Quasi-Stochastic Electricity Markets

Jacob Mays

FERC Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency and Enhancing Resilience through Improved Software

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Motivation

Rich Glick
@RichGlickFERC

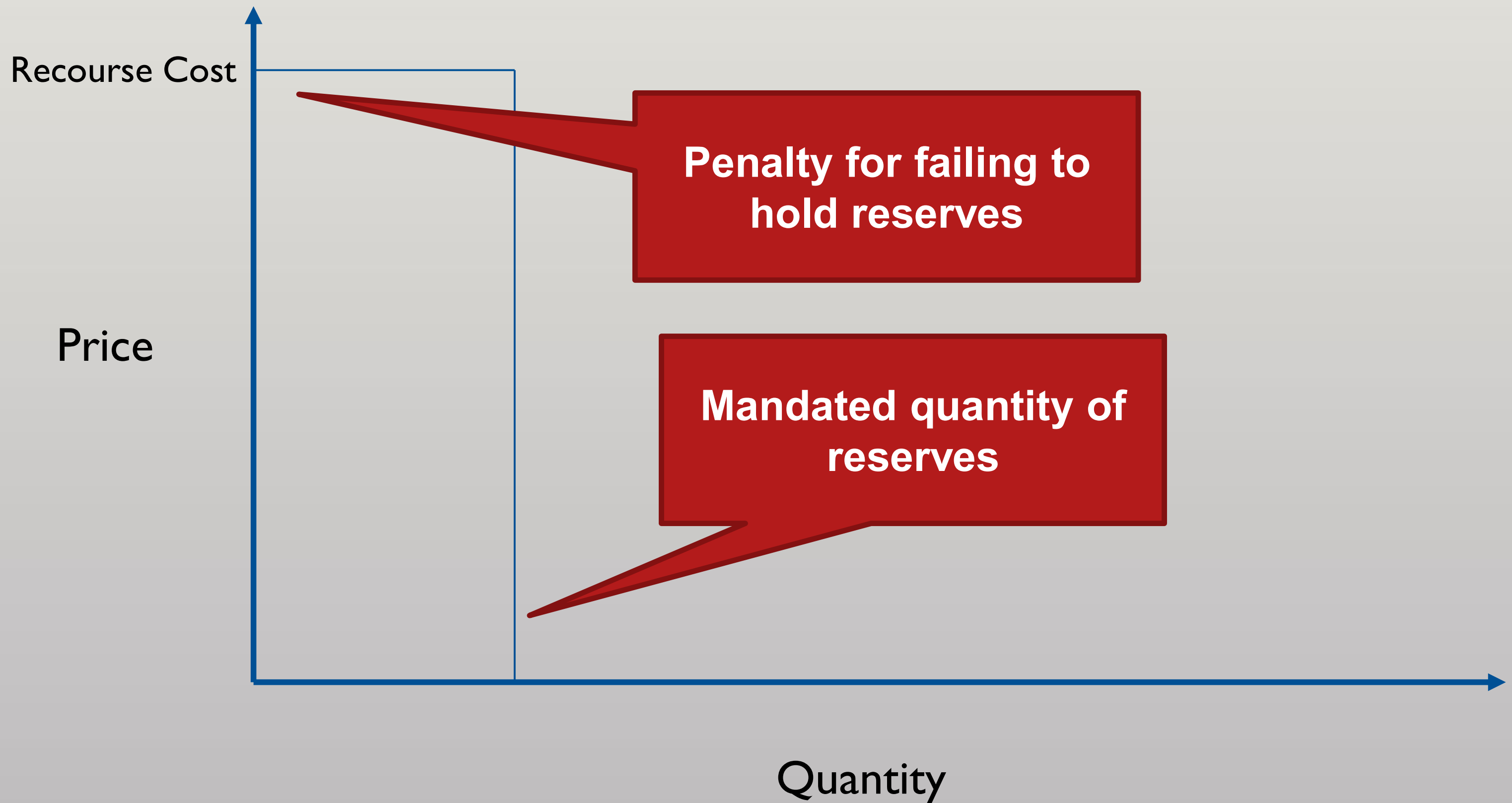
I dissent on @FERC's overhaul of @PJMinterconnect's energy & reserve market design. #FERC is forcing consumers to pay scarcity pricing all of the time – regardless of scarcity or not. This is expected to cost consumers between $500 Million to $2 Billion w/o additional benefits.

10:54 AM · May 21, 2020 · Twitter Web App

Operating reserve demand curves

ORDC proposals alter demand for reserves above minimum quantity

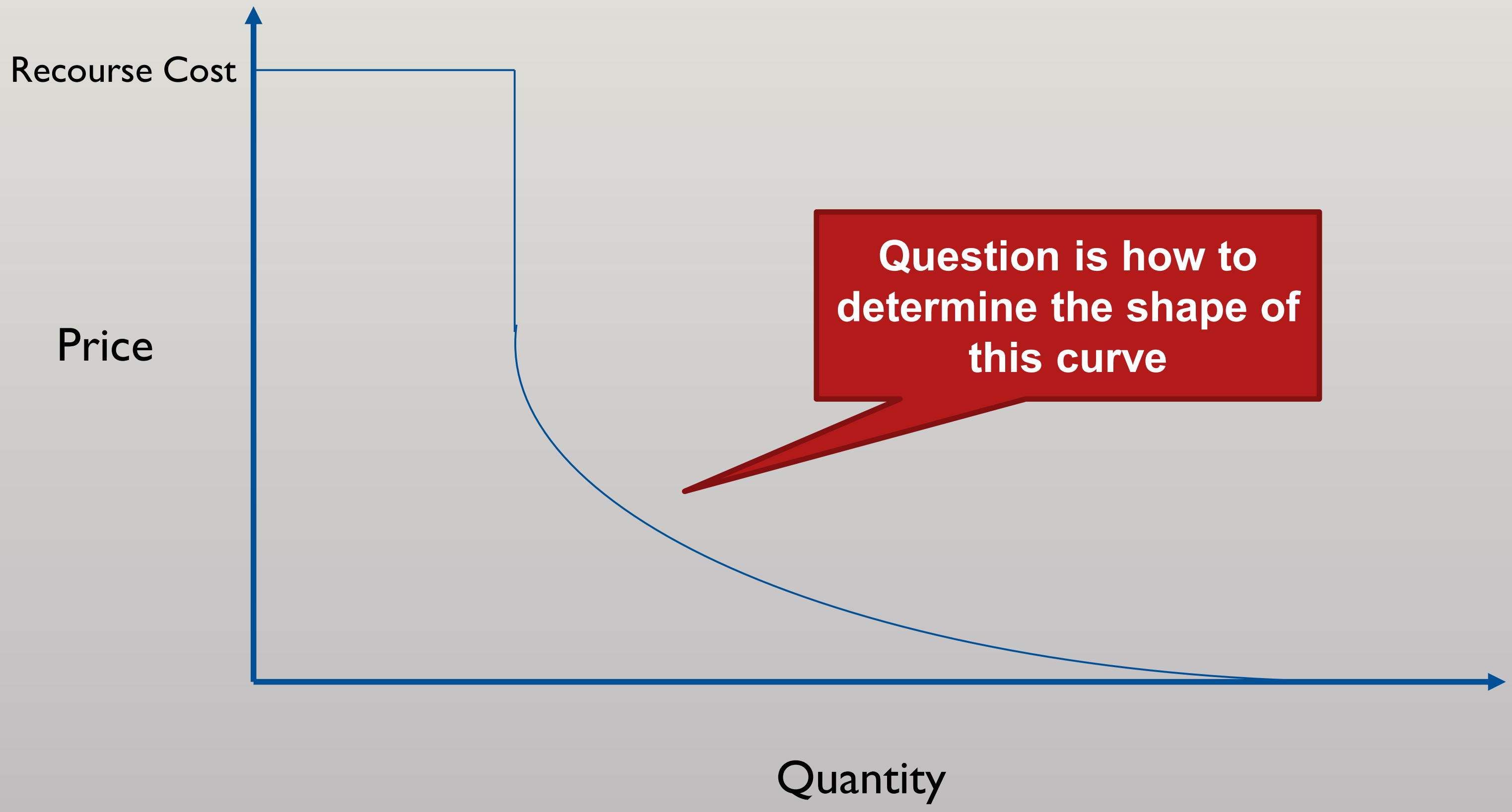
Vertical demand curve for operating reserves



Operating reserve demand curves

ORDC proposals alter demand for reserves above minimum quantity

Sloped demand curve for operating reserves



Operating reserve demand curve proposals

- **Current ORDCs are undertheorized, with no shared understanding of why they might be useful or how to construct them**

Contributions

This talk hopes to convince you of three things:

1. **Current deterministic models for unit commitment and economic dispatch lead to inefficient pricing**

2. **The goal of ORDCs should be to approximate outcomes expected in efficient stochastic markets**

3. **If ORDC efforts are successful, uplift payments and enhanced pricing schemes to address non-convexity should be revisited**

Outline

- Stochastic ideal
- Deterministic defects
- Quasi-stochastic improvements
- A challenge for non-convex pricing

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- **Stochastic ideal**
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Stochastic ideal

Solve stochastic unit commitment → Uncertainty resolves → Solve dispatch and pricing

Example system

Suppose we want to serve a known demand of 200 MW in a single period with the following generators:

Resource	Min Output (MW)	Max Output (MW)	No-load Cost ($/period)	Energy Cost ($/MWh)
Wind	0	$U(0,100)$	0	0
Gen 0	0	120	0	50
Gens $n = 1 \ldots 100$	1	1	$n + 50$	0

100 block-loaded units arranged in order of no-load cost

Wind is sole source of uncertainty

Cost is incurred if unit committed

We need to maintain reserves of $20 - \varepsilon$, and have recourse action (or penalty) of $950/MWh in the event of a shortfall

Stochastic unit commitment

Stochastic unit commitment problem for the example system can be stated as

$$\max_{u:u_g \in \{0,1\}} \quad -\sum_{g \in G} C_g^{NL} u_g + \mathrm{E}[H(u;W)]$$

Commitment status of thermal generators

Expected surplus in dispatch given uncertain wind availability

Stochastic unit commitment

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$$\max_{u:u_g\in\{0,1\}} \quad -\sum_{g\in G} C_g^{NL} u_g + \mathrm{E}[H(u;W)]$$

Observations:

- **If available wind $W = 50$ MW, need 170 MW of thermal capacity to meet 200 MW while providing $20 - \varepsilon$ MW of reserves**
- **This can be achieved with 120 MW from Generator 0 plus 50 block-loaded units**

Stochastic unit commitment

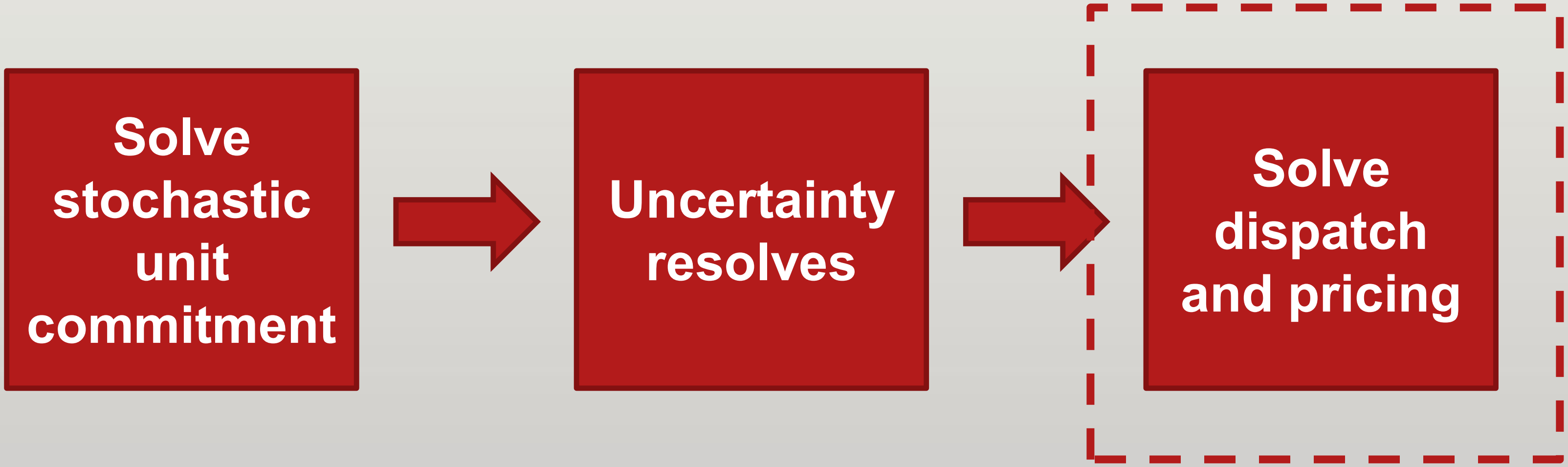
Stochastic unit commitment problem for the example system can be stated as

$$\max_{u:u_g\in\{0,1\}} \quad -\sum_{g\in G} C_g^{NL} u_g + \mathrm{E}[H(u;W)]$$

Solution:

- **Optimal: commit Gen 0 through Gen 90**
- **210 MW of thermal capacity is committed**
- **Ten percent chance of reserve shortfall**
- **Last unit committed has total cost $C_{90}^{NL} = \$140$**

Stochastic ideal



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Economic dispatch with known wind

Value of serving load

Value of reserves

Cost of energy

$$\max_{p,r,d,o,w} \quad V^D d + V^R o - \sum_{g \in G} C_g^{EN} p_g$$

$$s.t. \quad d - w - \sum_{g \in G} p_g = 0$$

Power balance

System reserve supply

$$o - \sum_{g \in G} r_g = 0$$

Minimum and maximum resource injections and withdrawal

$$P_g^- u_g \le p_g \qquad \forall g \in G$$

$$p_g + r_g \le P_g^+ u_g \qquad \forall g \in G$$

$$d \le D^+, o \le R^+, w \le W$$

$$p_g, r_g \ge 0 \qquad \forall g \in G$$

$$d, o, w \ge 0$$

Commitment status fixed

$$u_g = \hat{u}_g \qquad \forall g \in G$$

Pricing

Prices come from economic dispatch problem:

$$\max_{p,r,d,o,w} \quad V^D d + V^R o - \sum_{g \in G} C_g^{EN} p_g$$

$$s.t. \quad d - w - \sum_{g \in G} p_g = 0$$

$$o - \sum_{g \in G} r_g = 0$$

$$P_g^- u_g \le p_g \qquad \forall g \in G$$

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$$u_g = \hat{u}_g \qquad \forall g \in G$$

Dual to power balance constraint gives energy price (LMP)

Dual to reserves constraint gives reserve price

Pricing results

- **LMP $\lambda(W;\hat{u})$ and reserve clearing price $\mu(W;\hat{u})$ depend on the chosen commitment solution $\hat{u}$ as well as the realization of wind W**
- **Assume optimal commitment $u^* = \hat{u}$ is chosen, i.e., 210 MW of thermal capacity is committed**

Prices given optimal commitment

Range	Probability	Wind (MW)	$\lambda(W;\hat{u})$	$\mu(W;\hat{u})$
1	0.1	$0 \leq W < 10$	\$1,000/MWh	\$950/MWh
2	0.9	$10 \leq W \leq 100$	\$50/MWh	\$0/MWh

Average LMP of \$145/MWh driven by 10% chance of reserve shortage

Bid cost recovery in expectation

Consider profitability of most expensive committed unit, Generator 90:

- **Incurs no-load cost of $\$140$**
- **Produces one unit of energy**
- **If $W \geq 10$, has loss of $\$140 - \$50 = \$90$**
- **If $W < 10$, has profit of $\$1,000 - \$140 = \$860$**
- **In expectation, profit of $\$5$ without any need for make-whole payments in scenarios with losses**
- **Expected profit would be exactly $\$0$ for marginal generator in convex system**

▶ **Bid cost recovery is not guaranteed in every scenario, but holds in expectation**

Stochastic market clearing

Principle of competitive markets:

- **Want the commitment and production schedule preferred by generators to be socially optimal**
- **If Generator 90 is risk neutral and shares the system operator's estimate of wind distribution, prefers to be committed despite potential for loss**

Bid cost recovery in expectation is a key property of stochastic competitive equilibrium

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- **Deterministic defects**
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Pricing issues

Two mechanisms, both connected to the use of deterministic models, likely lead to inefficiently low prices in current markets:

1. **Load biasing in deterministic non-market reliability unit commitment processes**

2. **Point forecasts in deterministic economic dispatch models**

Deterministic unit commitment

Suppose operators use a deterministic unit commitment model in the example system:

Deterministic unit commitment

Deterministic UC with average wind output:

$$\max_{u,p,r,d,o,w} \quad V^D d + V^R o - \sum_{g \in G} (C_g^{NL} u_g + C_g^{EN} p_g)$$

$$s.t. \quad d - w - \sum_{g \in G} p_g = 0$$

$$\text{o} - \sum_{g \in G} r_g = 0$$

$$P_g^- u_g \le p_g \qquad \forall g \in G$$

$$p_g + r_g \le P_g^+ u_g \qquad \forall g \in G$$

$$d \le D^+, o \le R^+, w \le \overline{W}$$

$$p_g, r_g \ge 0 \qquad \forall g \in G$$

$$d, o, w \ge 0$$

Replace wind random variable with its expected value

Deterministic unit commitment

Deterministic unit commitment on its own will not yield good solution given underlying uncertainty:

- **Demand of 200 MW**
- **Reserves of $20 - \varepsilon$**
- **Wind assumed at 50 MW**
- **Balance of 170 MW supplied by 120 MW from Generator 0 plus 50 block-loaded units**

With no adjustments, deterministic solution is to commit only 50 block-loaded units instead of 90

Load biasing

Operators can bias load to produce a better solution:

$$\max_{u,p,r,d,o,w} \quad V^D d + V^R o - \sum_{g \in G} (C_g^{NL} u_g + C_g^{EN} p_g)$$

$$s.t. \quad d + b - w - \sum_{g \in G} p_g = 0$$

$$o - \sum_{g \in G} r_g = 0$$

$$P_g^- u_g \le p_g \qquad \forall g \in G$$

$$p_g + r_g \le P_g^+ u_g \qquad \forall g \in G$$

$$d \le D^+, o \le R^+, w \le \overline{W}$$

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$$d, o, w \ge 0$$

Add biasing term b to power balance constraint

- **Ideally, operators choose bias $b = 40$ to induce optimal solution of 90 block-loaded units**

Price effect of load biasing

Committing additional units affects the probability of reserve shortfall after uncertainty is realized

Expected prices given different load biases

Bias	Probability of Reserve Shortfall	$E[\lambda(W;\hat{u})]$
40	0.10	$145.00/MWh
45	0.05	$97.50/MWh
50	0.00	$50.00/MWh

Expected prices drop below total cost of most expensive unit

- **Any conservatism on the part of operators can lead to violation of bid cost recovery in expectation**

Point forecasts in economic dispatch

In reality, random variables are known only after dispatch, and vary throughout dispatch interval:

Economic dispatch with nominal wind

Deterministic ED with average wind output:

$$\max_{p,r,d,o,w} \quad V^D d + V^R o - \sum_{g\in G} C_g^{EN} p_g$$

$$s.t. \quad d - w - \sum_{g\in G} p_g = 0$$

$$o - \sum_{g\in G} r_g = 0$$

$$P_g^- u_g \le p_g \qquad \forall g \in G$$

$$p_g + r_g \le P_g^+ u_g \qquad \forall g \in G$$

$$d \le D^+, o \le R^+, w \le \overline{W}$$

$$p_g, r_g \ge 0 \qquad \forall g \in G$$

$$d, o, w \ge 0$$

$$u_g = \hat{u}_g \qquad \forall g \in G$$

Replace wind random variable with its expected value

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Price effect of point forecasts

- **Price from deterministic model is marginal cost under expected operating conditions**
- **In example system, if $\overline{W} = 50$ MW is used then reserves are plentiful and $\lambda(\overline{W}; \hat{u}) = \$50/\text{MWh}$**
- **Price under expected conditions is much lower than expected price given potential conditions, i.e.,**

$$\lambda(\overline{W}; \hat{u}) < E[\lambda(W; \hat{u})]$$

With "hockey-stick" marginal cost curves typical of electricity markets, point forecasts can prevent bid cost recovery in expectation

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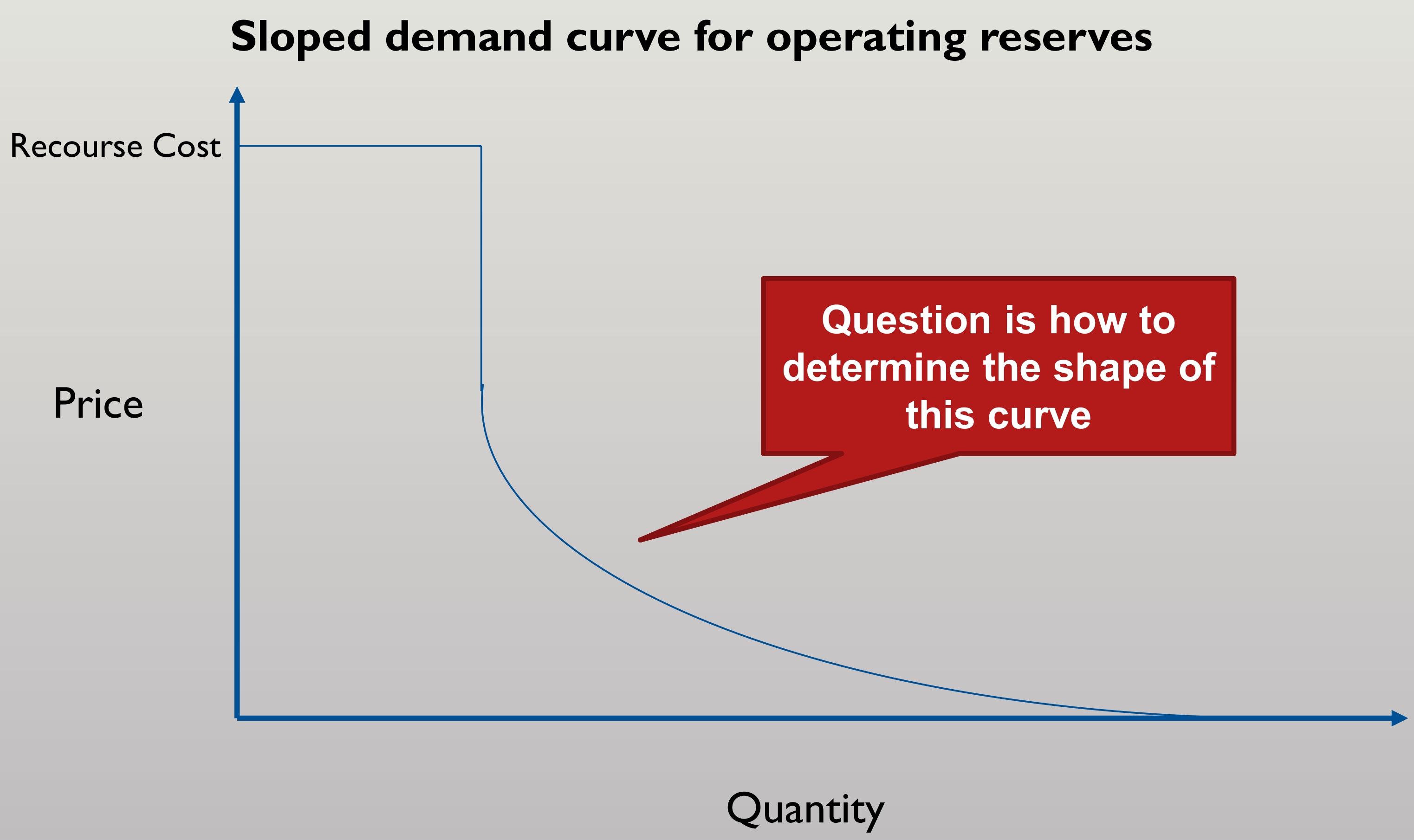
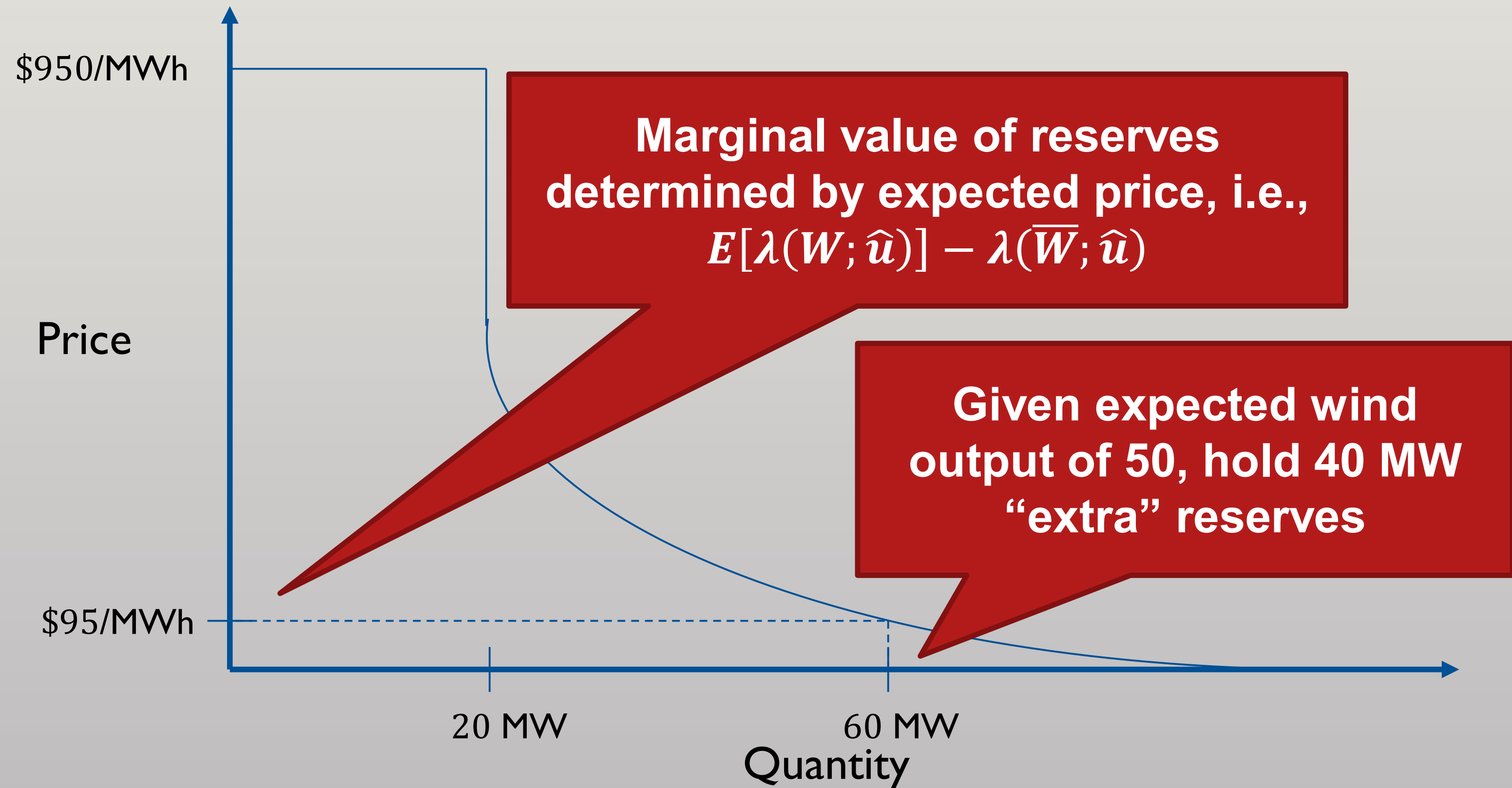


Approximating the stochastic ideal

Proposed goal for ORDCs is to connect marginal value with prices arising stochastic model

Sloped demand curve for operating reserves



Economic dispatch with sloped ORDC

ORDC segments defined based on marginal value

$$\max_{p,r,d,o,w} \quad V^D d + \sum_{c \in C} V_c^O o_c - \sum_{g \in G} C_g^{EN} p_g$$

$$s.t. \quad d - w - \sum_{g \in G} p_g = 0$$

$$o - \sum_{g \in G} r_g = 0$$

$$P_g^- u_g \leq p_g \quad \forall g \in G$$

$$p_g + r_g \leq P_g^+ u_g \quad \forall g \in G$$

$$d \leq D^+, o \leq R^+, w \leq \overline{W}$$

$$p_g, r_g \geq 0 \quad \forall g \in G$$

$$o_c \geq 0 \quad \forall c \in C$$

$$d, w \geq 0$$

$$u_g = \hat{u}_g \quad \forall g \in G$$

Clearing price for energy determined by reserve price plus marginal energy cost = $145/MWh

Clearing price for reserves determined by marginal value = $95/MWh

Wind random variable retains its expected value

Implementation

- Proposed goal of ORDC is to approximate outcomes of stochastic ideal:
  - Restore expected energy price (or revenue)
  - Restore (approximately) the property of bid cost recovery in expectation
- Could achieve this goal through various means:
  - Direct calculation of prices and quantities through stochastic model (see working paper)
  - Inferring expected prices through load bias and commitments in deterministic model
  - Ex-post evaluation of administrative ORDCs developed through other means

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Uplift payments

Stochastic analysis prompts a reevaluation of the notions of uplift and bid cost recovery

Deterministic analysis	Stochastic analysis
• Losses are due to non-convexity • Need side payments to guarantee bid cost recovery and ensure generators have incentive to participate in market	• Losses are due to unlucky random variable realizations • Prices without side payments provide appropriate incentives • Effect of side payments is socializing losses and privatizing gains

To properly justify enhanced pricing schemes, need ex ante rather than ex post analysis

Conclusion

1. Current deterministic models for unit commitment and economic dispatch lead to inefficient pricing

2. The goal of ORDCs should be to approximate outcomes expected in efficient stochastic markets

3. If ORDC efforts are successful, uplift payments and enhanced pricing schemes to address non-convexity should be revisited

- Working paper posted at http://www.optimization-online.org/DB_HTML/2019/10/7414.html

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