# SINGLE CLEARING PRICE IN ELECTRICITY MARKETS

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# Perhaps the Most Celebrated Result in Economics

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The single clearing-price auction is perhaps the most basic building block of markets. Buyers submit demand bids and sellers submit supply offers. The auctioneer then forms the aggregate supply and demand curves, and finds the clearing price at which supply and demand balance; that is, where the supply and demand curves cross. All demand bids above the clearing price and all supply offers below the clearing price are accepted. The winning buyers pay the clearing price and the winning sellers are paid the clearing price for their accepted quantities.

The single clearing-price auction is important because of its simplicity and effectiveness at answering the most basic questions: who should get the goods, who should produce the goods, and at what prices. Based on each market participant's expressed preference, the single clearing-price auction awards the goods to all consumers who value the goods more than the cost (the clearing price) and the goods are produced by all suppliers who have a cost less than their payment (the clearing price). In this way, the clearing-price auction maximizes gains from trade: consumption comes from demand with the highest values and production comes from supply with the lowest cost. This is perhaps the most celebrated result in economics.

It should be no surprise that the single clearing-price auction is the centerpiece of restructured electricity markets. Most electricity systems use the single clearing-price auction in many places. The most important application is the spot energy market, which is a real-time market to determine the price of electricity at a particular time and location. Setting aside the complexities of transmission and other physical limits of the system, the spot market is as simple as above—the lowest-cost generators produce energy for demand, up until the point where all demand at prices above the clearing price is satisfied. Moreover, the complexities of transmission and other physical limits are readily handled within the same structure simply by adding the physical limits as constraints in the pricing process.

If the market is competitive, in the sense that no single buyer or seller is large enough to impact prices, then the clearing-price auction has two wonderful properties. The first is short-run efficiency. The dispatch of generation throughout the day is efficient—the electricity is generated at least-cost to the system, since all generation is supplied by the producers with the lowest cost. The second is long-run efficiency. The single clearing-price auction motivates efficient investment in new generation. This investment result is more subtle and often difficult to achieve in practice, leading many electricity systems to add a long-term capacity market (also based on the single clearing-price auction), which further coordinates new investment and more directly motivates the right quantity and quality of system resources.

The only debate about the single clearing-price auction rests on the qualifier, "if the market is competitive." No real market is perfectly competitive. The largest buyers and sellers are inevitably in a position to impact price at least to some degree. This makes the efficiency of the single clearing-price auction only approximately true in practice, and invites the question of whether there may be a better approach that somehow addresses market power more effectively. The basic issue is that in the single clearing-price auction large participants may at times have an incentive to distort their bids and offers away from their true preferences. These distortions may adversely impact the short-run efficiency of the system.

My considered view is that consumers and suppliers are much better off with the single clearing-price auction than with any other alternative. System operators have many methods to mitigate market power problems. These include rules against physical withholding, offer caps, automatic mitigation of bids in particular circumstances, and *ex post* review of behavior by an independent market monitor. Perhaps the most effective instruments come from the related forward energy markets and capacity markets. These medium-term and long-term markets often put suppliers in a nearly balanced position entering the spot market. A supplier in a balanced position—that is, who has energy commitments roughly equal to its efficient dispatch—has the incentive to offer its resources (at the margin) at marginal cost.

The main argument against a single clearing-price auction is political, not economic. When electricity prices are high as a result of the high cost of the marginal fuel (*e.g.*, natural gas), critics point to the disparity between the electricity clearing price and the marginal cost of generators using less expensive fuel (*e.g.*, nuclear). What they fail to appreciate is that these higher profits of the low-cost generators are needed to cover the much higher fixed-costs of these resources that use less expensive fuel, such as hydro, nuclear, solar and wind. In addition, the higher spot price motivates the demand side to conserve.

A recent U.S. Court of Appeals for the District of Columbia Circuit ruling underscores these benefits (http://pacer.cadc.uscourts.gov/docs/common/opinions/200901/07-1130-1160521.pdf):

> "[T]he high returns earned by low-cost generators charging market rates provide an incentive for the development of new generation facilities as well as increased efficiency on the part of existing generators. Furthermore, higher prices are likely to affect consumers' behavior, reducing the strain on the system created by high demand."

> "At the same time that they reflect existing scarcity, these high rates also serve a critical signaling function: encouraging new development that will increase supply."

It is a pleasure to recommend Ross Baldick's *Single Clearing Price in Electricity Markets*. His paper provides an elegant and more comprehensive treatment of the issues I raise above. This paper is required reading for anyone seeking a policy debate over the single clearing-price market.

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# EXECUTIVE SUMMARY

In every market, including all commodity markets, there is a natural tendency for trading to occur at a single market-clearing price. This is called "the law of one price" and there are several examples that illustrate this law. Moreover, in some markets, such as stock exchanges, there are explicit mechanisms that seek the market-clearing price and use this as the single price for trade.

In organized electricity markets, energy is sold at a single price, namely the market-clearing price. Putting aside demand bids and transmission constraints for simplicity, the market-clearing price is the offer price of the highest accepted offer in the market. This paper discusses the reasons for a single price rule in electricity markets and its advantages over alternatives such as "pay-as-bid."

The primary reason for using the market-clearing price to set the single price in electricity markets is the incentives it provides for efficient dispatch and optimal investment. In a competitive market, generators will offer energy at prices closely reflecting their "marginal costs," which results in operationally efficient dispatch, and, with sufficiently liquid forward markets, optimal investment will take place in expectation going forward. Efficient dispatch means that demand is served by resources whose total fuel bill is the lowest possible, an important public policy goal. Optimal investment means that the right generation technologies are built in the right places at the right times, with the investment risks borne by merchant investors rather than by ratepayers.

That is, there are compelling reasons for using the single market-clearing price in electricity markets. The reasons build on the fundamental requirement in electricity for centralized coordination. This requirement is due to the lack of stockpiles of electricity, the variation of demand for electricity throughout the day, and the varying production costs of generators.

Despite the compelling reasons for using the single market-clearing price for electricity, alternative pricing rules are sometimes proposed. One such alternative proposal is "pay-as-bid," where each accepted offer is paid its offer price. However, there is no empirical or experimental evidence that pay-as-bid or other alternatives would reduce prices significantly compared to a single market-clearing price design. In fact, some evidence suggests that pay-as-bid would increase prices compared to explicitly setting the single market-clearing price. Moreover, pay-as-bid has some significant drawbacks.

Another proposed alternative would apparently do away with the process that is used to determine the single market-clearing price. Such proposals fail to carefully consider the essential role of centralized coordination in electricity and do not provide a viable alternative. Centralized coordination without a single market-clearing price market would abandon the efficiency advantages of this market design.

# 1. ELECTRICITY MARKET AUCTIONS

Subsequent to the Federal Energy Regulatory Commission's Order No. 888 in 1996, the electricity industry in the United States has undergone significant changes. An underlying goal of electricity industry restructuring has been to harness competition to reduce both short- and long-term costs, to better allocate risks and rewards, and to encourage technological innovation. The last decade has seen a deepening of electricity industry restructuring in some regions as well as an increase in fuel and construction costs. However, rising electricity prices have prompted concerns about electricity restructuring and re-opened debates about restructuring.

## 1.1 The single market-clearing price rule

An issue that is often discussed in connection with electricity markets is the "pricing rule" for electricity in the organized markets of the Northeast, Midwest, the Electric Reliability Council of Texas (ERCOT), and California. The various energy- and capacity-related products in these markets are typically traded through a daily (or day-ahead) or shorter-term auction process where the pricing rule is to set a uniform price in each market. Even though there may be several offers and bids at various prices for any given hour, all energy is sold at one single price, called the market-clearing price. Similarly, each of the other products besides energy is also sold at a single price.

Generally speaking, the market-clearing price is the offer price of the highest accepted offer. For example, consider a simple electricity system with baseload coal generators having low production costs of approximately $25/MWh, and gas-fired peakers having higher production costs of approximately $100/MWh. Off-peak, when demand is lower, only the coal generators may be necessary to meet demand. The market-clearing price for energy is set by the coal offer price, which can be expected to be around $25/MWh. However, on-peak, when demand is higher, both the coal and the gas-fired generation may be required to meet demand and the market-clearing price will be set by the offer of the gas-fired generation, which can be expected to be around $100/MWh. On-peak, both the coal and the gas-fired generation receive the market-clearing price. The difference between the market-clearing price on-peak and the production costs of coal enable the capital-intensive coal generator to cover at least some of its capital cost.

An auction is used as the coordination mechanism for finding the generators with the lowest production costs to meet consumer demand in an electricity market. The large geographic markets overseen by independent system operators (ISOs) and regional transmission organizations (RTOs) allow the coordination of generators owned by multiple companies across areas that are much larger than the historical service areas of traditional vertically integrated utilities. The larger areas mean that opportunities to use lower production cost generation can, in principle, be better coordinated.

This auction that is used in electricity markets is often called "offer-based economic dispatch" and is used to choose the generators with the lowest offers to meet demand, so demand is met by resources with the lowest possible total fuel bill. Minimizing the total fuel bill is an important public policy goal and an explicit design feature of offer-based economic dispatch. Demand bids can also participate in such an auction process and provide important price "elasticity" that helps inform generation investment decisions and mitigates the potential exercise of market power.

# 1.2 Benefits of the single clearing price design

The application of the single market-clearing price rule to electricity markets has a number of benefits. The principal benefit, and a benefit that is shared by all markets, is that the market-clearing price has a very important property under the assumption that the offer prices reflect the sellers' valuations, as represented by their production costs, and the bid prices reflect the buyers' valuations. Consider all the possible choices of transfers of commodity from a selection of the sellers to a selection of the buyers. Among all these choices, if we choose to transfer the commodity only from the sellers having valuation at or below the market-clearing price to the buyers having valuation at or above the market-clearing price, then we will have chosen the transfer that maximizes the gains from trade.

If offers and bids reflect valuations, then sellers with valuation less than or equal to the market-clearing price will be happy to sell and buyers with valuation greater than or equal to the market-clearing price will be happy to buy at the market-clearing price. Offers will reflect valuations when there is sufficient competition. Under these circumstances, the transfer of commodity by the willing traders will have resulted in the greatest gains from trade. As mentioned previously, in the context of electric generation, this means that the total fuel bill to meet demand is minimized. By definition, it is desirable to derive a market-clearing price since this price aligns the actions of the sellers and buyers with maximizing the gains from trade.

By definition, supply and demand are equal, or balanced, at the market-clearing price. When demand and supply balance, the market is said to "clear." Therefore, a market clears at the market-clearing price. Although market-clearing prices do not always exist, and there are some technical issues that have not been included in this introduction, such as the cases where a range of market-clearing prices exists or where transmission is limited, the above discussion shows that the formation of a market-clearing price can facilitate the trading that results in the greatest gains from trade.

# 1.3 Centralized coordination

Unlike other commodities, electricity cannot be stockpiled. Electrical energy must be produced at essentially the same time as it is consumed. Demand for electricity varies markedly throughout the day, requiring the production of electricity to ramp up and down to follow varying demand. These special properties of electricity make it essential to centrally coordinate supply to meet demand.

There are significant economic implications of the lack of stockpiles, the variation of demand, and the variation of production costs. Understanding these economic implications requires a consideration of total production costs, average production costs, and marginal costs. "Total production costs" of an electric generator means the cost of the fuel consumed (and the cost of any other operational costs incurred) per hour at a given level of production in megawatts (MW). The total production costs are measured in $/h. The "average production costs" are the total costs in $/h divided by the production in MW, and are therefore measured in $/MWh. The average production costs are the average of the total costs over the total production in MW. The "marginal costs" are the calculus derivative of the total production costs, and are also measured in $/MWh.

Various fuels have differing costs, differing generation technologies have differing efficiencies, and, for a given generator, those efficiencies can vary with the amount of power being produced by the generator. Because of variation in fuel costs and variation in efficiency, the marginal costs of generators vary significantly, from below $25/MWh to above $100/MWh in 2008 dollars. Therefore, generation costs vary markedly.

If a generator with a marginal cost of $100/MWh is used to produce electricity when a generator with marginal cost of $25/MWh is available, then there would be an avoidable waste of $75/MWh. The "dispatch," or choice of generation, would be inefficient, where "inefficient" means that there was an avoidable waste of resources. In this example, for each hour and for each megawatt of such inefficient dispatch, $75 would be unnecessarily wasted, meaning that the total fuel bill would be $75 higher than necessary.

In North America, there are approximately 1 million megawatts of generation capacity. To see the scale and importance of using the lowest production cost generators whenever possible, suppose that just 1 percent of the generation capacity were to be inefficiently dispatched in the manner described above for a year, consisting of 8,760 hours. This would involve a waste of approximately $6 billion per year. That is, the total fuel bill would be $6 billion higher than under efficient dispatch. Although this is a small fraction of the total retail bill for electricity, the magnitude of this amount clearly indicates that efficiency of dispatch is desirable in the electricity sector.

The variation of generator production costs interacts with the lack of stockpiles. In particular, as discussed above, because of the need to match supply and demand, a centralized process is necessary in electricity. To avoid inefficient dispatch, it is therefore necessary to coordinate generation, not only to meet demand, but also to make sure that lower production cost generators are used whenever possible in preference to higher production cost generators. The auction process of offer-based economic dispatch and the single clearing price rule aligns the incentives of generators and consumers with achieving efficient dispatch.

Recently, there have been proposals to abandon the centralized single market-clearing price auction. See, for example, Showalter (undated). However, even in the absence of this centralized auction, there would still be a need for centralized coordination. A serious drawback of abandoning the auction is that the still necessary coordination would then not achieve the goal of using the lowest production cost generation to meet demand. In contrast, by design, a single market-clearing price auction aligns the profit-seeking incentives of the generators with achieving low-cost efficient dispatch that minimizes the total fuel bill. Furthermore, by making transparent prices available based on offers, effective market monitoring can also be carried out and generation investment decisions can be better informed.

## 1.4 Real-time, day-ahead, and futures markets

In electricity, the spot market is called the "real-time" market or the "balancing" market since it balances supply and demand in real-time. Analogous to other commodity markets, there are also forward contracts for electricity that allow market participants to lock in prices in advance of the spot market. As with forward markets in other commodities, the day-ahead market helps to hedge against spot market volatility and the day-ahead prices reflect expectations about the spot, or real-time, prices.

Longer-term forward contracts set forward commitments over longer durations and further into the future. In addition to the centralized day-ahead forward market, it is possible to trade forward and futures contracts for electricity in exchanges and over the counter. That is, there are various opportunities to hedge against volatility.

A buyer and seller are free to ignore the day-ahead and real-time electricity prices in setting their forward contract prices if they choose to do so. However, as with trade in other commodities, longer-term bilateral prices will typically be based on expectations. In the case of electricity, these expectations are of day-ahead and real-time prices. Even if most market participants are hedged via longer-term contracts against exposure to day-ahead and real-time market prices, the day-ahead and real-time prices have an important role, since expectations of day-ahead and real-time prices will help determine forward contract prices. That is, the single market-clearing prices in the day-ahead and real-time markets provide a price formation “marker” for the price negotiations in bilateral contracts. These prices also provide signals for investment, as will be discussed in the next section.

## 1.5 Incentives for operation and investment

By explicit design, the pricing rule in offer-based economic dispatch results in many generators being paid more than their offer. These result in “inframarginal” returns, since the offer price is below the “marginal” offer that sets the market-clearing price. Whenever a generator is paid more than its offer, it is making an operating profit, which contributes to paying down the debt or other obligation incurred by the owner to purchase the generator. Generators have strong incentives to keep production costs low because their operating profit depends on the difference between the market-clearing price and their production costs. Moreover, without such inframarginal returns, generators would become bankrupt and no new investment would take place.

There is nothing wrong with inframarginal payments and inframarginal returns are not indicative of excess profits or adequate profits. In fact, a generator could be receiving inframarginal payments and still not cover its debt. If it received only enough revenue to cover its operating costs, it would not be able to pay down any of its debt.

On the other hand, if prices are high enough to support new investment, and forward contract prices suggest that prices will continue to be high enough to support new investment, it is likely that new investment will occur. That is, forward contracts can help with investment decisions by providing information about future needs for generation and also by providing collateral that can be used to help finance development.

## 1.6 Incentives for demand

By similar arguments to the case for generators, the single market-clearing price provides energy to demand at a price that is, by definition, less than the value of consuming that energy. Moreover, by exposing demand to the cost of producing its energy, correct incentives are provided for demand response.

# 2. THE LAW OF ONE PRICE AND SINGLE CLEARING PRICES IN MARKETS

The single price rule described in the last section may seem unfamiliar and unintuitive. In this section, I will discuss the idea of single price in markets besides electricity markets and give some examples of how a single price for all trade is commonplace in typical markets.

## 2.1 Price at a supermarket

Consider items for sale at a supermarket. Typically, a price per item or a price per unit weight is posted by the store. To be concrete, consider a particular variety of orange that is for sale. Oranges are usually sold by weight and the store posts a price per unit weight. There is a single price per unit weight for all oranges sold in the store at any given time, and, typically, that price is constant throughout any given day. Of course, different products sell at different prices, but identical products sell at similar or identical prices. Similarly, gasoline prices at a gas station will be the same for all gas of a particular octane rating at any given time, and, typically, constant throughout any given day.

## 2.2 Prices at several linked markets

Now consider sales of oranges at several nearby supermarkets. Although the prices for oranges may not be exactly the same at the different supermarkets and will change over time, we would expect that at any given time the prices would be similar at all supermarkets. That is, even though there are various sellers of oranges, the prices on any given day at the various stores will track each other. Similarly, prices at various gas stations in a neighborhood tend to track each other.

One reason that the prices tend to track is that the existence of a large disparity between prices would tend to cause customers to shift from a higher priced store to a lower priced store, which would in turn tend to encourage the respective shopkeepers to adjust their prices in a way that brought the prices back together. This observation was first formalized in the eighteenth century by W. Stanley Jevons and is called the “law of one price”: in the same market at any time, there is only one price for a single type of commodity or item (Jevons, 1879).

## 2.3 Prices to producers

The observations in the last section are familiar to consumers. Analogous observations hold for producers. For example, all producers of oranges in a particular region will receive a similar price for their oranges, despite individual variation in the cost of production of oranges at particular farms.

More generally, similar observations apply to all commodities, such as oil, metals, and grains. In each commodity, the price tends to be roughly uniform throughout the world despite regional variation in the cost of production, putting aside transportation costs. For example, a particular grade of oil and its close substitutes tend to trade at the same price all over the world. As another example, the price set for metals such as aluminum on the London Metal Exchange are adopted by other traders to set their prices, despite variation in the cost of production of aluminum in various parts of the world. That is, each producer of aluminum will receive approximately the same price for its production at a particular time based on the current price of aluminum. When market prices dip below production costs, an aluminum producer will stop producing, at least temporarily. Moreover, the producer has strong incentives to keep production costs low because its operating profit depends on the difference between the market price and its production costs.

To summarize, any particular commodity may be produced in a number of locations having different production costs. Nevertheless, despite the variation in production costs, all commodity trading in markets worldwide will be at approximately the same price on any given day, despite the variation in the specific production costs. This is the law of one price in action and applies despite the variations in the cost of production of, for example, aluminum throughout the world. Similar observations apply to every commodity, including other metals, oil, and commodity food grains. It is a tendency of market prices to track each other when the marketplaces are linked.

Moreover, prices for all sales of each particular commodity are the same at any given time despite variations in the cost of production, providing incentives for all producers to reduce their production costs. Similarly to the discussion in the context of electricity, the market-clearing price will result in the production and use of the commodity that results in the greatest gains from trade.

As suggested by the examples above, the law of one price does not exactly apply when there are multiple marketplaces—multiple supermarkets, multiple gasoline stations, or multiple commodity exchanges—because of transportation costs between the marketplaces and because of other issues that may divide the overall market into separated or only partially connected sub-markets. However, it is a tendency of market prices to track each other when the marketplaces are linked. Moreover, prices for all sales of each particular commodity are similar or the same at any given time despite variations in the cost of production.

## 2.3 Summary

In this section, several examples show that a single price is typical in most markets for all trade at a given time. This single market-clearing price arises by the natural behavior of market participants and occurs despite underlying variations among sellers in the cost to produce the traded good. Even though there may be no explicit centralized mechanism to set the price, prices in typical markets will approximate the market-clearing price, despite variations in production cost amongst producers.

# 3. MARKETS WITH AN EXPLICIT SINGLE PRICE RULE

The previous section showed how all markets have a natural tendency to trade at a single price, the market-clearing price. This section considers several marketplaces where a central entity explicitly sets a single market-clearing price for all sales, despite there being offers and bids at various prices.

## 3.1 Opening and closing prices on stock exchanges

Opening and closing prices in stock exchanges are typically found (and trades consummated) on the basis of a "periodic call auction" where bids and offers are accumulated by the "auctioneer." At a particular time or times, the market-clearing price for the accumulated offers and bids is determined, and the appropriate trades are consummated at the market-clearing price. This type of auction is called a "double-sided" periodic call auction since there are both offers and bids and the market-clearing price is based on the highest consummated offer price or the lowest consummated bid price. Since all trade is consummated at one price, it is a single price auction. That is, a single market-clearing price is found that will be at or above the prices of all consummated offers to sell and will be at or below the prices of all consummated bids to buy.

For example, opening and closing prices at the New York Stock Exchange are found by the exchange acting as auctioneer. For the opening price, offers and bids are accumulated overnight after the close of trading from the previous day. Although all shares of a particular share class in a single company are alike, there can be various estimates of the value of a share based on various estimates of the future performance of the company, resulting in differing offer prices and differing bid prices for the shares. A call auction uses the offers and bids to determine the opening price and consummated trades. All consummated trades are made at the single opening price, which is the market-clearing price. For the closing price, offers and bids that have not been consummated by the end of the day are batched together to find a closing price and to consummate corresponding trades, again at the single market-clearing price specified by the closing price.

As well as the New York Stock Exchange, the following is a non-exhaustive list of stock exchanges that also use call auctions to determine the opening and closing prices:

- Australian Securities Exchange, (Australian Securities Exchange, 2008),
- Deutsche Börse, (Deutsche Börse, 2008),
- Euronext Amsterdam N.V., Euronext Brussels S.A./N.V., Euronext Lisbon S.A., and Euronext Paris S.A, (Euronext, 2008, pages 12-13).

In addition, a few of the stocks on the Warsaw Stock Exchange (about 5 out of 371) trade exclusively under a single price auction that is conducted twice per day, (Warsaw Stock Exchange, 2008).

Single market-clearing prices are determined as part of a double-sided auction process for the opening and closing prices at many stock exchanges. Even though offer prices may be below and bid prices may be above the single price, all trade is consummated at the single price determined by the opening and closing price auctions. The single price is the market-clearing price for the offers and bids that are considered in the auction.

## 3.2 U.S. Treasury Securities

The U.S. Treasury conducts auctions to sell some types of securities. In these auctions, the U.S. Treasury is the single seller and there are multiple buyers who submit bids. The bid consists of a maximum quantity of securities (in dollars) and a rate or yield, depending on the security. The bids are ordered according to bid rate or yield from lowest to highest, until the total bid quantity equals the quantity of securities being auctioned.

The U.S. Treasury uses a single price auction for all Treasury Bills, Notes, Bonds, and Inflation-Protected Securities (U.S. Department of the Treasury, 2008a and b) and has done so since about 1998 (Kremer and Nyborg, 2004). Despite various valuations by the bidders, the winning bids all pay the market-clearing price, as specified by the bid rate or yield of the highest accepted bid. Some index-linked bonds in the United Kingdom are also sold in a single price auction (Binmore and Swierzbinski, 2000). Appendix B.3 discusses empirical results comparing single price and pay-as-bid auctions for U.S. Treasury Securities.

## 3.3 Regional Greenhouse Gas Initiative

The Regional Greenhouse Gas Initiative (RGGI) involves 10 Northeast and Mid-Atlantic states (Regional Greenhouse Gas Initiative, 2008a). They have agreed to a regional cap-and-trade program for greenhouse gases, with a proposal for auctioning an annual regional emissions allocation. The first auction was held in September 2008 and this and subsequent auctions are single price auctions, with all trade at the market-clearing price (Regional Greenhouse Gas Initiative, 2008b).

## 3.4 Summary

A single price rule is explicitly used in a number of important markets, most notably to set the opening and closing prices at stock exchanges. In such markets, the explicit pricing rule is to set the price for all consummated trades equal to the market-clearing price.

# 4. SINGLE PRICE RULE VERSUS PAY-AS-BID RULE

Despite the important advantages of using a single price rule, alternative pricing rules have been considered, responding to concerns about unfamiliarity with uniform prices, market power, transfers from consumers to generation asset owners, and volatile prices. (These issues are discussed in detail in Appendix A.) One alternative proposed rule is a "pay-as-bid" market, where each unit of production that is sold is paid its offer price.

The basic hope of pay-as-bid proposals is that prices will be, on average, significantly lower than in a single market-clearing price market. A fundamental observation, however, is that a change in the pricing rule from single market-clearing price to pay-as-bid would result in a change in the offers submitted to the market. From a theoretical viewpoint, the change in behavior will offset and counteract the change in rules, resulting in prices under pay-as-bid that, under idealized conditions, are all very close to the market-clearing price. From a practical perspective, there is no empirical or experimental evidence that pay-as-bid would reduce prices significantly compared to single clearing price. In fact, some evidence suggests that pay-as-bid would increase prices compared to single clearing price. As discussed further in Appendices B and C, the theoretical, experimental, and empirical evidence does not support a change to pay-as-bid.

There are also a number of very serious drawbacks to pay-as-bid, including: inefficient dispatch; difficulty of participation for small, competitive asset owners; the reduced ability of demand response to mitigate market power; and difficulties for market monitoring. These drawbacks are described in detail in Appendix D. Given the lack of compelling reasons for pay-as-bid pricing and its significant drawbacks, consumers are best served if electricity markets retain the single price rule that is standard in organized markets in the United States. Claims that pay-as-bid might improve the performance of electricity markets are unsupported.

# 5. CONCLUSION

Given the substantial benefits of the single market-clearing price rule in offer-based economic dispatch and given the lack of compelling alternatives, electricity markets should maintain the single price rule that is standard in organized markets in the United States. There is no support for claims that introducing pay-as-bid pricing or otherwise eliminating the single clearing-price auction would improve the performance of electricity markets. The nature of electricity requires coordination of supply and demand. The single market-clearing price auction is the efficient way to enable this coordination and should be maintained.

# APPENDICES

## A. Principal criticisms of single clearing price

Sections 1 through 5 of this paper describe the inter-locking, coherent, and mutually supporting incentives in the short- and the long-term of using the single, market-clearing price for electricity. The technological necessity of centralized coordination is implemented in an electricity market through offer-based economic dispatch that determines the market-clearing price. In the absence of market power, the market-clearing price provides the incentives for generators to serve demand at the least total cost of fuel. Expectations of forward prices provide incentives for new investment.

Nevertheless, prices in the electricity industry have been increasing in the last few years and this has prompted calls for changing market rules and design. In this appendix, we consider four principal criticisms of using the market-clearing price to set a single price: unfamiliarity with using a single price in Appendix A.1; market power in Appendix A.2; excessive payments to generators in Appendix A.3; and volatility in Appendix A.4.

## A.1 Unfamiliarity of a centralized single price setting mechanism

As discussed at length in Sections 2 and 3, single clearing prices are, in fact, familiar in various markets, including all commodity markets. Moreover, there are examples, such as opening prices at stock exchanges, U.S. Treasury auctions, and the Regional Greenhouse Gas Initiative auction, of centralized auctions that explicitly set a single market-clearing price. Furthermore, there is a fundamental need for centralized coordination of supply and demand in electricity because of its unique properties. An auction is used in organized electricity markets to coordinate efficient production.

However, various critiques of using single price in electricity markets include references to the supposed unfamiliarity or uniqueness of this process. For example, according to the Electricity Consumers Resource Council, "[n]o other commodity is traded in such a pool or exchange" (ELCON, 2002). This type of argument, though literally true, is disingenuous since it ignores the necessity of centralized coordination in electricity, ignores the existence of analogous centralized markets in shares and financial instruments, and ignores the law of one price in all markets. Single, market-clearing prices arise wherever multiple sellers and buyers interact.

## A.2 Market power

The potential exercise of market power remains a concern in electricity markets. However, as will be discussed further in Appendices B and C, if market power is a concern in a single clearing price market then it would also be a concern under alternative market designs such as a pay-as-bid market. That is, a change from single market-clearing price does not prevent the exercise of market power.

Moreover, there are a number of measures available to mitigate market power in electricity markets. Some of these measures will be discussed in Appendix D. All of these mechanisms build on and are completely consistent with a single market-clearing price rule. None of them involve changing the underlying single market-clearing price based on the results of an auction. Concerns about possible market power should prompt further development of these approaches to market power mitigation, not abandonment of the single market-clearing price. Furthermore, as will be discussed in Appendix D, abandoning the single market-clearing price auction would tend to defeat several of these market power mitigation measures.

## A.3 Excessive payments to generators

Since market-clearing prices in restructured markets may be set by the offers of gas units that have been relatively expensive in recent years, there has been criticism of the level of payment to baseload resources such as coal. As discussed in Section 1.5, the fact that an offer is inframarginal is, in itself, not evidence of excessive payments to generators.

However, recent increases in spot prices and forward prices have been of concern to market participants. For example, the Electricity Consumers Resource Council claims that "the requirement that all successful bidders receive the `clearing' price is extremely lucrative to suppliers at the expense of consumers" (ELCON, 2002), and observes that "[c]onsumers no longer benefit from the lower marginal costs of coal-fired or nuclear generation because LMPs with no inter-fuel competition or Demand Response routinely exceed the short-run marginal costs of these generators" (ELCON, 2005). The American Public Power Association highlights "substantially higher power prices in long-term bilateral markets, prices that seem to bear little relationship to sellers' actual costs" (APPA, 2004, page 4).

The operating profits of baseload resources may indeed currently meet the bare minimum to provide an acceptable rate of return for new investment, considering the risks involved with development of generation assets. However, it is precisely such higher operating profits to particular types of assets that signal and prompt the need for new investment, eventually eroding the returns to such generation and reducing the market clearing prices. Emerging evidence in Northeast U.S. markets shows that temporary higher prices have brought forth new capacity, which has helped to then moderate prices (Pfeifenberger, *et al.*, 2008, figure 3).

The criticism of excessive payments is particularly directed at current owners of older, baseload assets whose construction costs were lower than current new construction costs. That is, despite expectations in the 1990s at the time of FERC Order 888, these older, baseload assets are currently producing relatively high operating profits. Many of these assets were sold in the last decade. Investors in those assets took on risks that the assets might be less or might be more profitable, moving the risk from "ratepayers," who traditionally shouldered investment risk, to investors. Changes in market rules aimed at reducing the operating profitability of these assets would be unfair. Moreover, it would signal to all investors in generation assets that they would only be exposed to downside risks and would be denied opportunities for upside profits. This would chill investment in the electricity industry.

Moreover, while older, baseload assets have proven to have relatively higher operating profits than expected, newer combined cycle units have been far less profitable than expected, in part because of rising gas prices. A fair assessment of electricity prices must consider both the higher operating profits of older generating units and the lower operating profits of newer units. Finally, it must be repeated that the current market prices and resulting operating profits provide the right relative incentives: relatively more new baseload generating assets are being proposed and relatively less gas generation is being proposed.

## A.4 Volatility

Volatility is the variability of prices. Since marginal costs vary considerably between generators, and since demand varies considerably, it is completely appropriate that market clearing prices vary to reflect this variability.

Sometimes, however, prices in electricity markets become extremely high for short durations, particularly when supply is tight. Two issues can drive this:

- Scarcity, and
- Market power.

In the former case, when supply is tight, interpreting price-insensitive demand as a bid with a very high bid price is instructive. In a double-sided auction, when not all demand is met, the demand bid prices set the market-clearing price. That is, when supply is tight, prices are appropriately set by high (implicit) bid prices of demand. Forward contracts, by design, remove this exposure to volatility. However, a legitimate concern is that in the absence of actual demand bids, prices may possibly be forced even higher by generator market power. Again, as will be discussed further in Appendices B and C, if such market power is a concern in a single market-clearing price auction it will also be of concern in alternative market designs.

# A.5 Summary

Unfamiliarity, market power, excessive payments to generators, and volatility are four principal criticisms leveled at single market-clearing price markets. In fact, the notion of a single market-clearing price is universal in markets and there are several examples of markets that by explicit design seek the single market-clearing price. That is, unfamiliarity is not a valid criticism of using a single market-clearing price in electricity markets.

In the case of market power, there are specific remedies for market power that are consistent with the single, market-clearing price rule. In the case of purported excessive payments to generators, market-clearing prices are currently providing only barely sufficient payments to bring forth new generation and therefore could not be excessive from that perspective. Forward contracts reduce exposure to volatility.

# B. Detailed comparison of prices under single clearing price and pay-as-bid

In this Appendix, we consider an alternative pricing rule to the single market-clearing price. In particular, we consider a pay-as-bid market. In a typical proposal for such a market, each offer by a generator into the market that is dispatched is paid the price that it offers, instead of being paid the market-clearing price. (Therefore, the pricing rule would be more appropriately called "pay-as-offered.")

The payment by demand is not completely standardized in such proposals, but typically involves the demand paying a price that equals the generation-weighted average of the prices paid to generators. Using the generation-weighted average price ensures that the total payment by demand equals the total paid to generators.

The pay-as-bid mechanism is typically put forward as a means to mitigate market power in electricity markets, reduce the payments to generators, particularly baseload generators such as nuclear and coal plants, and reduce volatility. That is, pay-as-bid is typically couched as a response to the criticisms identified in Appendices A.2, A.3, and A.4, and occasionally put forward as a "remedy" to the specious criticism identified in section A.1. In particular, under the assumption that the generator offers were to remain approximately the same despite the change in the pricing rule, then pay-as-bid would reduce prices paid to generators and overturn the law of one price. As observed by many commentators, however, the assumption that generator offers would remain the same is extremely naïve (Kahn *et al.* 2001, Stoft, 2002, Tierney *et al.*, 2008). For example, as (Kahn *et al.* 2001) put it:

> "The critical assumption is, of course, that after the market rules are changed, generators will bid just as they had before. *The one absolute certainty, however, is that they will not.*"

To summarize, the naïve expectation that pay-as-bid would change prices dramatically fails to recognize that offers and bids are formed by active market participants who are aware of the pricing rule. For example, suppose we consider a very small market participant making a "short-lived" offer that applies for a single dispatch interval with certain demand. We first consider the offer by this market participant under the single, market-clearing price rule. Under a single price rule, if the market participant does not have market power then it can maximize its profits by offering at marginal cost, since it will be paid the market-clearing price and maximize its operating profit by being dispatched whenever its marginal cost is no greater than the market-clearing price.

We now consider the profit maximizing actions of the same market participant in a pay-as-bid market, assuming, for concreteness, that the offers of other market participants remain the same. We first observe that there is still a well-defined market-clearing price. However, in the pay-as-bid market, instead of all market participants receiving the market-clearing price for energy that they sell, they receive their offer price.

In a pay-as-bid auction, the small market participant can obtain the same payment as it would have received under single price, so long as it is able to predict the market-clearing price. In the pay-as-bid auction, in order to maximize profits, the small market participant must predict the market-clearing price and then offer at that price. Notice that the net payment to the small market participant would be the same in both the single price and the pay-as-bid auctions. That is, the change in offer behavior by the small market participant has exactly counteracted the change in rules and has defeated the goal of reducing the payment, under the assumption that the small participant can predict the market clearing price.

Despite the particular conclusion for a small market participant making a short-lived offer, the change in the pricing rule could affect payments in more general settings with market power, albeit by less than the naïve hope. We will consider a number of approaches to estimating the change in prices resulting from a change in the pricing rule. These will include auction theory, experimental economics, and empirical analysis.

In auction theory, a well-known result called the "revenue equivalence theorem" describes several alternative auction rules that all result in the same prices paid in the auction, using analogous arguments to the one above in the example of the small market participant. The basic results most relevant to comparing pay-as-bid and single price markets are summarized in Appendix B.1, with a more detailed review in Appendix C.

Since the theoretical results from auction theory are not completely dispositive of the comparison between pay-as-bid and single price markets, I will then turn to the experimental economics literature in Appendix B.2 and the limited empirical results in Appendix B.3. Appendix B.4 summarizes the results. The overall conclusion is that there is unlikely to be any major reduction in prices through changing from a single price market to a pay-as-bid market, even under assumptions that are sympathetic to a pay-as-bid market. In fact, prices might increase under pay-as-bid.

# B.1 Theoretical results

There have been a number of papers aimed at comparing models of single price and pay-as-bid in the specific context of electricity markets. It is important to understand, however, that all of the models abstract from the full complexity of electricity market rules. Since some of the conclusions rest on particular assumptions that may or may not be met in reality, this tends to weaken any sweeping conclusions in the comparisons. A number of such papers are reviewed in Appendix C.

Overall, the specific analysis that is relevant to electricity markets in the presence of market power finds that revenue equivalence does not hold in many cases, with lower prices under pay-as-bid than under a single market-clearing price. Moreover, volatility may be lower under pay-as-bid. However, in the presence of a requirement for long-lived offers, such as fixed offers throughout all hours of a day, differences between single price and pay-as-bid are attenuated or disappear.

In many cases, the theoretical comparisons that suggest pay-as-bid might result in lower prices depend critically on model assumptions and on the plausibility of market participants making offers in pay-as-bid markets that are *random*. Such assumptions and behavioral models are possibly unrealistic and, in any case, require a level of sophistication on the part of asset owners that is unlikely to be possessed by small competitive companies. The implications of this observation for new entry by small market participants will be discussed in Appendix D.

# B.2 Experimental economics results

As discussed in Appendix B.1, theoretical analysis tends to simplify and approximate the underlying complexity of electricity markets. Consequently, theoretical conclusions may depend on crucial simplifying assumptions. In "experimental economics," human subjects are asked to simulate the profit maximizing behavior of firms, typically in a computer-based simulation of the market setting. Considerable institutional detail can be included in the simulation of the market setting.

For example, Mount *et al.*, (2001) ran a series of experiments comparing pay-as-bid to single price auctions. They also assessed a hybrid that involves paying either:

- the market clearing price if the market clearing price is less than a “soft cap,” and
- paying the maximum of the soft cap and a firm’s offer if the market clearing price is above the soft cap.

The hybrid mimicked a design imposed on the California real-time market for a few months in 2001. The pay-as-bid auction resulted in *higher* prices than the single price auction. The hybrid auction performed similarly to the pay-as-bid auction, again resulting in higher prices than the single price auction.

In another study, Rassenti, Smith, and Wilson (2003) compared single price and pay-as-bid. Their conclusion was that prices were *higher* under pay-as-bid, while volatility was lower.

To summarize, the experimental evidence points to higher prices in pay-as-bid compared to single clearing price markets. A change to pay-as-bid is not supported by the experimental economics literature.

# B.3 Empirical results

In this Appendix, the limited empirical results regarding single price and pay-as-bid auctions will be reviewed. The salient examples are:
- The California real-time market in 2001,
- The changes in the England and Wales market, and
- United States Treasury auctions.

As mentioned in the previous section, the California real-time market briefly had a hybrid market that included elements of pay-as-bid, replacing the previous single price auction. The results of the change did not improve the performance of the market (Mount *et al.*, 2001).

From 1990 until March 2001, the England and Wales electricity market involved day-ahead offers that were economically dispatched to set single, market clearing prices in each of 48 half-hour periods. That is, offers were “long-lived.” In March 2001, the market was significantly changed. Bilateral scheduling took the place of the day-ahead offers, a real-time market was established with “short-lived” offers, and pay-as-bid pricing was used in the real-time market (Federico and Rahman, 2003). Furthermore, there had been two rounds of divestitures in 1996 and 1999 that had affected the market concentration in the England and Wales market (Baldick, Grant, and Kahn, 2004). Any or all of these changes can be expected to have had some effect on prices.

The confounding effect of many simultaneous and near-simultaneous changes in the rules and structure of the England and Wales electricity market make it difficult to assess the effect on prices, if any, of the change from single price to pay-as-bid. For example, Fabra, von der Fehr, and Harbord (2006, section 1) describe the range of conclusions in the literature about the relative importance of the various changes in the England and Wales market on the observed changes in prices. Given the confounding issues, it is not possible to discern what specific change in prices, if any, was due to the change from single price to pay-as-bid.

Prior to 1998, The United States Treasury had mostly used a pay-as-bid auction but had experimented with uniform price auctions at various times (Binmore and Swierzbinski, 2000). Several comparisons of auctions from the 1970s onwards show mixed results with no definite advantage of either pay-as-bid or single price for Treasury auctions (Binmore and Swierzbinski, 2000, section 4).

To summarize, the limited empirical evidence comparing pay-as-bid to single price auctions confirms that there are no significant differences in prices between the two. As discussed previously, changes in behavior largely counteracted the change in rules.

## B.4 Summary

From the theoretical, experimental economics, and empirical evidence that is available, the difference in average prices between pay-as-bid and single clearing price markets are relatively small, with pay-as-bid sometimes resulting in similar average prices to single price markets, sometimes higher, and sometimes lower. In the specific context of electricity markets, the experimental economics points to a higher price under pay-as-bid. That is, in practice, pay-as-bid does not offer lower prices in electricity markets. Regarding volatility, the limited experimental evidence suggests that volatility may be decreased under pay-as-bid, but the reduced volatility is typically concomitant with a higher average price. That is, there is no empirical or experimental evidence that pay-as-bid would reduce prices significantly compared to single clearing price. In fact, some evidence suggests that pay-as-bid would increase prices compared to single clearing price.

To summarize, pay-as-bid will not significantly reduce prices in electricity markets and may increase prices. Moreover, as discussed in Appendix D, there are very serious drawbacks of pay-as-bid markets including: inefficient dispatch; difficulty of participation for small, competitive asset owners; the reduced ability of demand response to mitigate market power; and difficulties for market monitoring. Furthermore, if pay-as-bid did provide the price reductions its proponents apparently hope for, investment in new generation would cease. Given the lack of compelling reasons for a pay-as-bid pricing rule from the perspective of reducing prices and the several compelling reasons against pay-as bid, electricity markets should maintain the single price rule that is standard in organized markets in the United States. Claims that pay-as-bid might improve the performance of electricity markets are unsupported.

# C. Detailed summary of theoretical analysis of revenue equivalence

In this section, several theoretical papers discussing revenue equivalence are reviewed. Appendix C.1 begins with basic results, with Appendix C.2 discussing the relationship to electricity markets. Appendix C.3 reviews specific results for electricity markets and Appendix C.4 summarizes.

## C.1 Review of basic results

Since offer-based economic dispatch is an auction process, the theory of auctions can be helpful in analyzing the effect of changes in the pricing rule on outcomes of the auction. The standard discussion of auction theory focuses on a "single-sided" auction, with a single seller of one item and multiple buyers. There are several types of pricing rule that can be utilized in such an auction.

The question arises as to how to predict the price resulting from the pricing rule, given a collection of assumptions about the buyers, including a model of how they value the item. This is tantamount to predicting how the buyers will bid and may involve taking probabilistic expectations when randomness is included in the model.

A key unifying principle in economics is the notion of the Nash equilibrium (Nash, 1950), which can be useful in predicting how self-interested economic agents behave, at least in idealized settings. In the auction context, a ("pure strategy") Nash equilibrium is a collection of bids by the buyers such that, for each buyer considered individually, the buyer cannot improve its net position by any unilateral change in its bid. That is, the Nash equilibrium is a mutually consistent collection of bids such that no bidder can improve its net position by unilateral action. If we imagine a process where bidders adjust their bids until they cannot obtain a better position, then a Nash equilibrium is the natural outcome of such a process. At the Nash equilibrium, each market participant is maximally exercising its market power. Comparison of Nash equilibria under alternative market models can therefore, in principle, provide a relative assessment of the effect of market power under the alternative models.

In some cases, no single set of bids will satisfy the definition of a Nash equilibrium. In this case, a generalized concept typically applies. A "mixed strategy" Nash equilibrium is a collection of probability distributions of bids for each economic agent, such that if each agent randomly chooses its bids according to the probability distribution, then, for each buyer considered individually, the buyer cannot improve its expected net position by any unilateral change in the probability distribution of its bids. A mixed strategy is a random mixture of "pure strategy" bids.

Somewhat surprisingly, under various assumptions about the buyers, a wide variety of reasonable auction rules will result in the same expected price for the sale of the item at auction. This result is called the "revenue equivalence theorem" (Klemperer, 1999). The intuition behind this result is that the change in the rules will result in a change in the equilibrium behavior of the bidders that opposes the effect of the change in the pricing rule. Under the hypotheses of the revenue equivalence theorem, the change in equilibrium behavior exactly offsets the effect of the change in the pricing rule, as in the example at the beginning of Appendix B. That is, the combination of pricing rule and equilibrium behavior results in the same expected price across all pricing rules.

Interestingly, for some auction designs, the equilibrium behavior involves nothing more complicated than a bidder knowing its own valuation of the item. For other auction designs, the equilibrium behavior relies on a more complicated calculation that may not be entirely realistic. For example, it may require randomly chosen mixed strategy bids that may be somewhat unsatisfactory from a practical viewpoint or may require knowledge about the distribution of values of other bidders. Nevertheless, within the assumptions of the revenue equivalence theorem, all of the auctions result in the same expected price.

# C.2 Relationship to electricity markets

Electricity market auctions differ from the basic auction model in several ways. First, electricity market auctions either involve:
multiple sellers making offers and a single buyer (the ISO), or
multiple sellers making offers and multiple buyers making bids.
The case of a single buyer and multiple sellers is called a "procurement" auction and can be analyzed with the same theoretical techniques as the "standard" single-sided auction described in Appendix C.1 by swapping the roles of seller and buyer. The case of multiple buyers and sellers is called a double-sided auction, which can differ in subtle ways from the single-side auction.

A second and more substantive deviation of electricity markets from the basic auction model is that electricity demand is not met as a single item by one supplier. In fact, demand is continuous-valued and is random in the sense that it depends, in part, on issues such as ambient temperature that are variable and can only be approximately predicted at the time offers are made. Moreover, generator offers typically involve a schedule of prices versus offer quantity, and allow for the possibility of the ISO dispatching none, some, or all of the total offer quantity. Furthermore, offers may be required to be "long-lived," spanning several dispatch intervals, effectively increasing the variability of the demand.

In some cases, a discrete approximation of the continuous nature of demand, capacity, and prices, can help with analysis. For example, in a "multi-unit" auction, demand is assumed to be an integer multiple of a fixed quantity "block," such as 1MW. That is, demand might be assumed to be either 1MW, or 2MW, and so on, but never 1.5MW. Moreover, offers might also be assumed to be specified through prices for each offered 1MW block. Furthermore, the costs and the offer prices might be assumed to be an integer multiple of a fixed price increment. For example, the cost of producing 1MW for an hour might be assumed to be either $10, or $20, and so on, but not $15. Similarly, the offer prices can either be $10, or $20, and so on, but cannot be $15.

If each generator offers only a single fixed quantity block, and rules allow that a generator either produces zero or all of the fixed quantity block, then a revenue equivalence result applies to the corresponding multi-unit auction when demand is known and constant. In particular, under mild conditions, both single price and pay-as-bid auctions will result in the same payment by demand in equilibrium (Klemperer, 1999, section 10.1). The result has been extended to the case of random demand in (Hinz, 2004), but still depends on the assumption that each generator offers a single block of fixed quantity. For the following discussion, we will call this the "single fixed block offer" case.

Unfortunately:

- in the more general case where some generators have capacity equal to a multiple of the fixed quantity block, and
- in the more realistic case of continuous-valued demand and continuous values for generator capacities and the possibility of partial dispatch of offers,

revenue equivalence does not hold in general (Ausubel and Cramton, 2002). The qualitative difference between these more general models of capacity and the single fixed block offer case is due to the difference in the impact of "withholding" on profitability. In the single fixed block offer case, either the generator sells nothing or it sells all of its single block. If it offers at a high enough price to withhold and therefore does not sell its single block then its operating profit falls to zero. Zero operating profit cannot be more profitable than selling the single block at a price that is at or above marginal cost.

In contrast, in the more general and realistic capacity models, there is the possibility that a generator sells some, but not all, of its capacity at a high price by partially withholding. The partial withholding can result in a higher profit than the profit from selling all of its capacity at a lower price. This qualitative difference between partial withholding in the more general models of capacity and the single fixed block offer case appears to underlie disruption of the revenue equivalence theorem in the more general models of capacity.

Although the revenue equivalence theorem does not hold exactly, it is still true that different auction rules result in different offers and that the change in offers will tend to offset the effect of the change in the pricing rule. That is, in general, changing the pricing rule will always result in a smaller change in the equilibrium prices than anticipated by the naïve expectation described at the beginning of Appendix B.

# C.3 Specific results for electricity markets

In this section, I describe the conclusions of several papers that are specifically aimed at modeling electricity markets. Although these papers deliberately try to model particular aspects of electricity markets, it is important to recognize that none of them model the full complexity of such markets.

Federico and Rahman, (2003) compare single price to pay-as-bid in two different cases:

- Each seller has one infinitesimal unit of output, and
- There is only one monopoly seller.

When demand is uncertain, they find in both cases that pay-as-bid results in lower total production (assuming some price responsive demand) and lower expected prices. They also find that offer curves are “flatter,” resulting in less volatile prices, but also reducing the effect of price responsive demand on mitigating market power.

The two cases considered in Federico and Rahman (2003) correspond to the polar opposites of perfect competition and monopoly. However, this does not necessarily provide insight into the more relevant case of market power in an electricity market, where there are typically at least two but less than, say, 10 large market participants. That is, the findings are not necessarily compelling in the context of a realistic market.

Fabra, von der Fehr, and Harbord (2006) model two market participants that submit offers for their capacity and compare the equilibria under single price and pay-as-bid. Offers may be partially dispatched by the ISO, so that partial withholding is effectively considered. They analyze several alternative arrangements and highlight the importance of particular modeling assumptions. Typically, the equilibrium with single price is a pure strategy Nash equilibrium, while under pay-as-bid, the equilibrium is typically a mixed strategy, where firms make offers that are based on random choices amongst pure strategy offers. In a practical setting, mixed strategy equilibria may not be plausible, undercutting conclusions in this and other papers that are based on mixed strategy equilibria.

With short-lived offers, Fabra, von der Fehr, and Harbord (2006) find that pay-as-bid results in lower expected prices than with single price auction. However, they also find that with long-lived offers, the difference between single price and pay-as-bid disappears, at least when the generators are identical. Under several other assumptions, pay-as-bid results in lower expected prices than single price. That is, revenue equivalence does not hold in these other cases. Fabra, von der Fehr, and Harbord (2006, section 6) also identify the value of offer caps in reducing expected prices.

Son, Baldick, and Lee (2004) describe a specific two firm example where the single price auction results in higher prices in expectation than pay-as-bid. Although their basic model uses blocks, one of the firms owns two blocks, while the other firm owns one. The model therefore deviates from the single fixed block offer case and tests whether the assumption of single fixed block offer is essential to revenue equivalence.

The fixed total demand is for two blocks and there is an offer cap. Similarly to Fabra, von der Fehr, and Harbord (2006), the example involves a pure strategy equilibrium under a single, market-clearing price rule. The equilibrium prices in the single price auction are equal to the offer cap. The equilibrium under pay-as-bid is mixed strategy, with expected prices lower than in the single price case. Certain generalizations of the basic formulation are also shown to violate revenue equivalence. The results in both Fabra, von der Fehr, and Harbord (2006), and Son, Baldick, and Lee (2004) rely on the plausibility of mixed strategy equilibria.

Ausubel and Cramton (2002) emphasize the importance of the difference between single unit and multi-unit auctions. In the single-sided auction model they consider, cast into the context of electricity markets, they show that pay-as-bid can yield higher dispatch efficiency and lower prices than a single price auction, again relying on mixed strategy equilibria (Ausubel and Cramton, 2002). Despite the positive result about pay-as-bid, they do not advocate pay-as-bid in electricity markets and highlight a number of countervailing issues that argue against pay-as-bid. For example, Ausubel and Cramton (2002, section 6) mention simplicity, fairness, efficiency in a competitive setting, and incentives for small entrants as advantages of single clearing price over pay-as-bid. Several such countervailing issues are reviewed in Appendix D.

Kremer and Nyborg (2004) highlight the importance of seemingly innocuous modeling assumptions. For example, they show that the assumption that all quantities are multiples of a fixed quantity block and the assumption that all prices are multiples of a fixed price increment can result in different equilibria to the case where quantities and prices are assumed to vary continuously. Fabra, von der Fehr, and Harbord (2006) also highlight analogous modeling issues. Generally speaking, the critical dependence of conclusions on modeling assumptions tends to undercut the strength of any theoretical comparisons between single clearing price and pay-as-bid.

# C.4 Summary

To summarize, specific theoretical analysis that is relevant to electricity markets in the presence of market power finds that revenue equivalence does not hold in many cases, with lower prices under pay-as-bid than under a single market-clearing price. However, in the presence of a requirement for long-lived offers, differences between single price and pay-as-bid are attenuated or disappear. In many cases, theoretical comparisons depend critically on model assumptions and on the plausibility of mixed strategy equilibria in pay-as-bid markets.

# D. Serious drawbacks of pay-as-bid

In Appendix B, it was observed that the benefits claimed by proponents of pay-as-bid are illusory. This Appendix will describe several significant drawbacks of pay-as-bid markets involving dispatch inefficiency, biases against small competitors, the negation of effectiveness of demand price responsiveness in mitigating market power, difficulty with market monitoring, and investment incentives.

# D.1 Dispatch inefficiency

As discussed in the example at the beginning of Appendix B, under pay-as-bid, a profit maximizing offer involves predicting the market clearing price (Tierney *et al.*, figure 2). In the practical situation where there are uncertainties, this prediction will be inaccurate and various market participants will forecast different values for the market-clearing price. Since the ISO must use the offers to decide on the dispatch, this means that occasionally a high marginal cost generator with a lower offer will be dispatched in preference to a lower marginal cost generator. That is, in the presence of uncertainties, the efforts to maximize profits will result in poor dispatch decisions. This outcome was observed in the experiments reported in Mount *et al.* (2001). As discussed previously, inefficient dispatch wastes costly resources and is therefore undesirable.

# D.2 Bias against small market participants

A key argument against pay-as-bid markets is that small market participants face relatively greater costs in the assessment required to form their offers in a pay-as-bid market than the assessment required for offers in a single price market. As discussed in the example at the beginning of Appendix B, in a single market-clearing price market, a small market participant can ensure that its profit is maximized simply by offering at marginal cost. In contrast, in a pay-as-bid market, a small market participant must predict the market-clearing price in order to maximize its profits. This requires considerably greater market knowledge than simply offering at marginal cost, requiring more investment in market analysis expertise and data. Moreover, the assessment is relatively more difficult for a baseload generator than for a peaking generator.

Large market participants can spread the costs of forecasting market-clearing prices across a greater amount of sales than can small market participants. Consequently, pay-as-bid tends to favor larger market participants, whereas single price allows smaller market participants to "free ride" on the market analysis of larger market participants (Federico and Rahman, 2003).

One remedy for market power is to encourage new entry by smaller market participants. A pay-as-bid market will make it relatively harder for new entry by smaller market participants than entry into a single, market-clearing price market. It will be particularly difficult for new entry of baseload resources. That is, new entry by small market participants, which is a principal long-term remedy for market power, is thwarted by pay-as-bid.

# D.3 Relative ineffectiveness of demand price responsiveness

As observed in the model of Federico and Rahman (2003) and as observed in the experiments of Mount *et al.* (2001), offers tend to be "flatter" and the range of prices tends to be smaller under pay-as-bid compared to single price, reducing volatility. One important remedy for market power is increased price-responsiveness of demand. However, if offers are "flatter," then price-responsive demand becomes less effective in mitigating market power because changes in demand will have less effect on prices (Mount *et al.*, 2001, section 4.3). That is, price-responsive demand, which is a principal approach to mitigating market power, is partially defeated by a pay-as-bid market.

# D.4 Difficulties with market monitoring

The basic function of a market monitor is to assess when prices are not competitive. This assessment usually involves consideration of offers. In a single price market, offers that do not reflect market power should equal marginal costs. Therefore, there is a relatively straightforward test of market power in a single clearing price market: assess whether offers track marginal costs. Egregious deviations from marginal costs are suggestive of market power.

In contrast, in a pay-as-bid market, competitive offers involve mark-up above marginal costs to the estimated market-clearing price. Offers must significantly deviate from marginal costs in order to sustain profitability. There is no easily applied standard to assess whether or not such offers are exploiting market power. That is, market power monitoring becomes essentially impossible in pay-as-bid markets.

# D.5 Investment

If pay-as-bid worked as its proponents apparently intend, the prices paid to generators would be driven towards recovery of operating costs only. As discussed in Section 1.5, this would fail to provide enough remuneration to cover investment costs. Generator owners would find themselves going bankrupt and new investment would cease, thwarting new entry. New entry is a principal remedy for market power.

# D.6 Summary

Although the revenue equivalence theorem does not hold exactly in electricity markets, similar logic reveals that a change to pay-as-bid would not result in a drastic reduction to market prices: as suggested in Appendix B, offers will increase towards estimates of market clearing prices. However, the resulting dispatch inefficiency described in section D.1 will not only waste resources but will also likely lead to poor information for investment decisions and, moreover, the added complexity of offer formation described in section D.2 will discourage entry by smaller market participants. That is, pay-as-bid is likely to result in inefficient capital additions by incumbent asset owners, exacerbating market power issues. Other principal remedies against market power such as demand price responsiveness and market monitoring are also thwarted by pay-as-bid.

Given the lack of compelling reasons for a pay-as-bid pricing rule from the perspective of reducing prices and the several other compelling reasons against pay-as bid, electricity markets should maintain the single price rule that is standard in organized markets in the United States. Claims that pay-as-bid might improve the performance of electricity markets are unsupported.

# REFERENCES


American Public Power Association (APPA), 2004, “Restructuring at the Crossroads: FERC Electric Policy Reconsidered,” Washington, DC. Available online, http://www.appanet.org/files/PDFs/APPAWhitePaperRestructuringatCrossroads1204.pdf. Accessed July 19, 2008.

Allez, Blaise, and Jean-Luc Vila, 1993, “Cournot Competition, Forward Markets, and Efficiency,” *Journal of Economic Theory*, 59(1): 1-17.

Ausubel, Lawrence M., and Peter Cramton, 2002, “Demand Reduction and Inefficiency in Multi-Unit Auctions,” Manuscript, University of Maryland. Available online, http://www.cramton.umd.edu/papers1995-1999/98wp-demand-reduction.pdf. Accessed July 26, 2008.

Australian Securities Exchange, 2008, “Calculating Opening & Closing Prices,” Available online, http://www.asx.com.au/resources/education/basics/open_Close.htm. Accessed July 10, 2008.

Baldick, Ross, Ryan Grant, and Edward Kahn, 2004, “Theory and Application of Linear Supply Function Equilibrium in Electricity Markets,” *Journal of Regulatory Economics*, 25(2):143-167, March.

Baldick, Ross, and William Hogan, 2006, “Stability of supply function equilibria: Implications for daily versus hourly bids in a poolco market,” *Journal of Regulatory Economics*, 30(2):119-139, August.

Binmore, Ken, and Joe Swierzbinski, 2000, “Treasury auctions: Uniform or discriminatory?” *Review of Economic Design*, 5:387-410.

Deutsche Börse, 2008, “Glossary,” Available online, http://boerse-frankfurt.com/pip/dispatch/en/pip/private_investors/wissen/boersenlexikon. Accessed July 10, 2008.

Electricity Consumers Resource Council (ELCON), 2002, “Locational Marginal Pricing (LMP): A Computer Program Pretending to be a Market,” Washington, DC, Available online, http://www.elcon.org/Documents/Publications/lmp.pdf. Accessed July 19, 2008.

Electricity Consumers Resource Council (ELCON), 2005, “Problems in the Organized Markets: A Special Report of the Electricity Consumers Resource Council,” Washington, DC, Available online, http://www.elcon.org/Documents/Publications/ELCONSpecialReportApril2005.pdf. Accessed July 19, 2008.

Euronext, 2008, “Euronext: Organization and procedures,” Available online, http://www.euronext.com/fic/000/010/706/107061.pdf. Accessed July 10, 2008.

Fabra, Natalia, Nils-Henrik von der Fehr, and David Harbord, 2006, “Designing electricity auctions,” *RAND Journal of Economics*, 37(1):23-46, Spring.

Federico, Giulio, and David Rahman, 2003, “Bidding in an electricity pay-as-bid auction,” *Journal of Regulatory Economics,* 24(2):175-211, September.

Hinz, Juri, 2004, “A Revenue-Equivalence Theorem for Electricity Auctions,” *Journal of Applied Probability*, 41:299-312.
Jevons, W. Stanley, 1879, *The Theory of Political Economy*, Macmillan, London.

Kahn, Alfred E., Peter C. Cramton, Robert H. Porter, and Richard D. Tabors, 2001, "Pricing in the California Power Exchange Electricity Market: Should California Switch from Uniform Pricing to Pay-as-Bid Pricing," Blue Ribbon Panel Report, California Power Exchange.

Klemperer, Paul, 1999, "Auction Theory: A Guide to the Literature," *Journal of Economic Surveys,* 13(3):227-286.

Kremer, Ilan, and Kjell G. Nyborg, 2004, "Underpricing and Market Power in Uniform Price Auctions," *The Review of Financial Studies*, 17(3):849-877, Autumn.

Mount, T. D., W. D. Schulze, R. J. Thomas, and R. D. Zimmerman, 2001, "Testing the Performance of Uniform Price and Discriminative Auctions," Presented at the *Rutger's Center for Research in Regulated Industries 14th Annual Western Conference: Advance Workshop in Regulation and Competition, Competitive Change in Network Industries*, San Diego, CA, June.

Nash, John F., 1950, "Equilibrium points in N-Person Games," Proceedings of National Academy of Sciences, 36(1):48-49, January.

Pfeifenberger, Johannes, Samuel Newell, Robert Earle, Attila Hajos, and Mariko Geronimo, 2008, "Review of PJM's Reliability Pricing Model (RPM)," Technical report, The Brattle Group, Boston, MA, June.

Rassenti, Stephen J., Vernon L. Smith, and Bart J. Wilson, 2003, "Discriminatory Price Auctions in Electricity Markets: Low Volatility at the Expense of High Price Levels," *Journal of Regulatory Economics*, 23(2):109-123.

Regional Greenhouse Gas Initiative, 2008a, "Design Elements for Regional Allowance Auctions under the Regional Greenhouse Gas Initiative," Available online, http://www.rggi.org/docs/20080317auction_design.pdf. Accessed July 10, 2008.

Regional Greenhouse Gas Initiative, 2008b, "Auction Results," Available online, http://www.rggi.org/co2-auctions/results. Accessed October 27, 2008.

Showalter, Marilyn, undated, "Power in the Public Interest Says Consumers `Deeply Disappointed' in Electricity Restructuring and Price Regulation," Available from http://www.ppinet.org/PDFs/PPI-ANOPR%20press%20release%20FINAL%20Lthd%20(2).pdf. Accessed December 12, 2008.

Son, You Seok, Ross Baldick, Kwang-Ho Lee, and Shams Siddiqi, 2004, "Short-Term Electricity Market Auction Game Analysis: Uniform and Pay-as-Bid Pricing," *IEEE Transactions on Power Systems*, 19(4):1990-1998.

Stoft, Steven, 2002, *Power System Economics*, IEEE Press and John Wiley & Sons.

Tierney, Susan, Todd Schatzki, and Rana Mukerji, 2008, "Pay-as-bid vs. Uniform Pricing," *Public Utilities Fortnightly*, March, pages 40-47.

US Department of the Treasury, 2008a, "How Treasury Auctions Work," Available from http://www.treasurydirect.gov/instit/auctfund/work/work.htm. Accessed July 10, 2008.

US Department of the Treasury, 2008b, "The Basics of Treasury Securities," Available from http://www.treasurydirect.gov/instit/research/faqs/faqs_basics.htm. Accessed August 25, 2008.

Warsaw Stock Exchange, 2008, "Session Statistics," Available from http://www.gpw.pl/zrodla/gpw/spws/spws1/statccen.html. Accessed July 11, 2008.

# SUGGESTED FOR FURTHER READING


Ausubel, Lawrence M. and Peter Cramton (2002), "Demand Reduction and Inefficiency in Multi-Unit Auctions," University of Maryland Working Paper 9607, revised July 2002.

Bernard, John C., Richard Zimmerman, William Schulze, Robert Thomas, Timothy Mount, and Richard Schuler (1998), "Alternative Auction Institutions for Purchasing Electric Power: An Experimental Examination," Working Paper, Cornell University.

Cramton, Peter (2004), "Competitive Bidding Behavior in Uniform-Price Auctions," *Proceedings of the Hawaii International Conference on System Sciences*, January, 2004.

Cramton, Peter (2006), "New England's Forward Capacity Auction," Working Paper, University of Maryland.

Cramton, Peter (2007), "Colombia's Forward Energy Market," Working Paper, University of Maryland.

Cramton, Peter and Steven Stoft (2006), "The Convergence of Market Designs for Adequate Generating Capacity," white paper for the California Electricity Oversight Board, March 2006.

Cramton, Peter and Steven Stoft (2008), "Forward Reliability Markets: Less Risk, Less Market Power, More Efficiency," *Utilities Policy*, 16, 194-201.

Cramton, Peter, Steven Stoft, and Jeffrey West (2006), "Simulation of the Colombian Firm Energy Market," Working Paper, University of Maryland.

Fabra, Natalia, Nils-Henrik von der Fehr, and David Harbord (2006), "Designing Electricity Auctions," *Rand Journal of Economics*, 37, 23-46.

Kahn, Alfred E. , Peter Cramton, Robert H. Porter, and Richard D. Tabors (2001), "Pricing in the California Power Exchange Electricity Market: Should California Switch from Uniform Pricing to Pay-as-Bid Pricing?" Blue Ribbon Panel Report, California Power Exchange.

Stoft, Steven (2002), *Power System Economics: Designing Markets for Electricity*, New York: John Wiley and Sons.

Tierney, Susan, Todd Schatzki, and Rana Mukerji (2008), "Pay-as-bid vs. Uniform Pricing," *Public Utilities Fortnightly*, March, 40-47.

Wolfram, Catherine D. (1998), "Strategic Bidding in a Multi-Unit Auction: An Empirical Analysis of Bids to Supply Electricity in England and Wales," *Rand Journal of Economics*, 29, 703-725.