Auction Design for Competitive Electricity Markets

presented at the HICSS Conference

January 7-10, 1997

Maui, Hawaii

by

Robert Ethier
Timothy Mount
William Schulze

Department of Agricultural, Resource, and Managerial Economics

Ray Zimmerman
Robert Thomas

Department of Electrical Engineering

Cornell University

Please direct correspondence to Robert Ethier at:

rge4@cornell.edu

Auction Design for Competitive Electricity Markets

by

Robert Ethier
Ray Zimmerman
Timothy Mount
William Schulze
Robert Thomas

Cornell University

Alternatively, the Market Coordinator could ask the private generating firms to furnish their operating cost data (confidentially of course) to facilitate system dispatch. We can see little reason for the private firms to say no or to try to play games and provide incorrect data. - Schweppe et al (1988), pp 115-6.

1. Introduction

Achieving efficient (least-cost) dispatch on an electric grid by a central authority requires knowledge of each generator's marginal cost curve as well as characteristics of the transmission system and demand nodes (e.g. responsiveness to price). Traditional regulated utilities are able to achieve efficient dispatch because, as vertically integrated entities, they know the marginal cost or heat rate curve of every generator on the system. This information will not be readily available in a competitive market for electricity. A mechanism for revealing generator marginal costs in a complex electric grid is needed.

Finding an institution which reveals generator marginal costs is not as straight forward as the above quote suggests. It is difficult because clearly generators, in seeking to maximize profits, will take advantage of opportunities to manipulate offers when this would result in greater profits (Newbery 1995). We take the position that while a perfectly efficient market for electric power is unlikely to be found, there is much room for progress and refinement of current institutions. This goal can be advanced through testing alternative institutions in a simulated grid environment.

This paper describes an application in experimental economics designed to test the performance of alternative market mechanisms. This testing environment is called Power Web (Thomas and Zimmerman, 1996) which solves unit commitment and Optimal Power Flow (OPF) problems in conjunction with a Second Price Uniform auction. A Second Price Uniform auction, which is theoretically cost revealing, is modified to incorporate locational loss and congestion adjustments while preserving the second price nature of the auction. The locational adjustments are calculated by a combined unit commitment/OPF algorithm. Adapting relatively simple market institutions with known properties to complex systems is far from straight forward and the resulting system characteristics are uncertain. The goal is to produce a system suitable for experimentation and testing with both human subjects and computer algorithms.

1.1 Background

The primary lesson from the literature on experimental economics is that the actual performance of a given form of auction is difficult to predict from theory, and there are often surprises when a new market structure is tested. Even for simple markets, there are uncertainties about their performance when changing from a fixed supply with competitive bids, for example, to fixed demand and competitive offers in an electricity supply setting. Furthermore, there are complications associated with the operation of an electric grid which have to be incorporated into any market structure. These complications include the stochastic nature of load, the associated need to maintain reliability, and the locational variability of transmission costs. Unfortunately, it is generally not possible to determine in advance how a particular modification to a competitive market will affect performance. These are the types of questions that can be addressed by experimental economics.

Even though the objective of our research is to evaluate different types of markets, this paper focuses on a particular form of market. The choice of market is based on the following four assumptions.

1) An Independent System Operator (ISO) controls operation of the grid.

Reliability of the electric grid is considered to be a primary requirement, and consequently, the ultimate authority over operations is given to an ISO. This is consistent with the concept of security constrained dispatch.

2) Financial markets for electric power exist separately from the spot market.

The ISO determines the unit commitment, OPF and spot prices at all demand and supply nodes. These prices reflect actual (ex-post) transmission losses. Bilateral trades of real power can be implemented by offering to supply power at a low price. The contracted prices for bilateral trades, however, would be considered as part of the Financial Market and would have no direct effect on the decisions made by the ISO.

3) Uniform spot prices modified for transmission losses are paid to all sellers in the spot market (and by all buyers).

Evidence from economic theory and experimental economics suggests that discriminatory auctions, in which participants receive their actual offers, do not provide incentives to reveal true costs. Uniform price auctions perform better, but not necessarily as well in practice as they do in theory. Multiple unit versions of single sided auctions do allow some scope for gaming, and this is an issue that must be evaluated carefully.

4) The spot market is one- sided and treats demand as fixed.

The current challenge for the electric utility industry is to determine whether efficient one-sided markets can be developed for a PoolCo system. Experience from the UK suggest that much work remains to be done (Newbery, 1995). Results from experimental economics (McCabe et al, 1991) suggest that two-sided double auction markets work better than one-sided markets, and two-sided electricity markets have been proposed in the literature (Wu and Varaiya 1995). However, it is unclear if a double auction could be modified to incorporate actual transmission constraints and losses, and if so, if it would maintain high levels of efficiency. We have chosen to pursue the one-sided market as the more immediate policy option.

Section 2 presents the Second Price Uniform and English auctions, market institutions discussed in the economics literature which theorectically produce cost-revealing offers, making them suitable for deregulated electricity markets. Section 3 discusses the adjustments necessary to adapt one market institution, the Second Price Uniform auction (hereafter the Uniform Price auction), to an electricity transmission system which takes into account AC load flows. The resultant World Wide Web based simulation tool that has been developed is called PowerWeb. Section 4 provides preliminary results. Section 5 describes areas of future research.

2. Alternative Market Institutions

The ISO in our proposed market would, in effect, be the single buyer in a Poolco. Thus, the Poolco must be run as a single-sided market. The following section discusses two single-sided markets, the Uniform Price and English auctions, in a simplified context which excludes transmission system characteristics.

The Uniform Price and English auctions are selected over alternatives such as the First Price Uniform and Discriminative auctions because of their theoretical cost revealing properties and experimental evidence about efficiency. Importantly, the Discriminative auction, in which participants are paid their offers, is not theoretically cost revealing. For a discussion and results see Cox et al (1985). Since the Discriminitive auction corresponds closely to the payment of nodal electricity prices as discussed in Schweppe et al (1988), payment of strict nodal prices is also unlikely to be cost revealing. For more background on alternative auction institutions in an electric power context, see Schulze and Mount (1996).

2.1. The Uniform Price Auction

The Uniform Price auction is a generalization of the Vickrey auction (Vickrey, 1961), first proposed by Friedman (1960), that allows for multiple units rather than just one unit to be traded. For reasons that will become apparent, sellers have incentives to submit offers at prices equal to costs. The uniform price paid for all purchased units is equal to the price of the first rejected offer and is called the reigning price. Thus to influence prices one must control the first rejected block or withhold quantities to shift up to the next rejected block. Note that offered quantities are defined as maximum quantities in this auction so that the purchaser can take, if desirable, only the part of the last block necessary to satisfy demand.

The most important feature of this institution is, however, its incentive structure. Since each of the suppliers receives a price greater than their offered price, submitting an offered price above cost exposes a supplier to the risk that units will be excluded from sale, with a resulting loss of income. Consequently, firms have a clear incentive to submit offered prices equal to cost and quantities equal to capacity. This also implies that the reigning price is a reliable signal of the marginal cost of the next available block of electric power. If the last accepted offer has remaining capacity, its offer price is also a reliable signal of marginal cost.

Although the theoretical properties of this institution are excellent (see Vickrey, 1961, Milgrom, 1989, and Riley, 1989), experimental tests reveal that the uniform price auction has good, but not excellent, properties in practice (Cox, et al. 1985). This would, potentially, raise electricity prices above and reduce efficiency below the theoretically attainable level.

An issue which applies to any auction with uniform prices is the possibility that a large firm might exploit market power to raise prices. Consider the case where the same firm manages two facilities with different costs and capacities. If the firm withholds its more expensive facility from the market, and this facility would have been either dispatched or the first rejected offer, the reigning price is driven up. The returns earned by supplying a smaller quantity at this higher price could exceed the returns earned by offering a higher quantity at a lower price. Note that the rise in prices is limited to the difference between the first currently rejected block and the second currently rejected block (if all blocks are the same size). Whether this produces higher returns in practice is an empirical question.

Two factors mitigate against such behavior. First, behavior of this sort would be obvious to knowledgeable observers and would likely attract suppliers from adjoining power pools, or if it persisted, would draw antitrust action. Second, as the recent large number of new power producers to enter the market in New York State demonstrates, power production is a contestable market. If a large firm were to maintain high prices in the wholesale market for electric power, new firms and capacity could well be attracted that would offer power at lower prices.

2.2. The English Auction

As noted above, experimental evidence suggests that the Uniform Price auction does not attain perfect efficiency. An alternative which produces improved efficiency, but has its own implementation problems, is the English auction. In this sequential auction, each seller would initially submit a quantity offer indicating the maximum number of units available for sale (capacity) for each generating facility to be entered into the auction. For simplicity, we will assume that each firm owns one facility. The auctioneer then begins the auction by starting a "clock" which sweeps down, lowering price continuously. Suppliers then progressively drop out of the auction, withdrawing their offered quantities as the price falls below profitable levels. The clock stops when the number of units withdrawn causes supply to fall below the quantity demanded. The clock is then reset to the last price at which supply exceeded demand. This price is then paid as a uniform price to all sellers remaining in the auction, which includes the last seller to withdraw in this example.

The theoretical analysis of this auction is identical to that of the Uniform Price auction and, in theory, sellers should withdraw just as price falls below their own cost. The English auction provides information on both the current marginal cost and on the marginal cost of the next available block of power. Experimental tests of this mechanism in a fixed supply setting have been very favorable (McCabe et al. 1990, Van Huyck et al. 1993). Recent evidence suggests that these favorable properties are maintained when demand is fixed (Bernard et al, 1996).

Two problems with the English auction become apparent in an electricity supply setting. One is the real-time nature of the auction, which imposes relatively high transaction costs when compared with a sealed bid auction. The second is that the English auction as described, fails to reveal the entire supply curve for suppliers who remain in the market, which is necessary for computing least-cost dispatch. These problems make the English auction a second choice to the Uniform Price auction in spite of its excellent experimental results in simple settings. Modifications, such as running the clock to zero, may yet produce a useful variant of the English auction and are currently being explored. The Uniform Price auction is used as the basis for further discussion.

3. Competitive Markets for Electricity

The Uniform Price auction discussed in Section 2.1 is modified to incorporate some of the relevant characteristics of electricity transmission, specifically line losses and congestion rents. The resultant auction is combined with a multi-node transmission system in PowerWeb, a World Wide Web-based tool for exploring transmission grid-based auction markets.

3.1. The ISO's Problem

The foundation of PowerWeb is an ISO solving the instantaneous cost minimization problem:

$$\min_{u} f(u)$$

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

where

$$f(u) = \sum_{i} c_i(u_i)$$

and u is the vector containing the real power output of each generator, c_i is the cost of generator i as a function of its output, and roughly speaking, x is the set of node voltages. The equality constraint on $g(\cdot)$ ensures that Kirchhoff's laws are satisfied. The individual equations $g_k(\cdot) = 0$ state that the net power injected (generation minus demand) at node k is equal to the net power leaving node k via the transmission grid. The inequality constraints $h(\cdot)$ contain upper and lower voltage limits, generator real and reactive power limits, transmission limits, and possibly other security limits.

The actual problem is more complicated because a generator's real power limit is typically non-zero, so the decision must be made as to whether it's best to run an "expensive" generator at its lower limit, or to shut it down completely and remove it from the above problem. Rather than run a unit commitment and separate OPF, which could dramatically change the auction incentives as offers would now face a two-tiered selection process, unit commitment is performed as part of the OPF. This more closely maintains the characteristics of the simple Uniform Price auction while including transmission costs in the selection process. This combined unit commitment/optimal power flow problem requires some simplification to make it tractable for use in an auction.

Since the Uniform Price auction utilizes discrete offers, one would ideally employ a discrete optimization algorithm in an attempt to find an exact solution. However, this is an enormous combinatorial optimization problem for systems of realistic size and it is not clear that a practical algorithm exists which is capable of solving this problem in a reasonable amount of time. A more feasible option in this setting is to fit a differentiable function to the discrete offers and then use a standard OPF algorithm to solve it. Typical OPF algorithms use sparse, non-linear, constrained optimization with differentiable objective functions and constraints.

Note that ideally, c_i is the true marginal cost of generator *i* as a function of power output. As discussed earlier, this is known in a regulated utility structure. In a competitive situation c_i becomes the submitted offer curve of each generator, so the cost-revealing properties of the chosen market institution are fundamental to achieving an optimal dispatch.

The ISO's cost minimization problem produces dispatch points for each generator and nodal spot prices for each node of the network. The nodal spot prices are the Lagrange multipliers (λ_k) associated with each of the equality constraints $g_k(\cdot)$. These nodal spot prices incorporate two important characteristics: transmission losses and congestion associated with each node. Importantly, transmission losses and congestion can only be computed as part of the OPF and can not be known a priori. Each λ_k depends on every other node in the system and changes with each change in system characteristics. (For a more complete treatment of the ISO's problem and resultant spot prices, see Schweppe et al, 1988.)

At nodes with generators operating within min and max limits, λ_i (where $i \quad k$) is equal to the marginal cost of generation at the dispatch point. But if these λ_i*'s* were used to compensate the generators, generators would no longer have an incentive to reveal their marginal cost of generation, as discussed in Section 2. So the problem becomes how to combine a cost-revealing auction mechanism which includes locational price adjustments determined by the actual system dispatch.

3.2. Adjusting the Offers

The proposed solution is to adjust each offer by the appropriate congestion rent and transmission losses (referred to as Locational Price Adjustments, or LPA's), rank order the adjusted offers from lowest to highest, and set the uniform price to be the first wholly rejected offer plus it's associated LPA. Thus the prices received by generators are not the nodal prices computed directly by the OPF. The auction mechanism uses LPA's and dispatch points from the OPF, but combines this information with submitted offers to produce prices. The OPF, in turn, uses submitted offers to produce a solution.

For the sake of exposition, assume that the bus with the highest nodal spot price computed by the OPF is chosen as a reference bus, and that each generator submits an offer for only one block. The OPF produces Lagrange multipliers, λ_k, the largest of which is the price at the most expensive node, denoted λ_{REF}. The appropriate LPA $\Delta\lambda_i$ for each generation node is then calculated by:

$$\Delta\lambda_i = \lambda_{REF} - \lambda_i \,, \tag{1}$$

where λ_i is generator i's Lagrange multiplier from equality constraint $g_i(\cdot)$ in the OPF. The offers τ_i for each generator plus the appropriate LPA $\Delta\lambda_i$ are then rank ordered from lowest to highest, with the first completely rejected block setting the uniform price P_{UNI}:

$$P_{UNI} = \tau_j + \Delta\lambda_j \,, \tag{2}$$

where j is the first completely rejected block and $\tau_j > \lambda_j$ by construction. The price P_i received by each generator i for each unit of power is then given by:

$$P_i = P_{UNI} - \Delta\lambda_i \,, \tag{3}$$

where $P_i > \tau_i$. This ensures that each accepted block receives a payment per KWh which is strictly greater than its offer price and that P_i is not directly dependent upon the offer associated with that block. This method generalizes to multiple blocks from each generator or node, and can also be used to compute LPA's for demand nodes. Graphically, the rank ordered offers are shown in Figure 1, with the nodal payments shown in Figure 2.

Figure 1. Rank Ordered Offers Plus LPA's

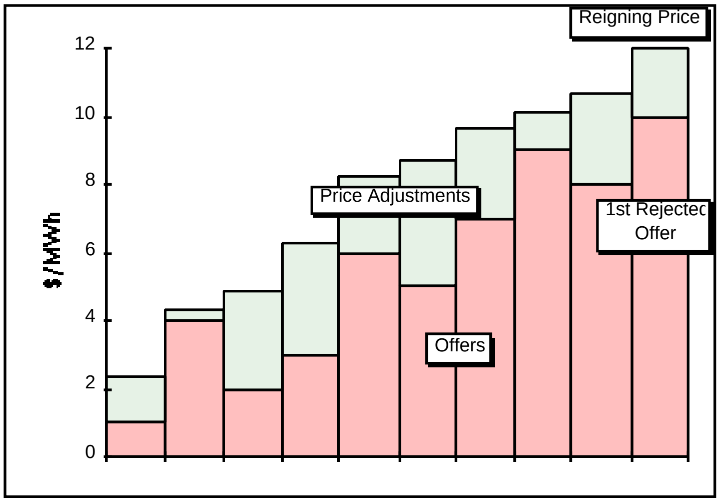
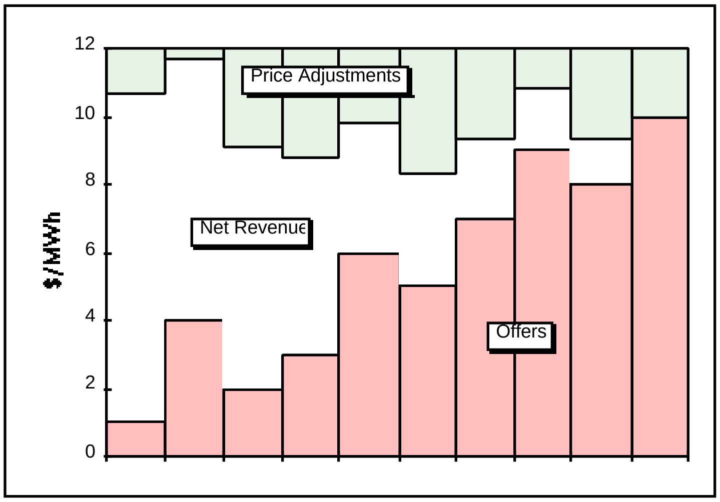


Figure 2. Generator Prices: P_{UNI}-LPA



As discussed earlier, even in a simple multiple unit Uniform Price auction there is the possibility of gaming by restricting quantities offered or when control of the first rejected offer is known. The importance of these problems is directly related to market power and the number and size of competitors in the auction. Under realistic system configurations, this is not expected to be a problem. Experimentation should help to provide information about the sizes and number of participants needed to ensure competitive markets.

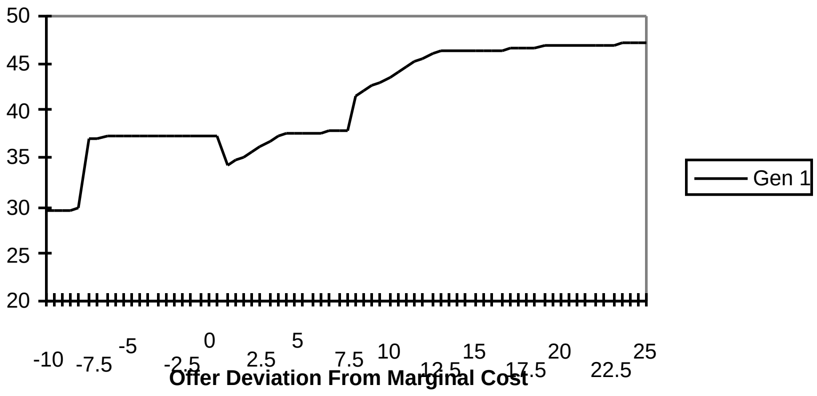
The added complication here is that $\Delta\lambda_i$, the LPA, is a function of each generator's dispatch point, which in turn is a function of τ_i, the submitted offer, so the LPA can be affected by each generator's submitted offer. While in theory this provides some scope for optimizing profits as a function of offers, the severity of the problem is unknown in a large and stochastic market. In a three generator system, the problem appears to be negligible.

Since this pricing mechanism provides an instantaneous price which can be expected to vary as system conditions vary in real time, it is proposed that hourly or half-hourly prices be the final basis of settlement, where the prices are set using ex-post nodal adjustments and actual power output. The OPF would solve for the uniform price using the most recent set of offers.

4. Results

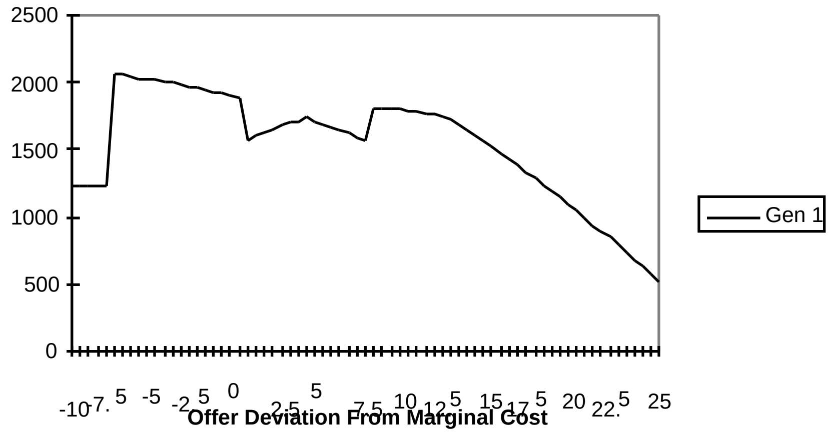
In a small simulated grid the ability to affect prices and returns is limited, as shown in Figures 3 and 4. These data were obtained from a 3 generator version of PowerWeb, with generators 2 and 3 offering all quantities at marginal cost while generator 1 submits different offers to generate a response function for the price and returns for generator 1.

Figure 3. Price P_1 as a Function of Generator 1's Offers



The discontinuities in the price curve in Figure 3 come from having a new offer become the first rejected offer. Moderately sloped portions occur when generator 1 controls the first rejected offer. The nearly flat portions of the curve reflect changes in the LPA for generator 1 as dispatch changes and the price is set by a block from another generator.

Figure 4. Generator 1's Return as a Function of Its Offer



Discontinuities in the price function result in discontinuities in the return function. Curved portions of the return function in Figure 4 show the trade-off between higher prices and lowered dispatch associated with higher priced offers.

Clearly the market price can be influenced by an individual generator's offer in a 3 generator system, where market power is inevitable. In spite of this, generator 1's incentive to adjust offers to influence the price is unclear. As Figure 4 shows, returns are not greatly affected by increases in offers, and the maximum return on this interval is acheived at offers below cost. Collusion could certainly change the incentives, but that situation is not unique to this market structure. While this example is purely illustrative, it does show that even with market power, there are no obvious incentives for making offers above cost in a Uniform Price auction as implemented in PowerWeb.

Experiments with a larger system using a variety of subject pools and computerized agents are planned for the near future. Dimensions to be explored include the importance of congestion, market power and the sophistication of the subject pool.

5. Direction of Future Research

A planned area of future research is to evaluate alternative single-sided market institutions. Preliminary research indicates that a single round uniform price auction with a very simple transmission system produces relatively low efficiencies with naive, inexperienced subjects (personal communication, V. Smith, November 1996). Experiments with more knowledgeable, experienced subjects are necessary. Alternative market mechanisms include an iterated version of the Uniform Price auction and a modified English auction which produces the entire supply curve. Modifications to the existing auction mechanism may include bid improvement rules in an iterated setting.

A number of issues must be dealt with if PowerWeb is to be expanded to incorporate more realistic system features. Linking auctions across a 24 hour dispatch period is important, especially when generators face start-up costs and limited ramp rates. One possibility is sequential auctions beginning at the 24 hour load minimum, allowing participants to implicitly cover start-up costs by providing tentative prices and dispatch points over the day. This would likely require an iterated setting.

An important part of system security is load following capability (e.g. Automatic Generation Control). Given the stochastic nature of electricity demand, it seems that an ideal system of compensation for AGC would make generators indifferent between being provided a fixed dispatch point or being compensated for load following. Spinning reserve must also be incorporated, ideally with a mechanism which, on the margin, would make generators indifferent between being spinning reserve and dispatched.

Ancillary services (e.g. VAR support) must also be accounted for. One possibility is that some expenses can be included in transmission system.

Must-Run generation for plants with either limited ramp rates (e.g. nuclear power) or external obligations to run (e.g. servicing a steam load) might be handled by submitting zero price offers. Such offers would still receive positive payments if losses and congestion were not severe and some non-zero offers were accepted. This mechanism can also be applied to bilateral transactions. A physical bilateral transaction which guarantees that a certain generator will produce a certain amount of power independent of the realized market price has the potential to force the system operator to operate at a point different from the economic optimum, producing inefficient operation of the entire power system. Allowing bilateral transactions to be financial arrangements only, via Contracts For Differences (see Hunt and Shuttleworth, 1996). A major implication of our proposal is that someone has to be responsible for paying the actual costs of transmission losses and congestion for all bilateral trades.

Other major issues are demand side pricing (i.e. zonal, nodal, or uniform), transmission system ownership and incentives, and strandable cost recovery. Final customers will have to pay above the nodal price to cover transmission, distribution, and strandable costs. The way in which these additional charges are handled will have significant demand effects (see Ethier and Mount, 1996).

References

Bernard, John, Mount, Timothy, and Schulze, William. “Auction Mechanisms for a Competitive Electric Power Market.” manuscript, submitted to the AAEA Summer Meetings, December 1996.

Coppinger, V.M., Smith, V.L., and Titus, J.A. (1980). "Incentives and Behavior in English, Dutch, and Sealed-Bid Auctions," *Economic Inquiry* 18: 1-22.

Cox, J., Smith, V.L., and Walker, J.M. (1985). "Expected Revenue in Discriminative and Uniform Price Sealed Bid Auctions." In Research in Experimental Economics, Vol. 3, ed., V.L. Smith. Greenwich, CT: JAI Press.

Ethier, Robert and Mount, Timothy (1996). “Competitive Electricity Markets in New York State: Empirical Impacts of Industry Restructuring.” ARME Working Paper Vol. 96-05. Cornell University.

Friedman, M. (1960). *A Program for Monetary Stability*, pp. 63-65. NY: Fordham University Press.

Hunt, Sally and Shuttleworth, Graham (1996). *Competition and Choice in Electricity*. NY: John Wiley and Sons.

Irwin, J.R., McClelland, G.H., McKee, M., Schulze, W.D., and Beckett, N.E. (1995). "Incentive Compatibility of the BDM: The Roles of Cognitive Transparency and Payoff Dominance," manuscript.

McCabe, K.A., Rassenti, S.J., and Smith, V.L. (1990). "Auction Institution Design: Theory and Behavior of Simultaneous Multiple Unit Generalizations of the Dutch and English Auctions," *American Economic Review* 81: 1276-1283.

McCabe, K.A., Rassenti, S.J., and Smith, V.L. (1991). "Smart Computer-Assisted Markets," *Science* 254: 534-538.

McClelland, G.H. and Schulze, W.D. (1991). "The Disparity Between Willingness to Pay and Willingness to Accept as a Framing Effect." In *Frontiers in Mathematical Psychology*, eds. D.R. Brown and J.E.K. Smith, pp. 166-192. NY: Springer-Verlag.

Milgrom, P. (1989). "Auctions and Bidding: A Primer," *Journal of Economic Perspectives* 3(3): 3-22.

Newbery, David M. (1995). “Power Markets and Market Power.” *The Energy Journal.* Vol. 16 No. 3, pp.39-66.

Oren, Shumuel S. And Bushnell, James. (December 1992) “Bidder Cost Revelation in Electric Power Auctions” PWP-006. Dept. Of Industrial Engineering and Operations Research, University of California at Berkeley.

Riley, J.G. (1989). "Expected Revenue from Open and Sealed Bid Auctions," *Journal of Economic Perspectives* 3: 41-50.

Sakk, Eric, Thomas, Robert J., and Zimmerman, Ray. (January 1997) “Power System Bidding Tournaments for a Deregulated Environment.” presented at HICSS 1997.

Schulze, William D. and Mount, Timothy D. “An Analysis of Market Institutions for Power Choice.” manuscript, Cornell University.

Schweppe, Fred C., Caraminis, Michael C., Tabors, Richard D., and Bohn, Roger E. (1988) *Spot Pricing of Electricity*. Boston: Kluwer Academic Publishers.

Van Huyck, J.N., Battalio, R.C., and Beil, R.O. (1993). "Coordination Failure, Game Form Auctions, and Tacit Communication," *Games and Economic Behavior* 5: 485-504.

Vickrey, W. (1961). "Counterspeculation, Auctions, and Competitive Sealed Tenders," *Journal of Finance* 16: 8-37.

Wu, Felix and Varaiya, P. (June 1995) “Coordinated Multilateral Trades for Electric Power Networks: Theory and Implementation.” POWER Working Paper 031. University of California Energy Institute.