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# Joint Energy and Reserves Auction with Opportunity Cost Payment for Reserves*

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**Abstract**

System operators in the electricity industry are required to procure reserve capacity to deal with unanticipated outages, demand shocks, and transmission constraints. One traditional method of procuring reserves is through a separate capacity auction with two-part bids. We analyze an alternative scheme whereby reserves are procured through the energy market using only energy bids, and capacity payments are made based on a generator's implied opportunity cost. By using the revelation principle, we are able to derive the equilibrium bidding function in this market and show that generators have a clear incentive to understate their costs in order to capture higher capacity rents. We then give a numerical example for a special case and examine the effect of the equilibrium bidding behavior on the generators' total revenues and on the energy payments.

## 1 Introduction

A common feature of restructured electricity markets is that an Independent System Operator (ISO) is charged with the task of maintaining reliability of the electricity network in real time. Typically the ISO will perform this task by procuring electricity reserves in advance which can then be quickly dispatched to maintain system reliability in real-time.

In competitive markets, the assignment of generating units to reserve status is done through some form of market mechanism. Traditionally, the ISO will run a reserve auction which is separate from any other energy markets it operates. Under this scheme, it will normally solicit a two-part bid from each generator—a capacity and energy price. The ISO will then compare all the bids by using some scoring rule, and based on that make assignment and dispatch decisions. Units which are assigned reserve status receive a capacity payment, regardless of whether or not they are actually called to generate energy ex post. Units which are dispatched to generate in real-time are given a supplemental energy payment.

The market design challenge is to devise the scoring and settlement rule in such a way so as to prevent generators from collecting excessive rents by gaming the market. A well known procurement auction of this sort which highlights the dangers of a poorly-designed mechanism were California's 1993 round of biennial resource planning update

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(BRPU) auctions. The mechanism was designed to resemble a Vickery auction (1961) whereby the bidder with the lowest score in the initial auction was allowed to negotiate terms for a contract similar to those offered by the bidder with the second-lowest score. The rationale for this auction mechanism was that because of its second-price nature, generators would be inclined to bid their true costs. Bushnell and Oren (1993), (1994) predicted that the specific scoring rule used in that auction would lead to an understatement of marginal costs, which turned out to be true.

To deal with this incentive problem, Bushnell and Oren (1994) devise a pricing and settlement rule, which relies on a discriminative pricing scheme. They show that in their auction, generators will reveal their true costs so long as they agree with the ISO on the probability distribution of energy calls. Chao and Wilson (2002) devise an alternative scheme which is based on a uniform settlement price, and show that truthful revelation of costs is incentive compatible under that settlement scheme. Furthermore, they point out that their design is more robust in the sense that it does not require the ISO and generators to agree on the probability distribution of dispatched energy. In contrast to these separate two-dimensional procurement auctions which have been analyzed in the past, we consider a reserve auction which is integrated with the day-ahead market and based solely on energy bids. Assignment to reserve status and subsequent dispatch is done based on the merit order of those energy bids. Generators which are dispatched to generate receive a uniform market clearing price for energy. Those which are held for reserves but not dispatched receive a capacity payment based on their implied opportunity cost, which is the difference between the uniform market-clearing price for energy and their own energy bid.

The main goal of this paper is to model the integrated market for energy reserves, and to derive the equilibrium bidding behavior of generators. The remainder of this paper is organized as follows. Section 2 presents a formulation for the market and derives the equilibrium bidding strategy of generators. In Section 3 we analyze the bidding behavior with a numerical example.

# 2 Bidding In The Reserve Market

We propose running a combined day-ahead market for energy and reserves. The ISO will procure reserve energy from this market based on its estimation of how much will be necessary to meet the next day's load reliably. Of these procured reserves, some will be dispatched to generate energy, which depends on the actual real-time load. Dispatched load will be paid a uniform market clearing price, and generation capacity which is procured but not dispatched will be given a capacity payment based on their opportunity cost. The chart in Figure 1 illustrates how the proposed market would settle for a given procurement and dispatch quantity.

## 2.1 Assumptions

We assume that the amount of energy procured will be a random variable, $Q$, which has an atomless distribution function $F(Q)$ with a support of $[q_0, q_1]$. One may think of this procurement quantity as some forecast of the load for the next day, plus a reserve margin which is an additional $r\%$ of that forecast quantity.

In real-time, a certain fraction, $d$, of that procured quantity will be dispatched to generate energy. Again, we assume this fraction $d$ to be random and to have a distribution function $H(d)$, with a support of $[\beta, 1]$. If we take the view that the procured quantity $Q$ is the forecasted load plus a reverse margin of $r\%$, then we might say $\beta = \frac{1}{1+r}$, and the actual fraction dispatched will be somewhere between the forecast quantity and the forecast plus the reserve margin. Note that since $d$ has an upper support of 1, we implicitly assume the ISO will never have a shortfall of procured resources.

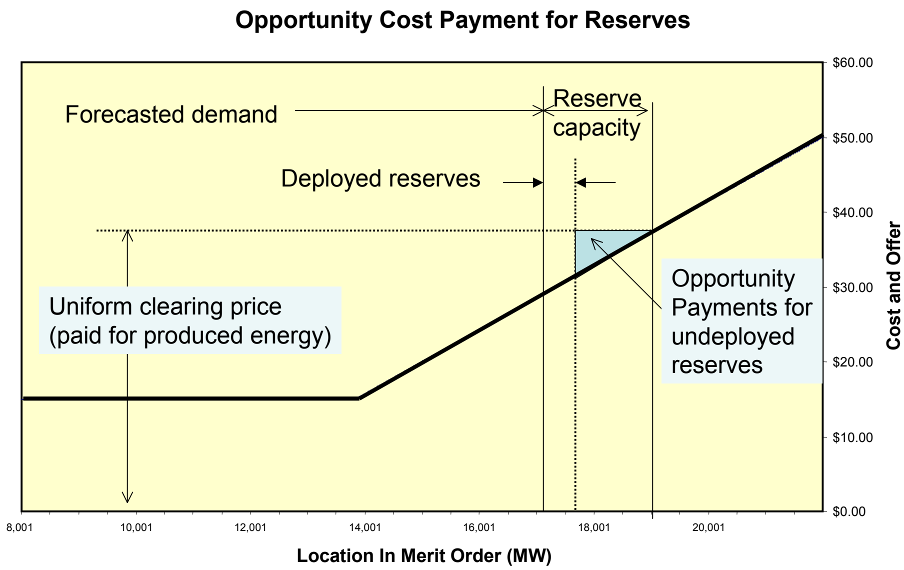


Figure 1: Market Settlement Example.

Naturally, we can define $E = d \times Q$ to be the total capacity dispatched for energy. The dispatch quantity, $E$, will also be stochastic and its distribution function, $G(E)$, will be implied by $F(\cdot)$ and $H(\cdot)$ and will have a support of $[\beta q_0, q_1]$. Finally, in our analysis of the opportunity cost auction, we will ignore network effects. This is equivalent to assuming there is no network congestion. We also ignore the possibility of different ramp rates among generators so that energy is always dispatched in merit order based on marginal cost. In a realistic setting where generators have different ramp rates the ISO may dispatch an 'out of merit' expensive but slow responding generator for energy before a low cost but fast responding unit in order to save the fast response unit for reserves in case of an emergency.

As for the generators, we assume they are risk-neutral profit-maximizing firms and that each MW of generating capacity, which is characterized by its location within the resource stack $q$, is bid individually of others (i.e. there are no multiunit effects). Generators have perfect information regarding the aggregate cost function, $c(q)$, where $q$ defines the location of each MW within the resource stack, along with their own position in the merit order. Using this information, generators will submit energy bids for each incremental MW of generation. The ISO will then procure capacity day-ahead based on the merit order of the energy bids. All generators which are called to generate in real-time will be paid a uniform market-clearing price which is the bid of the marginal *procured* (not dispatched) unit. Generators which are procured but not dispatched will receive their implied opportunity cost of being held for reserve, which is the difference between the market clearing price and their own bid.

## 2.2 Derivation Of Equilibrium Bidding Function

We theorize that due to the opportunity cost based capacity payment used in this market, generators will have an incentive to shade their bids below cost in order to capture capacity rents. To derive the equilibrium bidding function of the generators, we use the condition that each generator is maximizing expected profits. Suppose that all generators bid according to a monotonically-increasing bid function, $b(q)$[1]. An arbitrary generator located at $q$ within the resource stack must choose a bid $\hat{b}$ to maximize its expected profits given the bidding behavior of the

[1]The monotonicity requirement is needed so the bid function preserves the merit order of the generators.

other generators. By using the revelation principle, we can liken this bid to a direct revelation mechanism, wherein the generator reveals a location within the resource stack. Thus, if we let $\hat{q} = b^{-1}(\hat{b})$, the generator's bid of $\hat{b}$ is equivalent to it revealing a location $\hat{q}$ within the resource stack. We can then express the generator's expected profits as a function of its actual ($q$) and revealed ($\hat{q}$) location within the stack:

$$\pi^e(\hat{q}, q) = \int_{\hat{q}}^{+\infty} [b(x) - b(\hat{q})]dF(x) + [b(\hat{q}) - c(q)] \times [1 - G(\hat{q})] \tag{1}$$

Differentiating equation 1 with respect to $\hat{q}$ gives the first-order necessary condition (FONC) for optimality of the bid choice $\hat{q}$. This FONC is:

$$\frac{\partial}{\partial \hat{q}} \pi^e(\hat{q}, q) = -b(\hat{q})g(\hat{q}) + \frac{db(\hat{q})}{d\hat{q}}[F(\hat{q}) - G(\hat{q})] + c(q)g(\hat{q}) = 0$$

Since this is a truthful revelation mechanism, we let $\hat{q} = q$ which yields the differential equation:

$$\frac{db(q)}{dq} = \frac{[c(q) - b(q)]g(q)}{G(q) - F(q)} \tag{2}$$

with the boundary condition,

$$b(q) = c(q) \text{ for } q \text{ s.t. } G(q) = F(q).$$

Thus, the optimal bidding behavior of the generators will be dictated by the differential equation 2. Note that if $G(q) \geq F(q)$, then $b(q) \leq c(q) \iff \frac{db(q)}{dq} \geq 0$. The condition $G(q) \geq F(q)$ is equivalent to $1 - G(q) \leq 1 - F(q)$ which makes intuitive sense because it says that for any quantity $\hat{q}$ there is a higher probability of having to procure at least $\hat{q}$ MW than having to actually dispatch at least $\hat{q}$ MW.

# 3 Numerical Example

In order to fully derive the equilibrium bidding behavior in this market, we must make an assumption on the two demand distributions and generator costs. We will study an example in which the two distribution functions $F(\cdot)$ and $H(\cdot)$ are uniform.

## 3.1 Bidding In Uniform Distributions Case

In our example, we assume the density of the procurement quantity will be:

$$f(Q) = \frac{1}{q_1 - q_0},$$

and likewise the density of the dispatch quantity will be:

$$h(d) = \frac{1}{1 - \beta}.$$

These two distribution functions imply the density of the dispatched quantity, which is:

$$g(E) = \begin{cases} \frac{1}{(1-\beta)(q_1-q_0)} \log(\frac{E}{\beta r_0}) & \text{for } \beta q_0 \leq E \leq q_0, \\ \frac{1}{(1-\beta)(q_1-q_0)} \log(\frac{1}{\beta}) & \text{for } q_0 \leq E \leq \beta q_1, \\ \frac{1}{(1-\beta)(q_1-q_0)} \log(\frac{r_1}{E}) & \text{for } \beta q_1 \leq E \leq q_1. \end{cases}$$

Using these density functions, we can derive the equilibrium bidding behavior in the market numerically[2]. In our example we assume values of $q_0 = 16,500$MW and $q_1 = 22,000$MW, a reserve margin of 10% which corresponds

[2]We are unable to derive a closed-form solution to the differential equations.

to $\beta \approx 0.9091$, and a linear cost function capped from below at \$15 per MWh. The chart in Figure 2 shows the equilibrium bidding strategies in relation to the cost of each unit. We see that generators which have a positive probability of being procured for reserves but not dispatched to generate energy have an incentive to shade their bids below true cost. This is due to two effects which confound one another. As a generator moves further up in the resource stack, its probability of being dispatched (or procured) falls. Thus there is a lower chance of it being forced to generate at a loss. Furthermore, when a generator is procured day-ahead, its probability of being dispatched for energy depends on how close it is to setting the market-clearing price. In other words, when the market clearing price is close to its own bid, then the probability of being dispatched is relatively low. It is only as the marginal unit is further up the resource stack (meaning the market clearing price is higher) that the probability of dispatch rises.

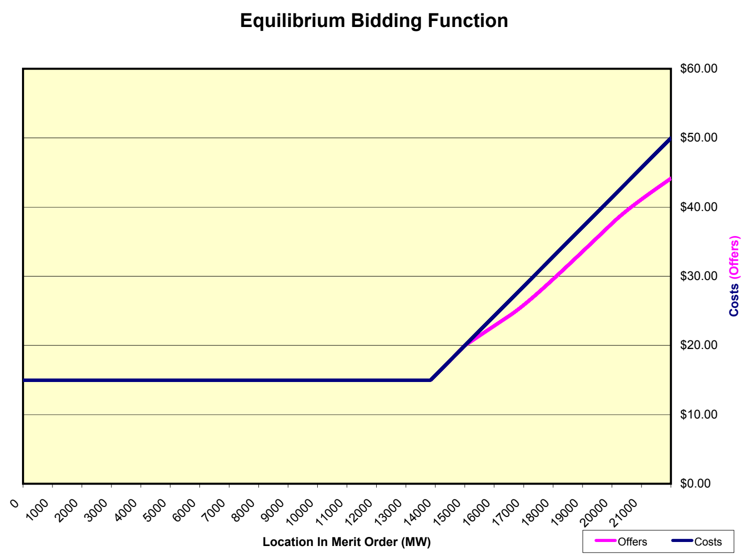


Figure 2: Equilibrium Bidding Function: Uniform Example.

## 3.2 Expected Procurement Costs

An interesting policy question is how total procurement costs of energy and reserves under the opportunity cost model compare to costs had generators not shade their bids below cost. While truthful revelation of costs will increase energy procurement costs, it could reduce the opportunity cost paid to reserves. For any given procurement and dispatch quantity $Q = p, E = s$ we can easily calculate the total procurement and energy costs to be:

$$K(p, s) = p \cdot b(p) - \int_s^p b(x)dx.$$

If we were to take the expectation of this over all possible values of $Q$ and $E$, the total expected cost for the system operator would be:

$$K^e = \int_{q_0}^{q_1} (p \cdot b(p) - \int_{\beta p}^{p} (\int_s^p b(x)dx) g(s|Q = p)ds) f(p)dp.$$

Using the data from our numerical example, we have calculated the costs under the equilibrium bidding function and if generators were to truthfully reveal costs. We find that when they bid using true costs, total procurement costs turn out to be higher (approximately \$715,020 as opposed to \$658,010). Thus it appears the Nash bidding strategy drives generator profits down (at least in the uniform distributions case).

One of the criticisms of using an opportunity-cost based settlement rule in the design of our market, is that the system operator overcompensates energy producers. This is due to the fact that dispatched energy is paid a uniform market-clearing price that is based on the total procurement of energy and reserves, rather than on just energy dispatched. This pricing rule could result in overcompensation of energy, however the equilibrium bid-shading behavior should mitigate such overpayment to some extent. The question is how the resulting payment for energy under the opportunity cost approach would compare to a system where energy is procured separately from reserves so energy is paid a market-clearing price corresponding to the true cost of the marginally dispatched unit. We can, again, numerically compare the expected energy payments under the two approaches. Under our approach, if the procurement and dispatch quantities are $Q = p$ and $E = s$ the cost of energy will be:

$$K_B(p, s) = s \cdot b(p).$$

Taking the expectation of this over all possible values of $Q$ and $E$ gives:

$$K_B^e = \int_{q_0}^{q_1} (\int_{\beta p}^{p} s \cdot b(p) g(s|Q = p) ds) f(p) dp.$$

Alternatively, if generators bid true costs and were paid based on the marginally *dispatched* (as opposed to procured) unit, the cost to the system operator of dispatching $E = s$ would be:

$$K_C(s) = s \cdot c(s).$$

Taking the expectation over all possible values of $E$ gives:

$$K_C^e = \int_{\beta q_0}^{q_1} s \cdot c(s) g(s) ds.$$

We can compare these two expressions using data from our numerical example and find that under our proposed scheme, dispatch costs would be approximately \$655,587, whereas under truthful revelation and payment based on the marginally dispatched unit, expected energy cost will be approximately \$664,942. Again, we see that in our example case, the proposed auction mechanism should cost less on average than one which elicits truthful bids. Figure 3 illustrates the difference in the settlement price when energy is paid the true marginal cost of the dispatched unit, as opposed to the shaded bid of the marginally procured unit under the proposed auction.

# 4 Concluding Remarks

We have shown that one viable alternative to the standard two-dimensional procurement auction for reserves is to conduct the procurement auction within the day-ahead energy market itself. By procuring excess capacity day-ahead and dispatching whatever resources are necessary in real-time, the system operator can run a single transparent market as opposed to two separate ones which is a standard design in use today. A clear advantage of this is that generators no longer have to decide which market to bid into, which can be an issue if the two are operated simultaneously. The fact that generators bid according to a monotonic function means the dispatch will be efficient. We have further demonstrated, at least for the uniform distributions case, that procurement costs when generators optimally bid in this market are below what they would be had they truthfully revealed costs. As for future work in this area, we hope to expand our analysis of joint auctions for energy and reserves with opportunity cost payments

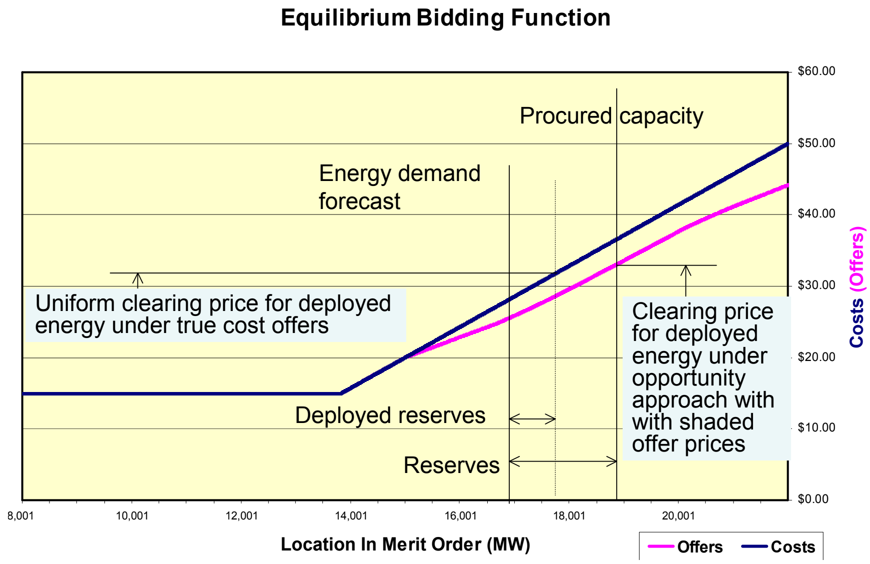


Figure 3: Cost Comparison Example.

for reserves in a network setting with locational prices due to congestion. We will also explore the effect of differential ramp rate which may alter the order in which generators are deployed for energy production.

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