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A Reserve Market Reform Proposal for NEPOOL

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1. Introduction

This is an abbreviated version of a document to be completed later. We have present here only the mechanics of the proposal, and not the background and problems that gave rise to the proposal.

2. The problem

To be added.

3. The solution

To address the above problems, our proposal consists of the following basic elements:

- Incorporate demand for reserves in market design
- Price reserves when energy and reserves are co-optimized
- Preserve reserve price information from unit commitment by assigning reserve units an "adder."
- Use an appropriate unit commitment model in each stage
- Maintain adequate replacement reserves and release uncommitted capacity
- Consider three alternative approaches with increasing sophistication

3.1. Demand Curve

As suggested by Cramton and Lien (2000), the development of an elastic demand function for reserves is fundamental. However, the use of demand function needs to take into account of several considerations. First, the reserve demand function may not be downward sloping. For instance, with peak load about 24 GW, NEPOOL imports about 1.5 GW of power from Hydro Quebec (HQ) through a major transmission intertie. The risk of losing HQ import (OP-4) constitutes the largest contingency that drives up the marginal value of reserves as the reserve capacity approaches the critical size of 1.5 GW. Second, the marginal value of reserve tends to drop quickly once the size of the reserve adequately exceeds the largest contingency. Third, it is difficult to obtain a reliable estimate on the value of lost load as the extensive economic literature has highlighted. While the value of load shedding may be estimated from the cost of backup generation incurred by sensitive loads, the cost of widespread power outages due to load imbalance remains elusive. The above considerations suggest that it would be technically

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difficult to let the market set the supply of reserves and then use the demand function to set reserve prices. Therefore, we consider using the reserve demand function in auctions to determine the reserve quantities and prices.

3.2. Co-optimization and Price Cascading

As we discussed above, a key requirement for reserve pricing is co-optimization of reserve and energy in unit commitment. Therefore, we focus on pricing reserves in the day-ahead market when units are committed. Given the essential role that unit commitment plays, it is important to ensure that the reserve requirements are represented appropriately. As a basic requirement, the reserve requirement constraints should allow cascading of higher to lower quality reserve types. For instance,

$$TMSR \geq RR_{TMSR}$$
$$(TMSR - RR_{TMSR}) + TMNSR \geq RR_{TMNSR}$$
$$(TMSR - RR_{TMSR}) + (TMNSR - RR_{TMNSR}) + TMOR \geq RR_{TMOR}$$

where RR represents reserve requirements.

Mathematically these constraints yield strictly decreasing shadow prices for reserves. By using shadow prices for reserve prices, we can guarantee the right price order. The only caveat is that California attempted something similar but then used an incorrect objective function that defeated the purpose.

3.3. Reserve or Reliability "Adder"

We propose placing an adder on the portion of a unit's capacity when that unit has been selected in unit commitment as a reserve unit. The adder is equal to the day-ahead reserve price. The advantage of the adder approach is that it:

- Does not over use flexible units for energy (see above discussion).
- Removes incentive to inflate the energy bids.
- Allows optimal dispatch of combined energy and reserves, by substituting (activating) reserves for energy when the energy price is high.
- Allows for reoptimization as real-time is approached. Since the energy bid information is preserved and the bids are not inflated, the information necessary for reoptimization is preserved. (Reoptimization has not been addressed here).

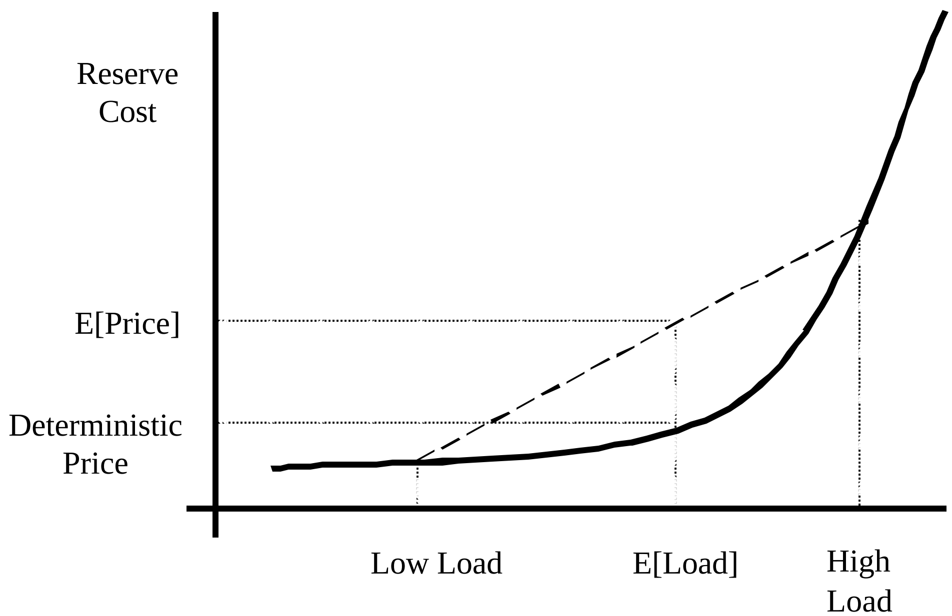
3.4. Replacement Reserves and Release of Capacity

To price reserves in the day-ahead market, the uncommitted capacity must be released. To ensure that the system operator can meet the security requirements established by NERC, a replacement reserve needs to be maintained. For instance, the replacement reserves will need to be available on demand in less than one hour. The requirement for replacement reserve (REPR) adds a new constraint as follows,

$$(TMSR - RR_{TMSR}) + (TMNSR - RR_{TMNSR}) + (TMOR - RR_{TMOR}) + REPR \geq RR_{REPR}$$

3.5. Load Uncertainty

Load uncertainty plays a large role in the value of reserves. If the cost of reserves is convex in load, then reserves should have a higher expected price than the deterministic price. If it is concave, then the expected cost of reserves will be lower.



• **Figure 1: Load Uncertainty and Reserve Prices**

3.6. Phased Approach

We consider a phased approach with three increasingly sophisticated designs for day-ahead reserve market.

- No reserve bids. (Energy bids + fixed costs)
- Reserve and energy bids
- Reserve and energy bids, with reserve demand function

The phased approach is both prudent and expedient, because it offers quick remedy while providing time for testing, learning and ordered transition. The three designs are described separately in the next three sections.

4. Procedures Step-by-Step

This section walks through the three basic approaches step-by-step.

4.1. Day-ahead reserve markets without reserve bids

The first approach provides a basic remedy to reserve markets that requires minimum change to the existing tools and procedures. For this purpose, we consider bids of energy and fixed costs but exclude reserve bids. The reserve requirements are handled as constraints in a unit commitment model. Reserves are committed and priced a day ahead using shadow prices from a unit commitment model.[2]

There are two methods ("Method A" and "Method B") of handling fixed costs in this section. In the first method, Method A, one has simple start-up and no-load cost payments. These fixed costs do not appear in the shadow prices because they are part of the mixed integer portion of the objective function. Thus there is no double payment. However, shadow prices are consequently lower. The result is a uniform price auction in reserve prices and a price discriminating (pay-as-bid) auction for start-up and no-load.

The second method (Method B) is to include the same fixed costs in the energy bids by raising the energy bids by that amount. The market administrator does for the Participants. This greatly simplifies unit commitment. The resulting shadow prices for reserves are higher. Costs that are now placed in uplift would be placed in reserves. We do not address Method B in this version of this paper.

The detailed procedure is described below.

Step 1. Each day, the system operator announces, for example, seven sets of hourly load forecasts for the next day, including a base scenario (index by 0) and a number of alternative scenarios (-3, -2, -1, +1, +2, +3) with estimated ranges of load and probabilities (PR_{-3}, …, PR_{+3}) that the actual load would fall into individual ranges.

Step 2. The resource owners submit bids for all available generation units. Each bid includes the following information:

- High operating limit (HOL) and low operating limit (LOL) – in MW
- Energy prices ($/MWh)
- Ramp rates (MW/minute)
- Start-up cost ($/start-up)

The ramp rates will be used to calculate the maximum capacity that can be ramped up in specific time intervals to meet the reserve requirements, including TMSR, TMNSR, TMOR and replacement reserves (REPR). We assume that replacement reserves will need to be available on demand in less than one hour.

Step 3. The system operator processes the bids using the unit commitment model A1 (described in the appendix) under the base scenario to determine the optimal commitments for

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[2] Like locational congestion pricing, the use of shadow prices provides a way to develop reasonable price signals before a more decentralized market mechanism is tested for implementation. Moreover, shadow pricing would eliminate some of the last man bidding problem in reserve markets.

energy and reserves jointly. The objective function of the model is to minimize the sum of total energy cost and fixed costs.

Step 4. The system operator reruns the unit commitment model under alternative load scenarios with reserve commitments fixed at the optimal levels obtained in step 3. The market clearing price of energy, ECP, and shadow prices of reserve are recorded for each load scenario. For instance, the shadow prices for TMSR are $SP_{-3}^{TMSR}, \ldots, SP_{+3}^{TMSR}$.

Step 5. A uniform market-clearing price of reserve (RCP) is calculated as follows.

- The shadow price (SP) is from the reserve constraint equations.
- The higher quality reserves will have higher shadow prices than the lower quality ones due to the constraint equations.
- The market-clearing price of reserve equals the expected value of the shadow prices. For instance, the market clearing price for TMSR,
$$RCP^{TMSR} = PR_{-3} \times SP_{-3}^{TMSR} + \ldots + PR_{+3} \times SP_{+3}^{TMSR}.$$
- All reserved resources will receive reserve payments for the capacity committed as follows,

$$\text{Payment} = \text{RCP} \times \text{committed reserve capacity}$$

Step 6. During the dispatch process, the merit order in the real-time stack is determined according to 1) the energy bids for the scheduled energy units and 2) the energy bids plus the reliability adder, *SP*, for the reserved units. This will cause the dispatch order for reserved units to be deferred in real-time.

Step 7. The market clearing price of energy, ECP, will be calculated after dispatch as the energy bid of the marginal energy unit or the energy bids plus the reliability adder if the marginal unit is a reserved unit. All resources that are dispatched in merit order will receive energy payments for the amount of energy generated according to the following formula:

For all units not on reserve: Payment = ECP × energy generated

For reserved units: Payment = (ECP – reliability adder) × energy generated

Step 8. All units that are dispatched out of merit order will be compensated as follows.

For constrained-off units:

Payment = [Min(Economic output, HOL) – Generation]x [ECP – Energy bid]

For constrained-on units (uplift):

Payment = [Generation – Max(Economic output, LOL)] × [Energy bid – ECP]

4.2. Day-ahead reserve markets with reserve and energy bids

In this section, we describe a more sophisticated design of day-ahead reserve markets. This approach allows for energy and reserve bids, enabling reserve bids to include information such as bilateral and external trading opportunity costs.

The use of unit commitment models in competitive electricity markets raises new technical issues. At a workshop co-sponsored by EPRI/DYMACS in 1999, researchers around the world reviewed a broad range of issues associated with the new generation of unit commitment models. The papers presented at the workshop will be published in a new book co-edited by Hobbs, Rothkopf, O'Neal and Chao in late 2000. In particular, the unit commitment model that supports reserve bidding with a three-part bid format involves solving a mixed integer programming (MIP) problem. MIP represents a class of problem whose computational complexity remains beyond the reach of the fastest computers available today. In practice, heuristics are often employed to search for satisfactory solutions. Therefore, the solution is usually not unique, and the choice of a particular solution may have substantially different impacts on different market participants. Therefore, this may raises the potential concern of equity in addition to the optimality of solution.

For simplicity, we describe an auction design in which the bidders are expected to incorporate fixed costs in reserve bids.[3] The detailed procedure for such a design is described below.

Step 1. Each day, the system operator announces, for example, seven sets of hourly load forecasts for the next day, including a base scenario (index by 0) and a number of alternative scenarios (-3, -2, -1, +1, +2, +3) with estimated ranges of load and probabilities (PR_{-3}, …, PR_{+3}) that the actual load would fall into individual ranges.

Step 2. The resource owners submit bids for all available generation units. Each bid includes the following information:

- High operating limit (HOL) and low operating limit (LOL) – in MW
- Energy prices ($/MWh)
- Reserve capacity levels (MW)
- Reserve prices ($/MW)

Step 3. The system operator processes the bids using the unit commitment model A2 (described in the appendix) under the base scenario to determine the optimal commitments for energy and reserves jointly. The objective function of the model is to minimize the sum of total energy and reserve cost based on bids.[4]

Step 4. The system operator reruns the unit commitment model under alternative load scenarios with reserve commitments fixed at the optimal levels obtained in step 3. The market

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[3] This two-part bidding format has been adopted in California. See Chao and Wilson (2000)

[4] A multiple round auction procedure may be needed to enable bidders to incorporate energy opportunity and fixed costs in reserve bids more accurately. A multiple round auction allows bidders to better estimate their energy opportunity cost. Robert Wilson proposed a method for doing this in California.

clearing price of energy, ECP, and shadow prices of reserve are recorded for each load scenario. For instance, the shadow prices for TMSR are $SP_{-3}^{TMSR}, \ldots, SP_{+3}^{TMSR}$.

Step 5. A uniform market-clearing price of reserve (RCP) is calculated as the expected value of the shadow prices. For instance, the market clearing price for TMSR, RCP^{TMSR} = $PR_{-3} \times SP_{-3}^{TMSR} + \ldots + PR_{+3} \times SP_{+3}^{TMSR}$. All reserved resources will receive reserve payments for the capacity committed as follows,

$$\text{Payment} = \text{RCP} \times \text{committed reserve capacity}$$

Step 6. During the dispatch process, the merit order in the real-time stack is determined according to 1) the energy bids for the scheduled energy units and 2) the energy bids plus the reliability adder, *SP*, for the reserved units. This will cause the dispatch order for reserved units to be deferred in real-time.

Step 7. The market clearing price of energy, ECP, will be calculated after dispatch as the energy bid of the marginal energy unit or the energy bids plus the reliability adder if the marginal unit is a reserved unit. All resources that are dispatched in merit order will receive energy payments for the amount of energy generated according to the following formula:

For all units not on reserve: Payment = ECP $\times$ energy generated

For reserved units: Payment = (ECP – reliability adder) $\times$ energy generated

Step 8. All units that are dispatched out of merit order will be compensated as follows.

For constrained-off units:

Payment = [Min(Economic output, HOL) – Generation] $\times$ [ECP – Energy bid]

For constrained-on units (uplift):

Payment = [Generation – Max(Economic output, LOL)] $\times$ [Energy bid – ECP]

4.3. Day-ahead reserve markets with reserve/energy bids and reserve demand function

In this section, we describe an even more sophisticated design for forward reserve markets. The main difference from the previous design is that this approach allows for the use of an elastic reserve demand function in conjunction with reserve bids to set the reserve requirements. The demand curve is expressed here as "expected outage costs" and is a function of the reserve quantities. The reserve quantities are variables. That is, less is actually purchased day-ahead.

The detailed procedure for such a design is described below.

Step 1. Each day, the system operator announces, for example, seven sets of hourly load forecasts for the next day, including a base scenario (index by 0) and a number of alternative scenarios (-3, -2, -1, +1, +2, +3) with estimated ranges of load and probabilities (PR_{-3}, …, PR_{+3}) that the actual load would fall into individual ranges.

Step 2. The resource owners submit bids for all available generation units. Each bid includes the following information:

- High operating limit (HOL) and low operating limit (LOL) – in MW
- Energy prices ($/MWh)
- Reserve capacity levels (MW)
- Reserve prices ($/MW)

Step 3. The system operator processes the bids using the unit commitment model A3 (described in the appendix) under the base scenario to determine the optimal reserve requirements and commitments for energy and reserves jointly. The objective function of the model is to minimize the sum of total energy and reserve cost based on bids and the expected outage cost. A multiple round auction procedure may be needed to enable bidders to incorporate fixed costs in reserve bids more accurately.

Step 4. The system operator reruns the unit commitment model under alternative load scenarios with reserve commitments and requirements fixed at the optimal levels obtained in step 3. The market clearing price of energy, ECP, and shadow prices of reserve are recorded for each load scenario. For instance, the shadow prices for TMSR are $SP_{-3}^{TMSR}, \ldots, SP_{+3}^{TMSR}$.

Step 5. A uniform market-clearing price of reserve (RCP) is calculated as the expected value of the shadow prices. For instance, the market clearing price for TMSR, RCP^{TMSR} = $PR_{-3} \times SP_{-3}^{TMSR} + \ldots + PR_{+3} \times SP_{+3}^{TMSR}$. All reserved resources will receive reserve payments for the capacity committed as follows,

$$\text{Payment} = \text{RCP} \times \text{committed reserve capacity}$$

Step 6. During the dispatch process, the merit order in the real-time stack is determined according to 1) the energy bids for the scheduled energy units and 2) the energy bids plus the reliability adder, *SP*, for the reserved units. This will cause the dispatch order for reserved units to be deferred in real-time.

Step 7. The market clearing price of energy, ECP, will be calculated after dispatch as the energy bid of the marginal energy unit or the energy bids plus the reliability adder if the marginal unit is a reserved unit. All resources that are dispatched in merit order will receive energy payments for the amount of energy generated according to the following formula:

For all units not on reserve: Payment = ECP $\times$ energy generated

For reserved units: Payment = (ECP – reliability adder) $\times$ energy generated

Step 8. All units that are dispatched out of merit order will be compensated as follows.

For constrained-off units:

Payment = [Min(Economic output, HOL) – Generation]x [ECP – Energy bid]

For constrained-on units (uplift):

Payment = [Generation – Max(Economic output, LOL)] × [Energy bid – ECP]

5. Conclusion

To be added.

Appendix

In this appendix, we present alternative mathematical formulations of unit commitment discussed in the proposal. These formulations include the following features:

- Co-optimize energy and reserve with reserve requirement constraints
- Include limits for each type of reserve on each generating resource
- Include limits on overall system ramping capability (a load following requirement)
- Include forward cascading of higher to lower quality reserve types

The key notation used in the formulations is summarized below.

i: index for units
j, k: indices for reserve type
t: time index
D: load
Δ, δ: ramp rates
u: commitment decision
q: power generation
r: scheduled reserve
$\hat{R}$: reserve requirement
R: max reserve available
b: reserve bid
$C(.)$: total energy cost
$S(.)$: adjustment (start-up and shut-down) cost
EOC: expected outage cost

A1. To minimize the sum of the total energy cost and fixed costs

$$\underset{u\in\{0,1\},q,r}{\text{Minimize}} \sum_{t=1}^{\mathrm{T}} \sum_{i=1}^{I} C_i(q_{it}) + \sum_{i=1}^{n} S_i(u_{i1},\ldots,u_{iT}),$$

subject to

$$\sum_{i=1}^{I} q_{it} = D_t, \text{ for } t = 1,\ldots,T$$

$$\sum_{j=1}^{k} \sum_{i=1}^{I} r_{it}^{j} \ge \sum_{j=1}^{k} \hat{R}_t^{j}, \text{ for } k = 1,\ldots,J;\ t = 1,\ldots,T$$

$$0 \le r_{it}^{j} \le u_{it} R_{it}^{j}, \text{ for } j \in Spin;\ i = 1,\ldots,I;\ t = 1,\ldots,T$$

$$0 \le r_{it}^{j} \le R_{it}^{j}, \text{ for } j \in Non-Spin;\ i = 1,\ldots,I;\ t = 1,\ldots,T$$

$$q_{it} + u_{it} \sum_{j=1}^{J} r_{it}^{j} \le u_{it} HOL_i, \text{ for } i = 1,\ldots,I;\ t = 1,\ldots,T$$

$$q_{it} \ge u_{it} LOL_i, \text{ for } i = 1,\ldots,I;\ t = 1,\ldots,T$$

$$q_{it} - q_{i,t-1} \le \Delta_i, \text{ for } u_{it} = u_{i,t-1} = 1$$

$$q_{it} - LOL_i \le \boldsymbol{d}_i, \text{ for } u_{it} = 1, u_{i,t-1} = 0$$

A2. Co-optimize energy and reserve bids

$$\underset{u\in\{0,1\},q,r}{\text{Minimize}} \sum_{t=1}^{T}\sum_{i=1}^{I} C_i(q_{it}) + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} b_{it}^{j} r_{it}^{j}$$

subject to

$$\sum_{i=1}^{I} q_{it} = D_t, \text{ for } t = 1,\dots,T$$

$$\sum_{j=1}^{k}\sum_{i=1}^{I} r_{it}^{j} \geq \sum_{j=1}^{k} \hat{R}_t^{j}, \text{ for } k = 1,\dots,J$$

$$0 \leq r_{it}^{j} \leq u_{it} R_{it}^{j}, \text{ for } j \in Spin$$

$$0 \leq r_{it}^{j} \leq R_{it}^{j}, \text{ for } j \in Non-Spin$$

$$q_{it} + u_{it}\sum_{j=1}^{J} r_{it}^{j} \leq u_{it} HOL_i$$

$$q_{it} \geq u_{it} LOL_i$$

$$q_{it} - q_{i,t-1} \leq \Delta_i, \text{ for } u_{it} = u_{i,t-1} = 1$$

$$q_{it} - LOL_i \leq \boldsymbol{d}_i, \text{ for } u_{it} = 1, u_{i,t-1} = 0$$

A3. Co-optimize energy and reserve bids with reserve demand function

$$\underset{u\in\{0,1\},q,r,\hat{R}}{\text{Minimize}} \sum_{t=1}^{T}\sum_{i=1}^{I} C_i(q_{it}) + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} b_{it}^{j} r_{it}^{j} + \sum_{t=1}^{T} EOC(\hat{R}_t^{1},\dots,\hat{R}_t^{J})$$

subject to

$$\sum_{i=1}^{I} q_{it} = D_t, \text{ for } t = 1,\dots,T$$

$$\sum_{j=1}^{k}\sum_{i=1}^{I} r_{it}^{j} \geq \sum_{j=1}^{k} \hat{R}_t^{j}, \text{ for } k = 1,\dots,J$$

$$0 \leq r_{it}^{j} \leq u_{it} R_{it}^{j}, \text{ for } j \in Spin$$

$$0 \leq r_{it}^{j} \leq R_{it}^{j}, \text{ for } j \in Non-Spin$$

$$q_{it} + u_{it}\sum_{j=1}^{J} r_{it}^{j} \leq u_{it} HOL_i$$

$$q_{it} \geq u_{it} LOL_i$$

$$q_{it} - q_{i,t-1} \leq \Delta_i, \text{ for } u_{it} = u_{i,t-1} = 1$$

$$q_{it} - LOL_i \leq \boldsymbol{d}_i, \text{ for } u_{it} = 1, u_{i,t-1} = 0$$