Sequential Pricing of Electricity

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PSERC Webinar

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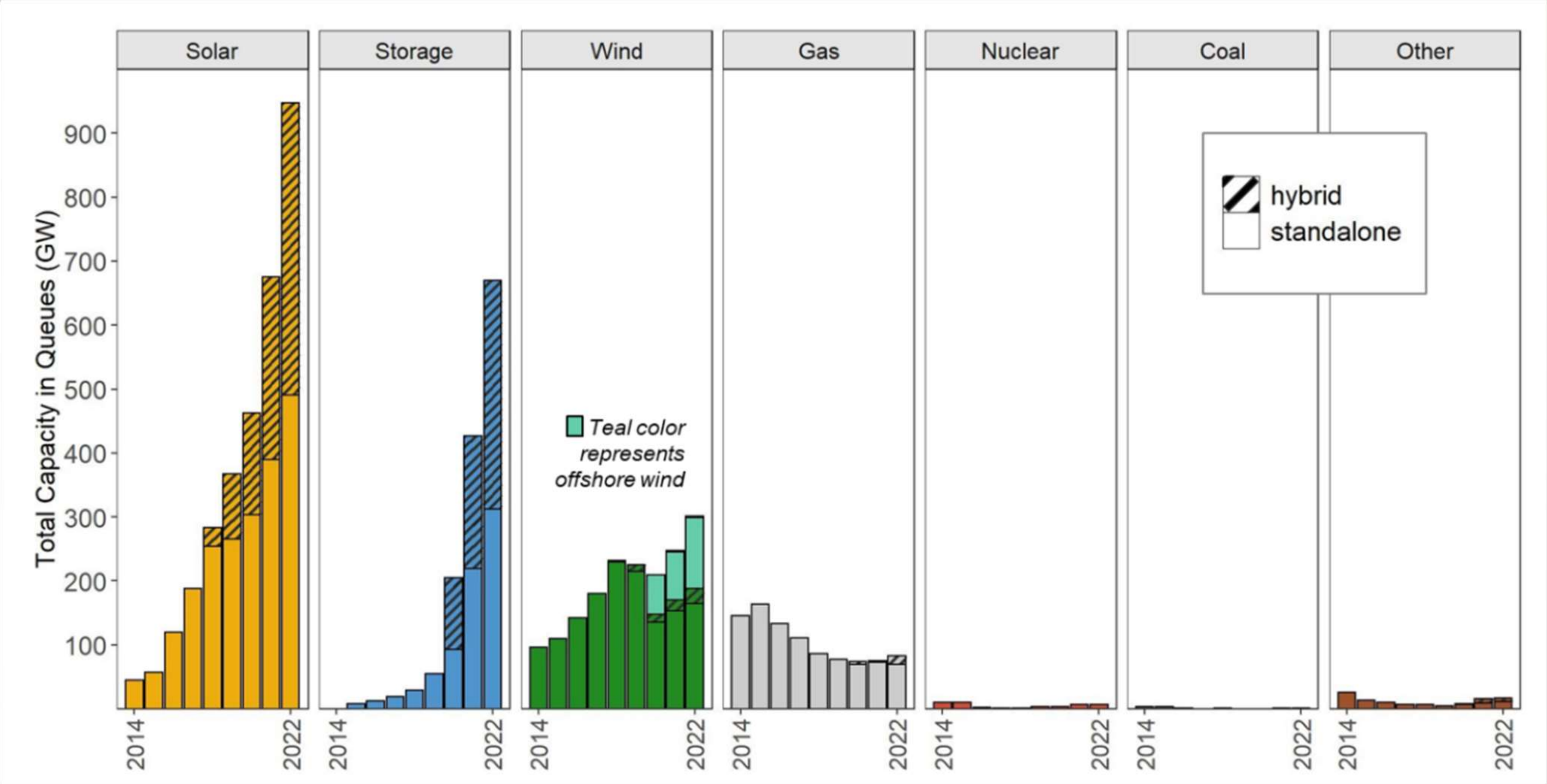
Interconnection queues

Interconnection queues across the country are dominated by solar, storage, and wind



Source: https://emp.lbl.gov/queues

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Market reform backdrop

greentechmedia:

How Wind and Solar Will Blow Up Power Markets

According to Ben Paulos, in the long run, the main zero-carbon energy sources are not compatible with conventional market design.

- **Variability, uncertainty, non-convexity, and intertemporal constraints present growing challenges for price formation**

The “existential challenge”

“Some resource … have low or no marginal costs … This fact, in our opinion, poses an existential challenge to the continuing operation of single-clearing priced auction markets for energy and related services in RTOs.”

-Tony Clark (former FERC commissioner) and Vincent Duane (former PJM executive)

Pricing reforms, ERCOT edition

FOX 26 HOUSTON

PUC Commissioners meet to discuss new proposal to improve power grid reliability

- **ERCOT market has contemplated many reforms following the 2021 disaster in Winter Storm Uri**

New market product in Texas

ercot

News Release

Jun 12, 2023

ERCOT Adds New Ancillary Service to Support Grid Reliability

- **“As energy demand continues to grow in Texas, adding ECRS will support grid reliability and mitigate real-time operational issues to keep supply and demand balanced.”**

Benefit cost analysis?

POTOMAC ECONOMICS

“We have evaluated the proposed AS methodology and find that it:

- **Is not based on sound reliability criteria;**
- **…**
- **Generated artificial shortages that produced massive inefficient market costs, totaling more than $12 Billion in 2023; and**
- **Diminished reliability by withholding units that are needed to manage transmission congestion.”**

Pricing reforms, PJM edition

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

- **In long process, FERC approved changes to PJM reserve products, then changed its mind a year later**

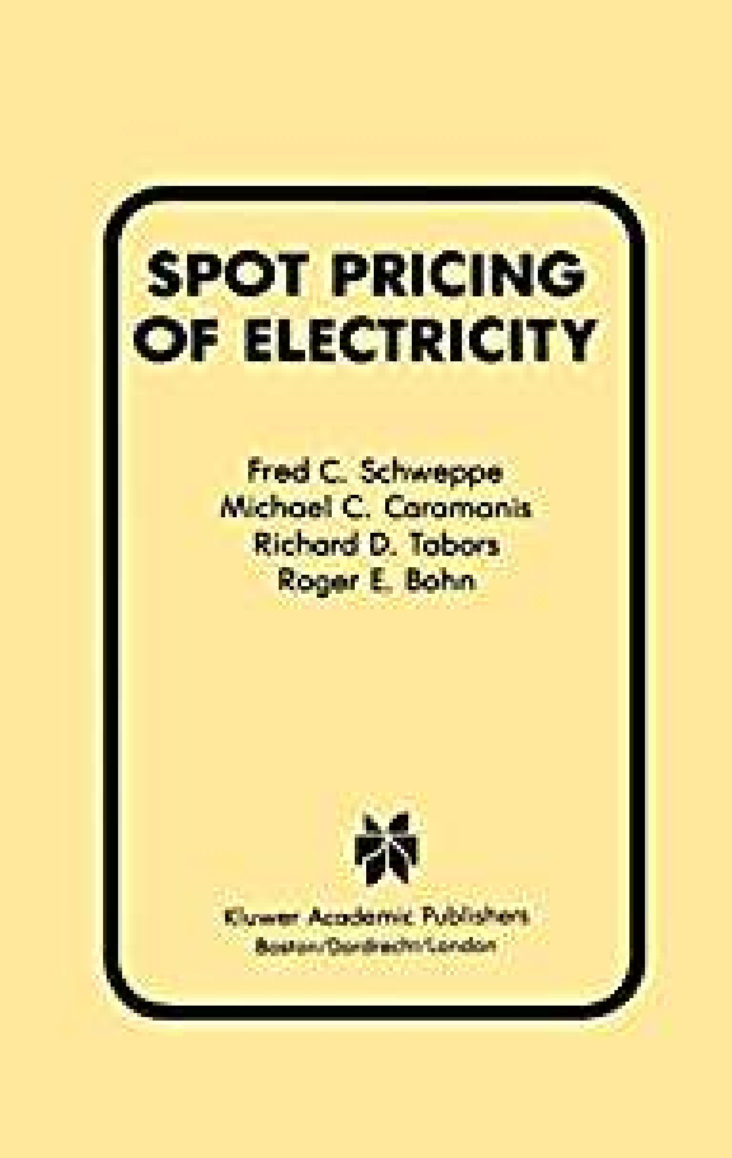
Motivation

1. Market reforms have significant consequences for cost, reliability, and climate impacts

2. Market operators and regulators do not have tools capable of correctly assessing market reforms

Return to first principles

What are we trying to accomplish with price formation?



Market design philosophy

Principle of competitive markets:

Transparent & Complete Price Signals → **Efficient Investment and Operation**

- **Want prices that support efficiency in both short-term operations and long-term investment**

Outline

- Static picture
- Idealized stochastic benchmark
- Sequential decisions
- Pitfalls of price formation design and analysis
- Policies for sequential decisions and prices
- Short-term price formation and long-run efficiency

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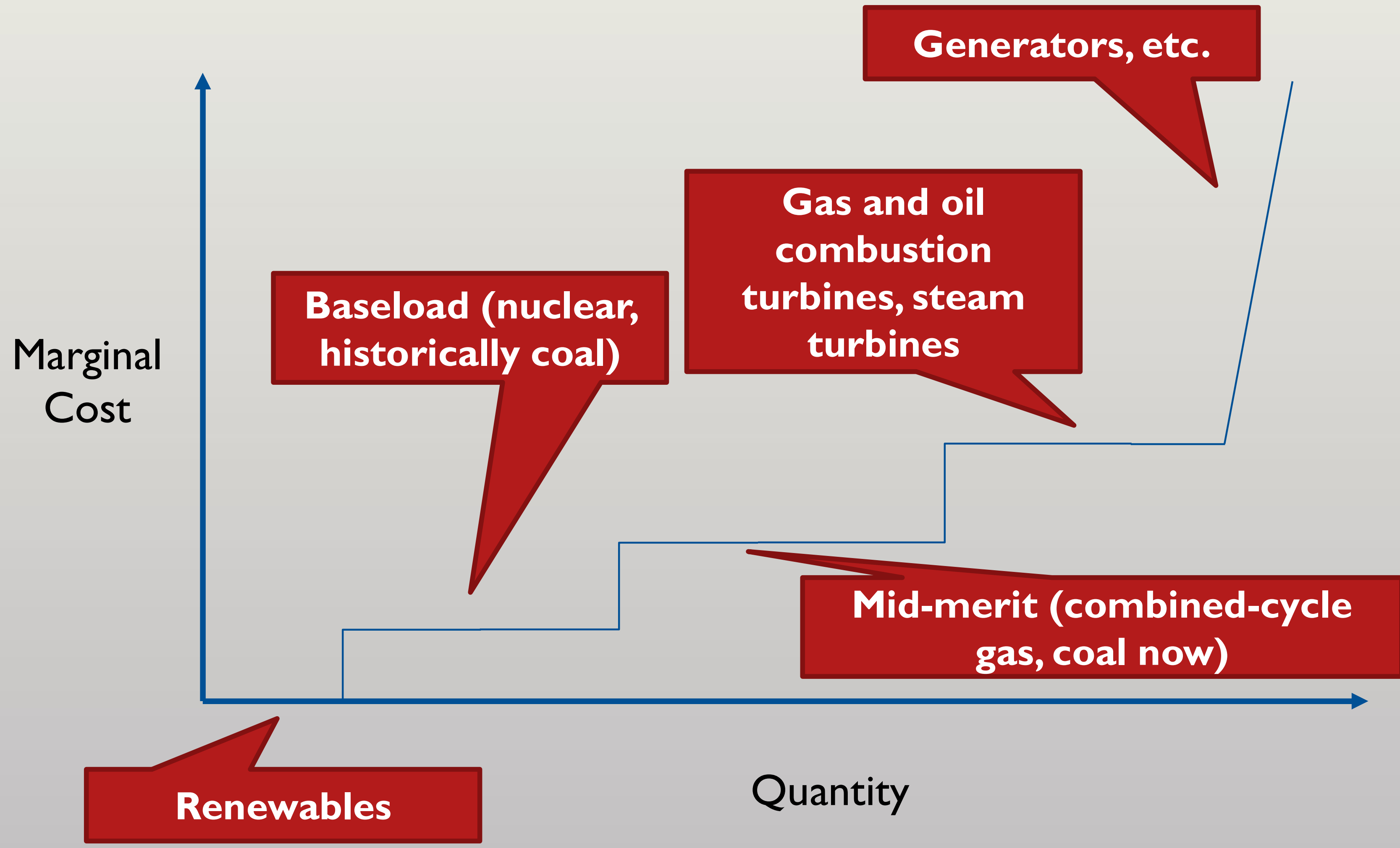
Static, single-period merit order curve



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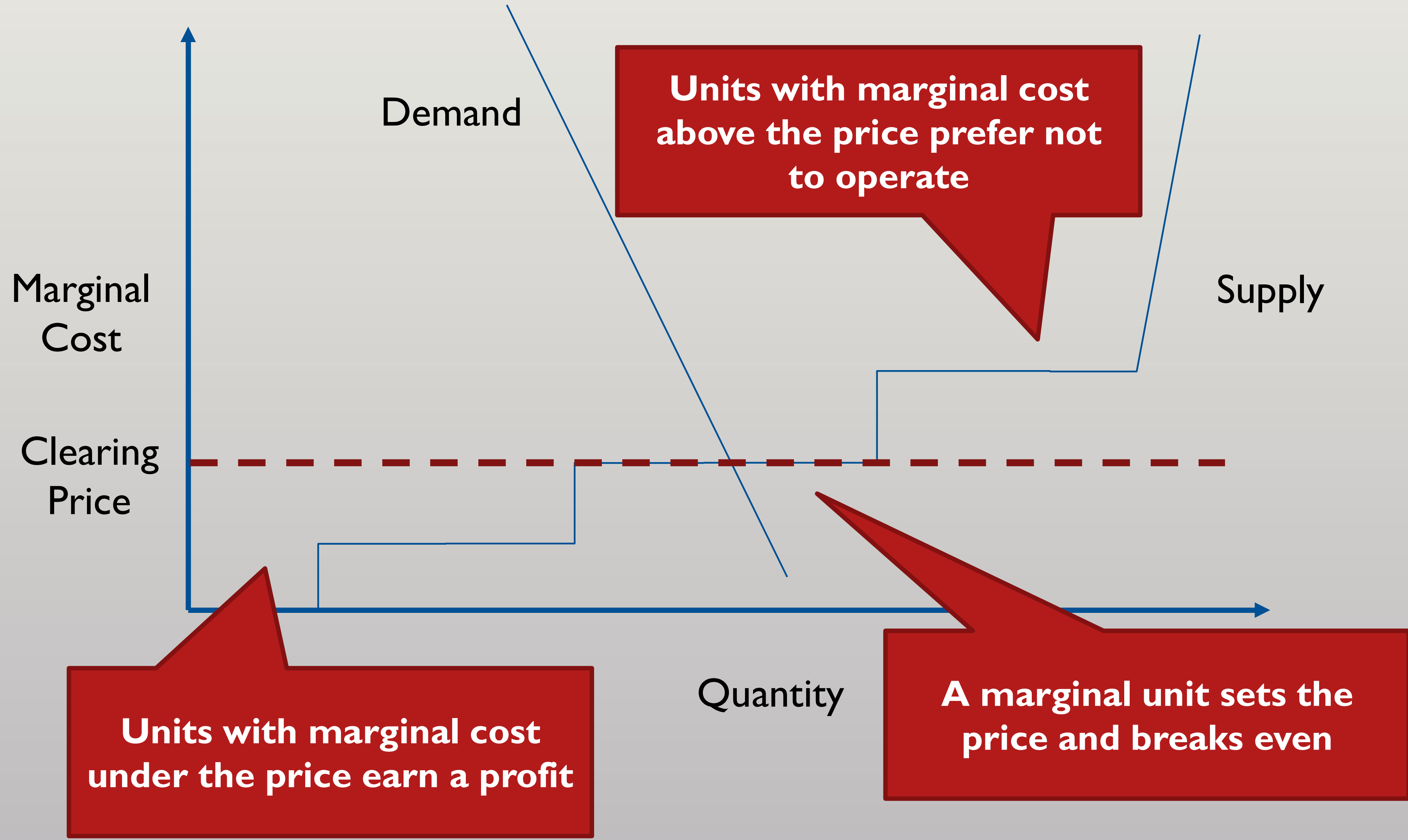
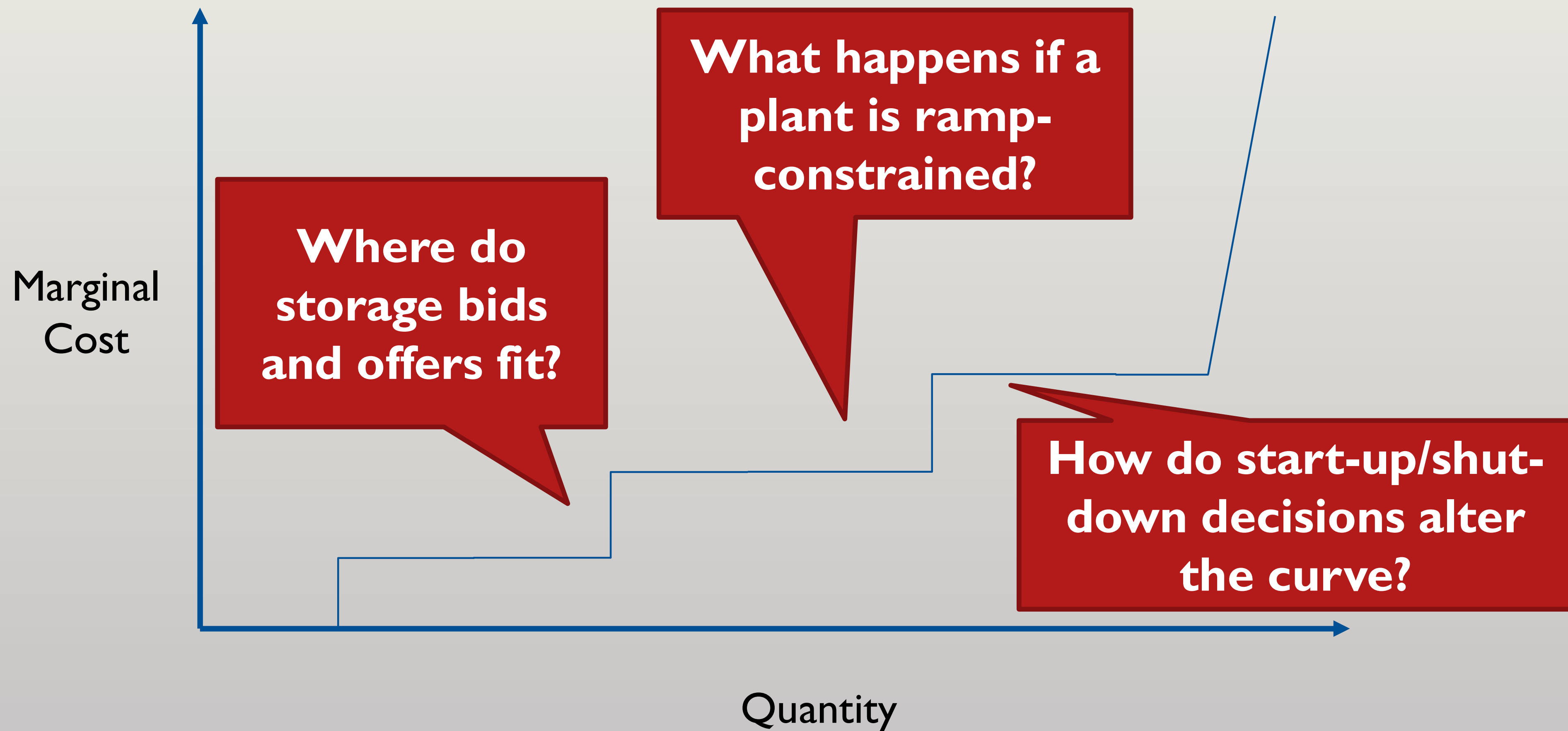
Clearing prices in the static picture



Dynamic questions



- **Need to move from a static to a dynamic view**

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Capacity expansion

Long-term goal is to find a collection of investments that maximizes value of operating the system minus the upfront cost

$$\max_{x} \quad -\sum_{g \in G} C_g^{inv} x_g + \mathrm{E}[V(x;\xi)]$$

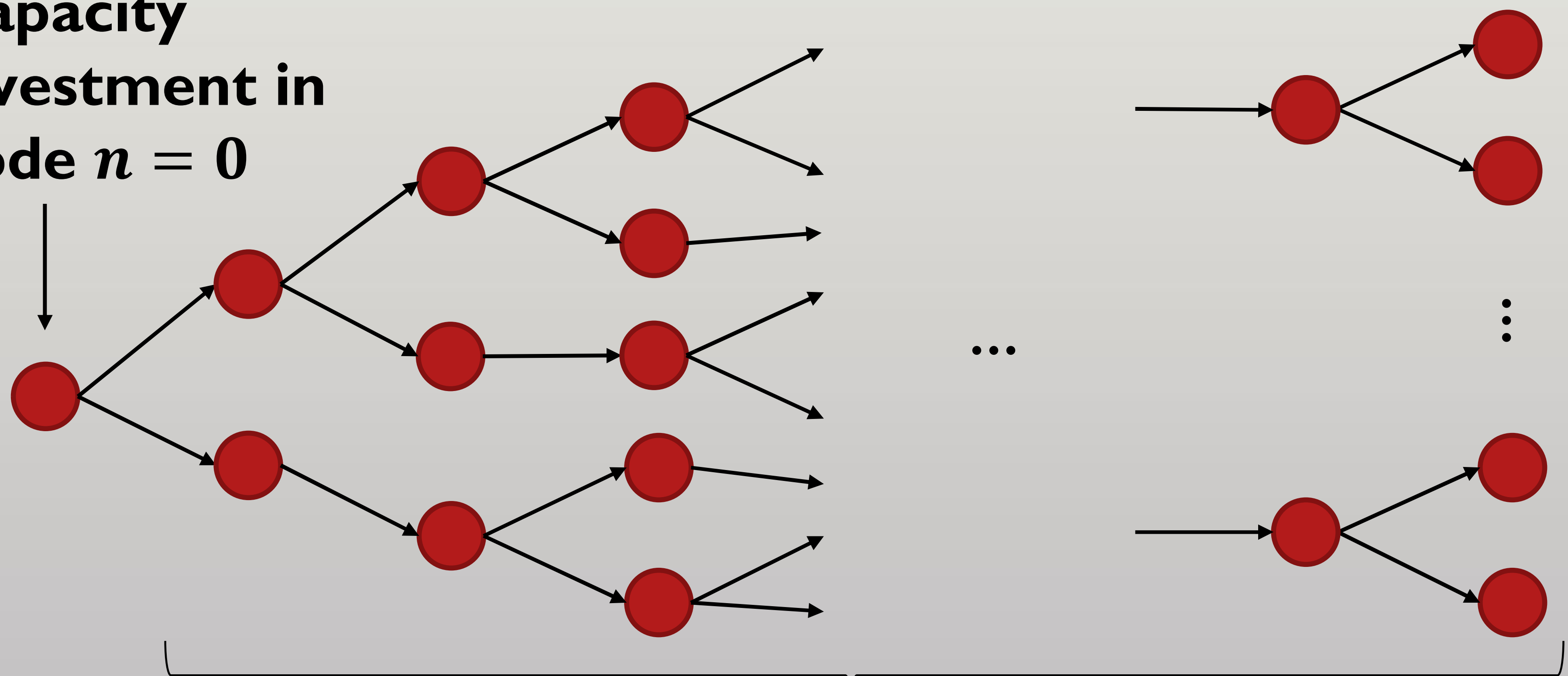
Investment cost

Expected surplus from operations given uncertainty

Modeling idealized prices

Suppose we are solving the joint capacity expansion and operating problem of a risk-neutral social planner:

Capacity investment in node $n = 0$



Year-long (8760 stage) operation under uncertainty through nodes $\mathcal{N}^{OP} = \mathcal{N} \setminus \{0\}$

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Capacity expansion on a tree

Cost of building generation

Cost of building storage

Operating cost of generation

Value of served load

$$\max_{y,p,k,d} \quad -\sum_{g\in\mathcal{G}} C_g^{INV} y_g - \sum_{b\in\mathcal{B}} C_b^{INV} y_b$$

$$+\sum_{n\in\mathcal{N}^{OP}} \sum_{l\in\mathcal{L}} \phi_n V_l^L d_{ln} - \sum_{n\in\mathcal{N}^{OP}} \sum_{g\in\mathcal{G}} \phi_n C_g^{OP} p_{gn}$$

$$s.t. \quad \sum_{l\in\mathcal{L}} d_{ln} - \sum_{g\in\mathcal{G}} p_{gn} - \sum_{b\in\mathcal{B}} k_b = 0 \qquad \forall n \in \mathcal{N}^{OP}$$

Power balance

Resource-specific constraints

$$\left.\begin{aligned} & p_g \in \mathcal{X}_g(y_g) && \forall g \in \mathcal{G} \\ & k_b \in \mathcal{X}_b(y_b) && \forall b \in \mathcal{B} \\ & d_l \in \mathcal{X}_l && \forall l \in \mathcal{L} \end{aligned}\right.$$

Long-run equilibrium

- Assume convexity and perfect competition
- Allow generic constraints between nodes
  - State of charge
  - Ramping limits
- Setting prices equal to dual of system-wide power balance constraint supports a long-run equilibrium at the socially optimal capacity mix
  - All agents maximize expected profit given individual constraints
  - All generation and storage have zero expected profit

Market design philosophy

Principle of competitive markets:

Transparent & Complete Price Signals	→	Efficient Investment and Operation

- **Idealized prices can be derived from an arbitrarily large stochastic program**

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Real-world implementations

- Impossible to construct and solve the idealized stochastic program
  - Limits on information
  - Limits on computation
- Instead, real-world operators solve a problem of sequential decisions under uncertainty
- Dual values from algorithms used in practice are unlikely to replicate duals from the idealized stochastic program

How do algorithmic choices in the design of policies for the sequential decision problem affect prices?

Optimizing policies

Operators solve a sequential decision problem (e.g., covering one year with hourly time steps)

We are searching for the best policy mapping states to decisions

We sum over all of the operational time periods, given our starting state S_0

$$\max_{\pi} \mathbb{E}[\sum_{t=1} C_t(S_t, X_t^{\pi}(S_t), W_{t+1})|S_0] \quad (1)$$

Function C_t tells us how much cost we incur in time period t given our state and decision

Policy π gives us a function that maps states S_t to decisions x_t

Base policy: deterministic lookahead

Assume at each time t we solve a deterministic lookahead model to determine our actions:

Look-ahead model covering F periods of the future and accounting for H periods of history

$X_t^{DLAC}(S_t|H,F) \in$

Value of load

Value of reserves

$$\arg\max_{\tilde{x}_t} \sum_{l\in\mathcal{L}} \sum_{t'\in\mathcal{T}_t^{H,F}} V_l^L \tilde{d}_{ltt'} + \sum_{t'\in\mathcal{T}_t^{H,F}} V^R \tilde{z}_{tt'} \qquad (2a)$$

No-load cost

Start-up cost

Energy cost

$$-\sum_{g\in G} \sum_{t'\in\mathcal{T}_t^{H,F}} (C_g^{NL} \tilde{u}_{gtt'} + C_g^{SU} \tilde{v}_{gtt'} + C_g^{EN} \tilde{p}_{gtt'})$$

- **Provisional decisions $\tilde{x}_t$ for all periods $t' \in \mathcal{T}_t^{H,F} = \{t - H, t + F\}$ as well as binding decisions $x_t = \tilde{x}_{tt}$**

Lookahead commitment constraints (1)

Constraints in the deterministic lookahead commitment model:

Power balance, with dual $\tilde{\lambda}_{tt'}$

$$s.t. \sum_{l\in\mathcal{L}} \tilde{d}_{ltt'} - \sum_{g\in\mathcal{G}} \tilde{p}_{gtt'} - \sum_{b\in\mathcal{B}} \tilde{k}_{btt'} = 0 \;\; \forall t' \in \mathcal{T}_t^{H,F} \quad (2b)$$

$$\sum_{l\in\mathcal{L}} \tilde{z}_{ltt'} - \sum_{g\in\mathcal{G}} \tilde{r}_{gtt'} - \sum_{b\in\mathcal{B}} \tilde{r}_{btt'} = 0 \;\; \forall t' \in \mathcal{T}_t^{H,F} \quad (2c)$$

Reserve balance, with dual $\tilde{\mu}_{tt'}$

- **We will derive provisional prices $\tilde{\lambda}_{tt'}$ and $\tilde{\mu}_{tt'}$ for all periods $t' \in \mathcal{T}_t^{H,F} = \{t-H, t+F\}$ as well as binding prices $\lambda_t = \tilde{\lambda}_{tt}$ and $\mu_t = \tilde{\mu}_{tt}$**

Lookahead commitment constraints (2)

Constraints in the deterministic lookahead commitment model (continued):

$$s.t. \quad \tilde{d}_{ltt'} \leq \tilde{D}_{ltt'} \qquad \forall l \in \mathcal{L}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2d)$$

$$\tilde{p}_{gtt'} + \tilde{r}_{gtt'} \leq \tilde{P}_{gtt'} \qquad \forall g \in \mathcal{G}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2e)$$

Generation capacity availability in time t', as estimated in period t

Demand in period t', as estimated in period t

$$\vdots$$

Ramping, state-of-charge, other resource-specific constraints

"Non-revisitionist" constraints covering historical periods

$$p_{gtt'} = p_{gt} \qquad \forall g \in G, t' \in \mathcal{T}_t^{H} \quad (2f)$$

$$\vdots$$

"Non-revisitionist" constraints for other decision variables

Binary commitment variables introducing non-convexity

$$\tilde{u}_{gtt'}, \tilde{v}_{gtt'}, \tilde{q}_{gtt'} \in \{0,1\} \qquad \forall g \in G, t' \in \mathcal{T}_t^{H,F} \quad (2g)$$

Specifying a price formation policy

1. Specifying the decision model (e.g., deterministic vs stochastic, robust, chance-constrained, etc.)
2. Specifying the parameterization (e.g., how forecasts for wind, solar, and load are updated)
3. Specifying treatment of binary variables (and any other modifications to the decision model)

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Implications for literature and practice

- **Viewing price formation through the lens of sequential decisions has several implications**
- **In general, price formation literature has focused on step 3 above, taking the formulation and parameterization as a given**
- **Implicitly provides guarantees on the *provisional* prices instead of the underlying problem and the *actual* prices**
- **I will focus on two implications in this section**
  - **Arbitrage, price convergence, and modeling day-ahead markets**
  - **Implementing and interpreting strategies for non-convexity**

Price convergence

- **Recall that we calculated provisional prices $\tilde{\lambda}_{tt'}$ at time t for our entire lookahead horizon**
- **Law of iterated expectations (or a no-arbitrage condition) suggests that we should have**

$$\tilde{\lambda}_{tt'} = \mathbb{E}_{W_{t+1},\ldots,W_{t'}}[\lambda_{t'}]$$

- **In other words, ideally the provisional price generated by our three-step process should relate to the potential values that might arise given uncertainty (wind, solar, load, etc.)**

Day-ahead markets

- In the sequential description above, prices were only binding for a single period
- Day-ahead markets result in 24 hours of binding prices from a single unit commitment model
- Day-ahead markets also include virtual bidders that drive convergence between day-ahead and expected real-time prices

Very common issue in production cost modeling is to produce day-ahead market prices with a persistent bias relative to real-time market prices

Strategies for non-convexity

- Recall that we have binary variables in the decision problem, complicating the calculation of market-clearing prices
- Most FERC-jurisdictional markets have introduced logic to "allow the commitment costs of fast-start resources to be reflected in prices"
  - Extended LMP in MISO
  - Fast-start pricing in ISO-NE, NYISO, PJM, SPP
- In academic literature, convex hull pricing often described as an "ideal"
- Analysis typically performed on a multi-period market with all periods binding

Implementing schemes for non-convexity

- Calculating prices from alternative schemes in the day-ahead market is not valid
  - Virtual bidders will drive prices back to expected real-time prices
- Instead, need to specify how the desired policy is instantiated in real-time price formation

Many academic proposals (e.g., convex hull pricing) are underspecified relative to what is required in the full sequential decision problem

Lookahead commitment convex hull

Recall the constraints in the deterministic lookahead commitment model:

How have we specified H and F?

$$s.t. \quad \tilde{d}_{ltt'} \leq \tilde{D}_{ltt'} \quad \forall l \in \mathcal{L}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2d)$$

$$\tilde{p}_{gtt'} + \tilde{r}_{gtt'} \leq \tilde{P}_{gtt'} \quad \forall g \in \mathcal{G}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2e)$$

How have we developed demand, solar, and wind forecasts?

$$\vdots$$

Will we also relax "non-revisitionist" constraints (no longer a convex hull) to allow commitment costs?

$$p_{gtt'} = p_{gt} \quad \forall g \in G, t' \in \mathcal{T}_t^{H} \quad (2f)$$

$$\tilde{u}_{gtt'}, \tilde{v}_{gtt'}, \tilde{q}_{gtt'} \in \{0,1\} \quad \forall g \in G, t' \in \mathcal{T}_t^{H,F} \quad (2g)$$

- **Not clear which if any convex hull prices could be considered ideal**

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Modifications to lookahead commitment

- **Above, presented deterministic lookahead commitment as a "base policy" due to correspondence with current practice**
- **Here we consider three modifications:**
  - **Net load biasing**
  - **Reserve tuning**
  - **Stochastic programming**

Net load biasing in deterministic lookahead

Common practice is to adjust parameterization of deterministic model to account for uncertainty:

$$\tilde{d}_{ltt'} \leq \widetilde{D}_{ltt'} \qquad \forall l \in \mathcal{L}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2d)$$

$$\tilde{p}_{gtt'} + \tilde{r}_{gtt'} \leq \tilde{P}_{gtt'} \qquad \forall g \in \mathcal{G}, \forall t' \in \mathcal{T}_t^{H,F} \quad (2e)$$

Adjust estimated wind/solar availability time t' downwards

Adjust demand forecast in period t' upwards (i.e., do not use expected value)

- **Can induce additional commitments for future periods, but may not affect prices in binding period**

Reserve tuning in deterministic lookahead

Another strategy is to increase willingness to pay for reserves (e.g., through creating a new product):

Higher value of reserves

$$X_t^{DLAC}(S_t|H,F) \in$$

$$\arg\max_{\tilde{x}_t} \sum_{l \in \mathcal{L}} \sum_{t' \in \mathcal{T}_t^{H,F}} V_l^L \tilde{d}_{ltt'} + \sum_{t' \in \mathcal{T}_t^{H,F}} V^R \tilde{z}_{tt'} \qquad (2a)$$

$$-\sum_{g \in G} \sum_{t' \in \mathcal{T}_t^{H,F}} (C_g^{NL} \tilde{u}_{gtt'} + C_g^{SU} \tilde{v}_{gtt'} + C_g^{EN} \tilde{p}_{gtt'})$$

- **Similarly increases demand, but attaches a payment for the reserve product (plus higher energy prices)**

Stochastic lookahead

Stochastic programming may better approximate the benchmark prices:

$$X_t^{SLAC}(S_t|H,F) \in$$

$$\arg\max_{x_t,\tilde{x}_t} \sum_{\omega\in\tilde{\Omega}_t} \tilde{\rho}_\omega \Bigg(\sum_{l\in\mathcal{L}} \sum_{t'\in\mathcal{T}_t^{H,F}} V_l^L \tilde{d}_{ltt'\omega}$$

$$+ \sum_{t'\in\mathcal{T}_t^{H,F}} V^R \tilde{z}_{tt'\omega} \qquad (3a)$$

$$- \sum_{g\in G} \sum_{t'\in\mathcal{T}_t^{H,F}} (C_g^{NL} \tilde{u}_{gtt'\omega} + C_g^{SU} \tilde{v}_{gtt'\omega} + C_g^{EN} \tilde{p}_{gtt'\omega}) \Bigg)$$

- **Construct scenario set $\tilde{\Omega}_t$ and solve stochastic program with nonanticipativity in binding period**

Opportunity cost bidding

Alternative used in some markets: do not use lookahead at all, just use participant bids/offers

Opportunity costs

- Storage (and others) forecast future prices
- Calculate bids and offers based on opportunity costs
- Submits curves to system operator
- System operator uses in dispatch

Stochastic programming

- Endogenously calculates an estimated opportunity cost for storage
- Dispatches the system consistent with this endogenous opportunity cost
- More useful for analysis since we do not have access to participant offers

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Large-scale test system

- Set of 456 generators mimicking installed capacity of ERCOT in 2018
- 5 GW of 4-hr batteries added to system
- Scenarios constructed from distributional forecasts for July 18 and 19, 2018 (48 hours)
- All tests include all 48 hours in each time period's problem
- Simulations conducted to compare three policies
  - Net load biasing (at varying levels)
  - Reserve tuning (at varying levels)
  - Stochastic programming

Production cost of competing policies

Tested policies result in similar operating cost…

Policy	Cost	Relative to SLAC
Net Load Biasing		
50th percentile	$833.5M	103.1%
65th percentile	$806.6M	99.7%
95th percentile	$819.9M	101.4%
Reserve Tuning		
40th percentile	$816.3M	100.9%
60th percentile	$832.2M	102.9%
Stochastic Program	$808.8M	100.0%

Revenue under competing policies

…but very different prices

Policy	Cost	Total Charges
Net Load Biasing		
50th percentile	$833.5M	$4,076M
65th percentile	$806.6M	$3,633M
95th percentile	$819.9M	$5,034M
Reserve Tuning		
40th percentile	$816.3M	$4,071M
60th percentile	$832.2M	$4,092M
Stochastic Program	$808.8M	$4,214M

ERCOT Contingency Reserve

RTO Insider LLC

ERCOT Board, IMM Debate Ancillary Service Costs

- **Now have a modeling framework to explain this and (in principle) perform a cost-benefit analysis**

Incentives for capacity

Choice of pricing policy affects resource compensation and incentives for investment

Too low prices → Insufficient capacity

- Widely understood that energy market prices in most markets are too low to support resource adequacy ("missing money" problem)

Have a modeling framework to assess how algorithmic choices contribute to missing money

Incentives for flexibility and diversity

Less recognized that suppressing volatility could have long-run consequences:

Too low volatility → **Insufficient flexibility**

- **Suppressing volatility weakens incentive for flexibility and assets with uncorrelated failures**

Resource-specific revenues

Storage in particular could be remunerated at very different levels under different policies

Profit relative to that under stochastic lookahead:

Policy	Steam	All	Storage
Net Load Biasing			
50th percentile	96.6%	96.7%	81.7%
70th percentile	84.9%	84.4%	68.5%
95th percentile	120.0%	119.5%	114.8%
Reserve Tuning			
40th percentile	95.7%	96.6%	114.4%
60th percentile	95.8%	97.1%	116.4%

Closing thoughts

Main points of this talk:

1. **Need a shift to dynamic models in the design and analysis of price formation in electricity markets**

2. **Need to be aware of the long-term consequences of different price formation choices**

3. **One area of concern is ensuring efficient compensation of flexibility (e.g., storage)**