Incentivizing Investment and Reliability: A Study on Electricity Capacity Markets

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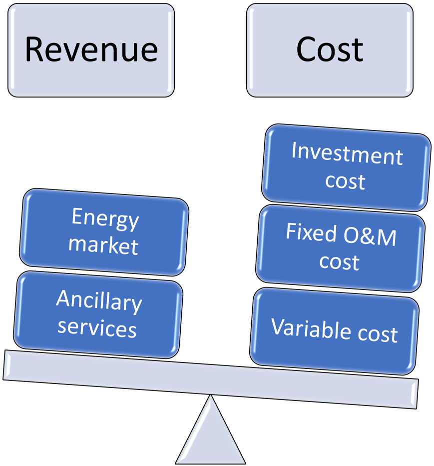
2021 Texas Power Crisis: Market Design in ERCOT

- ERCOT (Electric Reliability Council of Texas) and SPP (Southwest Power Pool) implement energy-only market
- All other independent system operators (ISOs) implement capacity market
- Energy-only market leads to price volatility and sustained high electricity prices

Background: Missing Money Problem & System Reliability



- Missing money: Revenue from energy and ancillary services (E&AS) is not enough to cover cost
- Difficulty in maintaining optimal generation portofolio
  - Efficient generators may not remain in the market
  - Necessary new generators may not enter the market
- Undermines the reliability of power grids

An Important Market Design Question

How to support optimal decisions in both investment and allocation?

Solving Missing Money Problem: Capacity Market vs. Energy-Only Market

Capacity market

- Capacity market auction held before energy market auction
- Pays generators for providing available capacity
- Revenue from capacity market + E&AS

Energy-only market

- Pays generators only for power produced
- Ensures reliability via scarcity price
- Revenue only from E&AS
- "No baker is paid for the *ability* to bake, but for the bread they bake."

Literature: Debate on Capacity Market's Necessity

Pros

- More stable electricity prices
- Improve supply reliability
- Reduce physical withholding
- Important source of income

Cons

- Distort energy prices
- Over-investment
- Favors high-carbon resources
- Supply-side and demand-side market power

- Based either on computational simulations or stylized models

Our Contributions: Methods for Analysis

- Novel analytical framework: rigorous analysis on market outcome
  - Analytical results without depending on computational simulations
  - Realistic models without over-simplifying complicating physical constraints and market features
  - Captures SO's market clearing and incentive of the generators
- Novel quadratic convex (QC) optimization model based on *NYISO Installed Capacity Manual*
- Trilevel leader-follower model for market power in joint capacity and energy markets
  - Can be solved efficiently for large-scale NYISO-based case study
- New perspective: Interplay between capacity and energy markets; impact on generators' revenue
  - "Traditional" perspective: influence on generation expansion planning

Our Contributions: Evaluating Capacity Market Performance

- Does the capacity market enhance system reliability?
- When is the capacity market more effective?
- How to mitigate market power in the capacity market?

Setup of Capacity Market Auction

- Overseen by the ISO (acts as the actioneer)
  - Sellers: generators
  - Buyers: load serving entities (LSEs)
- Goal (spot market auction): ISO procures capacity for LSEs to satisfy capacity requirement

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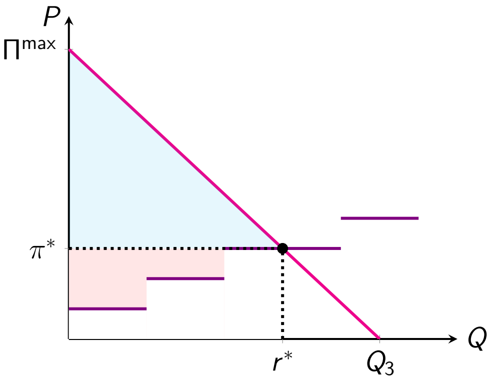
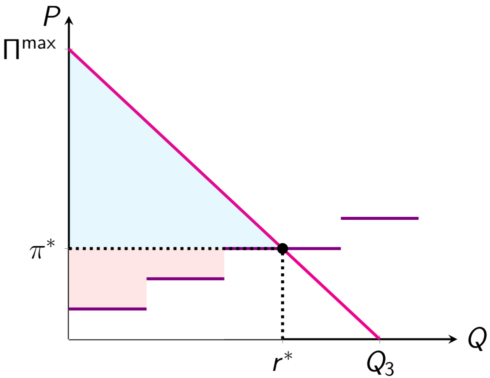
Market Clearing in Capacity Market Auction



- π^*, r^*: market clearing price and quantity
- Sellers:
  - Offer price: net cost of new entry (CONE) $W_g =$ (investment cost - energy market profit)$^+$
    - Long-run marginal cost of capacity
    - Depreciation in resale value, assuming linear depreciation
  - Offer capacity $h_g \leq$ qualified capacity $F_g^U P_g^{max}$
  - Obligated to offer allocated quantity q_g in the energy market
- Buyers: Represented by a linear demand curve $P = -AQ + \Pi^{max}$ (Provided by the ISO)

Quadratic Programming Model for Capacity Market



Maximize social welfare:

$$\max \overbrace{\sum_{g\in\mathcal{G}}(\pi - W_g)q_g}^{\text{supplier surplus}} + \overbrace{\frac{\Pi^{\max} - \pi}{2}}^{\text{consumer surplus}} r$$

$$\text{s.t.} \quad r = \sum_{g\in\mathcal{G}} q_g \quad \rightarrow \text{market clearing}$$

$$\pi = -A\sum_{g\in\mathcal{G}} q_g + \Pi^{\max} \quad \rightarrow \text{demand curve}$$

$$h_g \le F_g^U P_g^{\max}, \forall g \in \mathcal{G} \quad \rightarrow \text{bound on offer capacity}$$

$$q_g \le h_g, \forall g \in \mathcal{G} \quad \rightarrow \text{bound on allocated quantity}$$

$$h_g, q_g \ge 0, \forall g \in \mathcal{G}$$

- The objective can be convexified: $-\frac{A}{2}r^2 + \sum_{g\in\mathcal{G}}(\Pi^{\max} - W_g)q_g$

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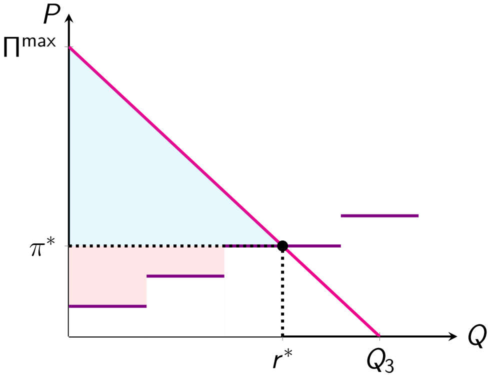
Revenue Adequacy of Generator g



- Let $\hat{\mathcal{G}}$ be the set of allocated generators, $\hat{g}$ be the marginal supplier
  - $g \in \hat{\mathcal{G}} \setminus \{\hat{g}\}$: positive profit
  - $g = \hat{g}$: non-positive profit
  - $g \notin \hat{\mathcal{G}}$: negative profit
- Capacity market benefits generators with low net CONE, e.g., wind, natural gas, and hydro
- Peaker has the highest net CONE and is unlikely to be profitable
  - A peaker is a generator which only operates when demand is high

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Energy Market and Net CONE

Net CONE = (investment cost - energy market profit)$^+$

- In energy market, generator produces electricity and is not marginal $\Rightarrow C_g^V < \lambda^*_{i(g),t} \Rightarrow$ energy market profit > 0
  - Generators with low variable cost, e.g., wind and nuclear
  - Those generators tend to have low net CONE
- If a generator never operates at full capacity, then $C_g^V \geq \lambda^*_{i(g),t} \Rightarrow$ net CONE = investment cost
  - Such as peakers
  - They benefit greatly from capacity scarcity and shortages, as $p_{it}^{\text{Unmet}} > 0 \Rightarrow \lambda^*_{i(g),t} = C^{\text{VOLL}}$

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Revenue Adequacy With vs. Without Capacity Market

Table: Effect of the Capacity Market (CM) on the Profitability of Generators

	Profitable	Not profitable
No CM	$W_g = 0$	$W_g > 0$ peaker
CM	$g \in \hat{\mathcal{G}} \setminus \{\hat{g}\}$ $\hat{g}$/peaker fully allocated	$g \notin \hat{\mathcal{G}}$ $\hat{g}$/peaker not fully allocated

- With capacity market, more generators are revenue adequate, especially those with low net CONE
- With capacity market, generators rely less on price spikes for profitability
- Revenue from the capacity market might not be enough to support peakers

Leader-Follower Game for Capacity and Energy Markets

- Leader: a dominant generator that can influence market outcome
  - Seeks to maximize its total profit
- Follower: ISO's market clearing process
- Research questions:
  - (CM) How does strategic behavior impact market outcome?
  - (CM) Suggestions on market power mitigation policy
  - (EM) When is the capacity market helpful in reducing physical withholding?

(CM) Capacity Market with Strategic Supplier

Proposition

If the leader is allocated and is not marginal, then it can increase the revenue by bidding a higher price and become the marginal supplier if $\exists \hat{\mathcal{G}}'' \in \mathbb{G}$ *such that* $B > W_{\hat{g}}$*, and if either of the following conditions is true:*

(i) $\max_{\hat{\mathcal{G}}'' \in \mathbb{G}, B < W_{\ddot{g}''}} B > \sqrt{A W_{\hat{g}} F_1^U P_1^{\max}}$;

(ii) $\max_{\hat{\mathcal{G}}'' \in \mathbb{G}} W_{\ddot{g}''} \left(\frac{\Pi^{\max} - W_{\ddot{g}''}}{A} - \sum_{i \in \hat{\mathcal{G}}'' \setminus \{1\}} F_i^U P_i^{\max} \right) > W_{\hat{g}} F_1^U P_1^{\max}$,

where $B = \frac{1}{2}(\Pi^{\max} - A \sum_{i \in \hat{\mathcal{G}}'' \setminus \{1\}} F_i^U P_i^{\max})$.

- Intuition: An allocated non-marginal supplier is likely to be untruthful in a sparse market or when demand is low
- Similarly: a marginal/unallocated supplier is likely to be the price setter in a sparse market or when demand is low, and bid 0 otherwise

(CM) Market Power Mitigation

- In a dense market or a market with high demand level or low demand elasticity:
  - Impose price floors on marginal and unallocated suppliers
- In a sparse market with low demand level and high demand elasticity:
  - Impose both price floors and price caps for generators with relatively high net CONE
  - Impose price caps for low net CONE generators with a low qualified capacity

(EM) Reducing Physical Withholding in Energy Market

- Physical withholding: strategic generator withholds its capacity to raise price
- Gain: $\sum_{t\in\hat{\mathcal{T}}'\setminus\hat{\mathcal{T}}}\left(\lambda^{*'}_{i(1),t} - C^V_1\right) q^{*'}_1 + \sum_{t\in\hat{\mathcal{T}}}\left(\lambda^{*'}_{i(1),t} - \lambda^{*}_{i(1),t}\right) q^{*'}_1$
- Loss:
  - With capacity market: $\pi^*(P^{\max}_1 - q^{*'}_1) + \sum_{t\in\hat{\mathcal{T}}}(\lambda^{*}_{i(1),t} - C^V_1)(P^{\max}_1 - q^{*'}_1)$
  - Without capacity market: $\sum_{t\in\hat{\mathcal{T}}}(\lambda^{*}_{i(1),t} - C^V_1)(P^{\max}_1 - q^{*'}_1)$
- Capacity market is more effective at preventing physical withholding if:
  - π^* is high $\Rightarrow$ low redundant capacity at peak hour
  - $P^{\max}_1 - q^{*'}_1$ is high $\Rightarrow$ high withheld capacity
- Capacity market is less effective if:
  - There is more congestion
  - There is more unmet load
- The energy-only market is more vulnerable to physical withholding: high peak price, no capacity payment

Trilevel Model & NYISO Case Study

Maximize: Leader's Profit

Subject to:

Upper-Level Constraints (Leader's Decisions)

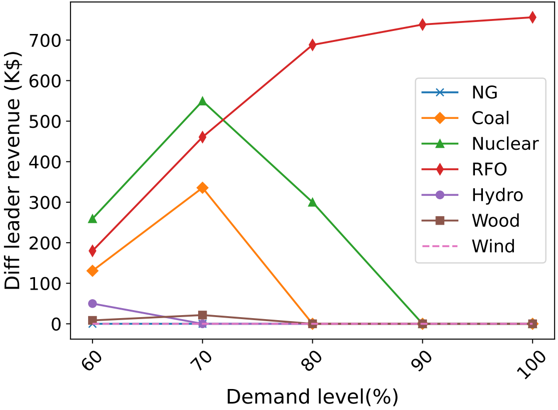
Middle-Level KKT Conditions (Capacity Market Clearing)

Lower-Level KKT Conditions (Energy Market Clearing)

- NYISO dataset: 12 zones, 13 transmission lines, 362 thermal generators, 33 wind farms
- Solving the trilevel model more efficiently: reformulate to 2 bilevel problems; valid inequality

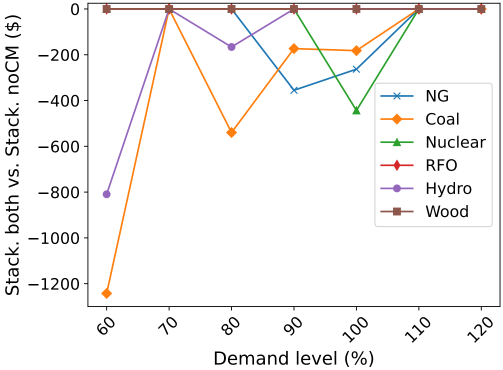
(CM) Market Power in Capacity Market: NYISO Case Study

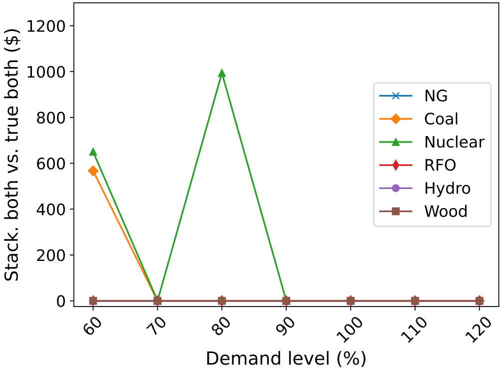
- Generators with higher net CONE tend to exercise market power
- Less affected by market power when demand is high



(EM) Capacity Market Reduces Physical Withholding in Energy Market

- Capacity market prevents many cases of physical withholding
- But it does not eliminate withholding





What We Learned About Capacity Market

- Does the capacity market enhance system reliability?
  - Maintaining generators with lower net CONE
  - Stabilizing electricity price
  - Preventing substantial physical withholding
  - Need additional measures to incentivize investment in peaking plants
  - Alleviating congestion and unmet load issues would further contribute to this objective
- When is the capacity market more effective?
  - Factor 1: low net CONE
  - Factor 2: high demand
- How to mitigate market power in the capacity market?
  - Using price floor or price cap
  - Depending on demand level and market density

Summary

- Novel analytical framework: rigorous analysis on market outcome
- Novel quadratic convex (QC) optimization model based on *NYISO Installed Capacity Manual*
- Trilevel leader-follower model for market power; efficiently solved for large-scale NYISO-based case study
- New perspective: Interplay between capacity and energy markets; impact on generators' revenue
- Evaluation on the performance of the capacity market; insights for both market participants and regulators

Future Directions

- Additional capacity market features
  - Incorporating stochasticity, such as renewable generation
  - More realistic capacity market model that includes all 3 stages
  - Transmission constraint in capacity market
- More broadly, subjecting energy policies to economic analysis without over-simplifications can greatly enhance our understanding of their implications
- Mechanism designs that incentivize optimal investment and allocation for markets with substantial upfront investments