible shortcomings of the auction rules tested by Plott (1997).

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. 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 generators 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.

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 will principally be either undergraduate engineering students or undergraduate business students at Cornell. To allow subjects time to learn in the auctions and to determine long run efficiencies, each auction will run 20 rounds. Efficiencies will be calculated as the ratio of lowest possible cost to meet demand to the actual cost to meet demand in an auction.

For the three auctions 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 all experiments will be constructed so that each subject has an opportunity to earn approximately $15. Enough subjects will be recruited for each treatment to allow for valid statistical comparisons.

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. Each Phase 2 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. RESULTS AND CONCLUSIONS.

A series of experiments using the three auctions described in Section 5 and PowerWeb are planned for the Fall, 1997. Results from these experiments will be presented at the conference in January, 1998. In pretesting, efficiency differences have already begun to appear. Efficiency rates of around 89% were evident in the two firm case for the FRO auction while the sealed bid English auction achieved 99% efficiency. Additionally, individual offers appeared substantially closer to actual generator costs in the English auction. These preliminary results lend hope that our new English auction with PowerWeb will show high efficiencies in markets for electric power.

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