Energy Storage Market Power & Strategic Withholding

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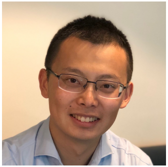
September 3, 2024

Seventh Workshop on Autonomous Energy Systems: NREL

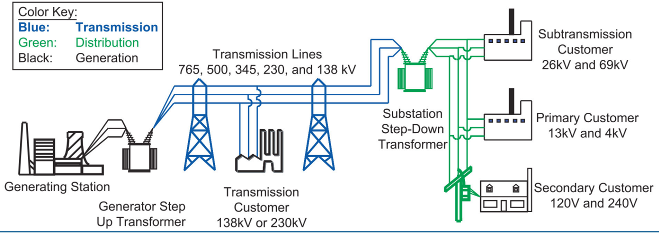
Acknowledgements


- **Yiqian Wu**, Columbia University
- **Bolun Xu**, Columbia University
- **Jip Kim**, Kentech

Traditional Power Systems Engineering

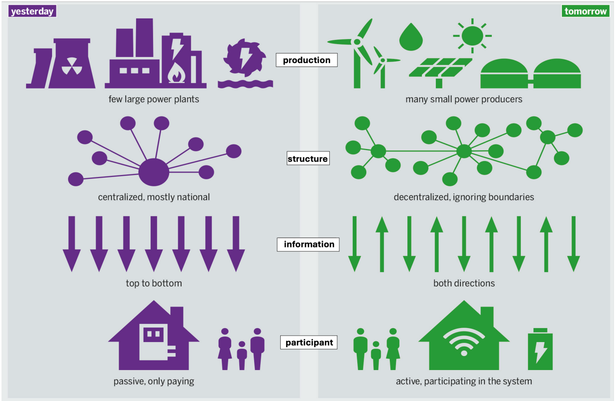
- Unidirectional power transmission from generators to end-users
- Centralized energy management system and electricity market



Source: Adapted from U.S.-Canada Power System Outage Task Force. (2004)

Paradigm Shift

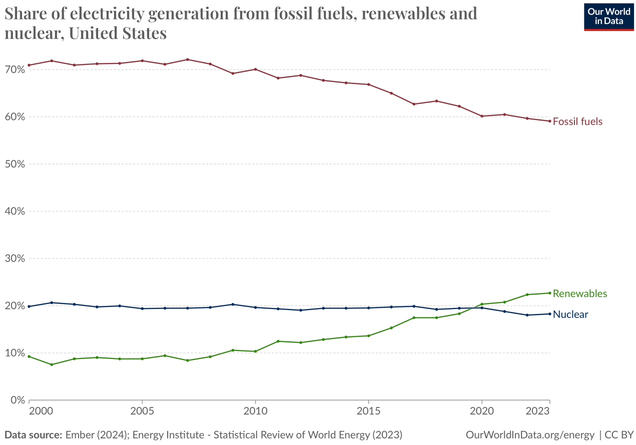
- Deployment of various Distributed Energy Resources (DERs)
- FERC Order 2222: DER aggregation directly participates in electricity markets [1]



Source: Adapted from Energy Atlas 2018: Figures and Facts about Renewables in Europe.

Electricity Production

Share of low-carbon resources in electricity mix gradually increasing

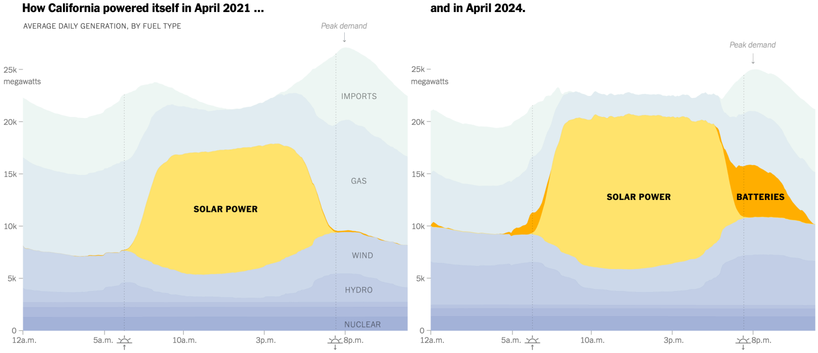


Source: https://ourworldindata.org/electricity-mix

Main Concerns & Challenges

Economic competitiveness in low-carbon electricity market

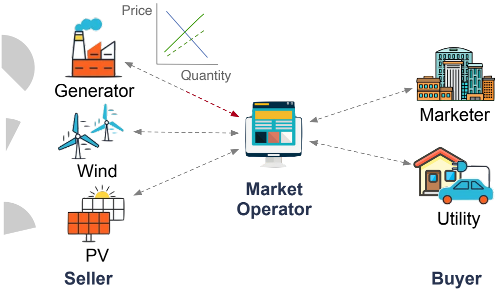
- Vague marginal cost related to renewables, energy storage units, etc.
- High uncertainty inherent in the output of distributed energy resources



Source: `https://www.nytimes.com/interactive/2024/05/07/climate/battery-electricity-solar-california-texas.html`.

Competition and Market Power

- Ideal market achieves perfect competition and maximizes social welfare
- **Market power:** the ability of a participant (**Price Maker**) to manipulate the market clearing price



Key Questions

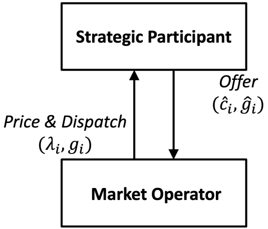
- How should market participant bid in order to gain extra profits?
- What measures can be taken to prevent such an inefficient market environment?
- How effective are these countermeasures?

Key Concepts

- **Price Taker:** accepts prevailing prices and lacks the market share to influence market prices
- **Price Maker:** typically maintains a large market share, anticipates the influence of their bids on market prices with sufficient knowledge of the system status
- **Physical Withholding:** Intentionally throttling generation output to drive up price
- **Economic Withholding:** Submitting strategic bids that deviate from the true marginal cost or utility

Strategic Bidding of the Market Participant

A bilevel bidding strategy based on the hierarchical market structure



Upper-Level Problem: optimal offer decision-making

$\Rightarrow$ Maximize individual profit

$\Rightarrow$ Decide offer:

marginal cost ($\hat{c}_i$) & capacity ($\hat{g}_i$)

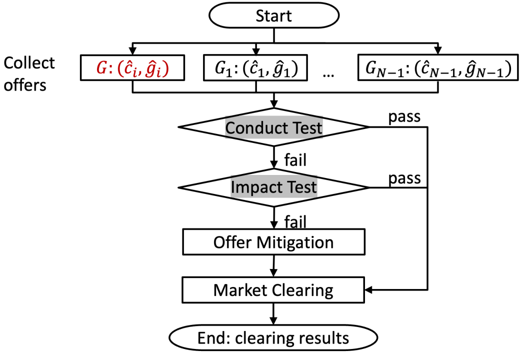
Lower-Level problem: market economic dispatch

$\Rightarrow$ Predict market outcome:

clearing price (λ_i) & dispatch (g_i)

Market Clearing Workflow: Conduct & Impact Tests

- **Conduct test:** compare submitted offers to reference levels
- **Impact test:** evaluate impact of conduct-test-failed offers on prices
- **Offer mitigation:** replace submitted offers with reference levels



Mitigation-Aware Strategic Bidding

Bilevel problem of the strategic generation company G (simplified)

- Submit offers below mitigation threshold to circumvent conduct & impact tests

$$\max_{\hat{c}_i, \lambda_m, g_i} \quad \sum_{i \in \Omega_G} \left(\lambda_{m(i)} - c_i\right) g_i \quad \texttt{// participant profit}$$

$$\text{s.t.} \quad 0 \leq \hat{c}_i \leq \overline{c}, \quad \forall i \in \Omega_G \quad \texttt{// market offer cap}$$

$$0 \leq \lambda_m \leq \overline{\lambda}, \quad \forall m \in \mathcal{N} \quad \texttt{// clearing price cap}$$

$$|\hat{c}_i - c_i^0| \leq x_i, \quad \forall i \in \Omega_G \quad \texttt{// conduct-test threshold}$$

$$|\lambda_m - \lambda_m^0| \leq y_m, \quad \forall m \in \mathcal{N} \quad \texttt{// impact-test threshold}$$

$$\lambda_m, g_i \in \arg\min_{\Xi^{LL}} \quad \sum_{i \in \Omega_G} \hat{c}_i g_i + \sum_{j \in \Omega'_G} \hat{c}_j g_j \quad \texttt{// generation cost}$$

$$\text{s.t.} \quad \sum_i g_i + \sum_j g_j = D_m + \sum_n p_{mn} - \sum_l p_{lm} : \lambda_m, \quad \forall m \in \mathcal{N}$$

$$p_{mn} = B_{mn}(\theta_m - \theta_n), \quad \forall (m,n) \in \mathcal{E}$$

$$-\overline{P}_{mn} \leq p_{mn} \leq \overline{P}_{mn}, \quad \forall (m,n) \in \mathcal{E}$$

$$0 \leq g_i \leq \overline{G}_i, \quad \forall i \in \Omega_G$$

$$0 \leq g_j \leq \overline{G}_j, \quad \forall j \in \Omega'_G$$

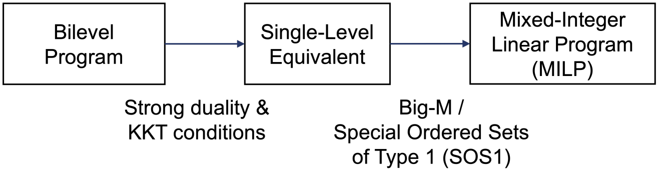
$$-\pi \leq \theta_m \leq \pi, \quad \forall m \in \mathcal{N}$$

Solution Techniques

Bilevel problems: strongly NP-hard [2]

Solution technique

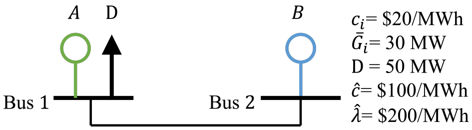
- Derive a (non-convex) single-level equivalent
- Linearize
- Off-the-Shelf solver for (non-convex) MILP



2-Bus Test System

Market participant

- **Unit A:** strategic participant
- **Unit B:** non-strategic competitor



Bidding & Clearing assumptions

- Perfect prediction for market outcome and reference levels
- Mitigation thresholds for conduct and impact tests set at 100%
- Tie-Breaking constraints to guarantee fairness among price-tied units

Impacts of Offer Mitigation on Strategic Bidding

Clearing results in the uncongested network

Strategy of Unit A	Unit	Before Mitigation				After Mitigation			
		$\hat{c}_i$	g_i	λ_i	Profit_i^*	$\hat{c}_i$	g_i	λ_i	Profit_i
Non-Strategic	A	20	25	20	0	-	-	-	0
	B	20	25	20	0	-	-	-	0

Recall for unit i:

- $\hat{c}_i$: offer price, \$/MWh
- g_i: dispatch decision, MW
- λ_i: clearing price, \$/MWh
- Profit_i: $= (\lambda_i - c_i)g_i$, \$, where c_i is the true cost, \$/MWh

Impacts of Offer Mitigation on Strategic Bidding

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		$\hat{c}_i$	g_i	λ_i	Profit$_i^*$	$\hat{c}_i$	g_i	λ_i	Profit$_i$
Non-Strategic	A	20	25	20	0	-	-	-	0
	B	20	25	20	0	-	-	-	0
Mitigation-Unaware	A	100	20	100	1600	20	25	20	0
	B	20	30	100	2400	-	25	20	0

recall for unit i

- $\hat{c}_i$: offer price, \$/MWh
- g_i: dispatch decision, MW
- λ_i: clearing price, \$/MWh
- Profit$_i$: $= (\lambda_i - c_i)g_i$, \$, where c_i is the true cost, \$/MWh

Impacts of Offer Mitigation on Strategic Bidding

Clearing results in the **uncongested network**

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Non-Strategic	A	20	25	20	0	-	-	-	0
	B	20	25	20	0	-	-	-	0
Mitigation-Unaware	A	100	20	100	1600	20	25	20	0
	B	20	30	100	2400	-	25	20	0
Conduct-Aware	A	40	20	40	400	-	-	-	400
	B	20	30	40	600	-	-	-	600
Impact-Aware	A	40	20	40	400	-	-	-	400
	B	20	30	40	600	-	-	-	600

Local market in the **uncongested network**

- Mitigation-Aware bidding can successfully bypass mitigation and gain additional profit
- Both strategic and non-strategic players benefit from market power exercise [3]

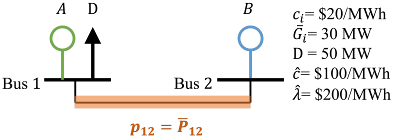
Impacts of Offer Mitigation on Strategic Bidding

Clearing results in the **congested network**

Strategy of Unit A	Unit	$\hat{c}_i$	g_i	λ_i	Profit$_i$
Conduct-Aware	A	40	27	40	540
	B	20	23	20	0
Impact-Aware	A	40	27	40	540
	B	20	23	20	0

Regional competition in the **congested network**

- Capacity limit and congestion are two major sources of market manipulation
- Conduct-Aware bidding strategy is more conservative v.s. Impact-Aware bidding



Main Takeaways

- Proposed a mitigation-aware strategic bidding model to study the influence and effectiveness of current mitigation practices
- Illustrated the vulnerability of electricity markets to market power manipulation with limited offer mitigation tools
- Our mitigation-aware bidding framework can serve as an analysis tool for alternative market designs

arXiv > eess > arXiv:2405.01442

Electrical Engineering and Systems Science > Systems and Control

[Submitted on 2 May 2024]

Market Power and Withholding Behavior of Energy Storage Units

Yiqian Wu, Bolun Xu, James Anderson

Energy Storage Unit Penetration

- Electricity markets experiencing a rapid increase in **energy storage unit participation**
- Quantifying **competitive operation** and identifying if a storage unit is **exercising market power** is challenging
- Lacks systematic studies on the intricacies of **multi-interval bidding strategies**

Energy Storage Unit Penetration: Challenges

- Electricity markets experiencing a rapid increase in **energy storage unit participation**
- Quantifying **competitive operation** and identifying if a storage unit is **exercising market power** is challenging
- Lacks systematic studies on the intricacies of **multi-interval bidding strategies**

Key Concepts

- **Price Taker:** accepts prevailing prices and lacks the market share to influence market prices
- **Price Maker:** typically maintains a large market share, anticipates the influence of their bids on market prices with sufficient knowledge of the system status
- **Capacity Withholding:** action taken by a **price maker** – resources purposefully limiting their supply despite the current price being higher than marginal production cost

Market Power and Price Sensitivity

Price sensitivity to market power exercise:

$$\lambda_t = \bar{\lambda}_t - \boldsymbol{\alpha_t} q_t$$

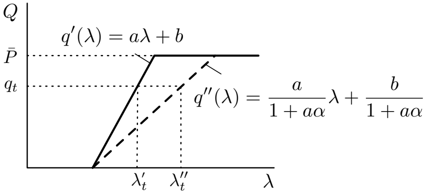
where at time t

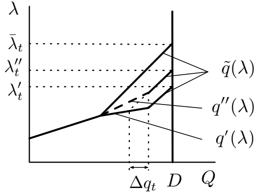
- λ_t: influenced clearing price, \$/MWh
- $\bar{\lambda}_t$: nominal clearing price, \$/MWh
- α_t: price sensitivity parameter, $\alpha_t \geq 0$
- q_t: dispatch decision, MW

Market Power and Price Sensitivity

Market power exercise – in supply-demand equilibrium based market

- Bid supply curves shift from **price taker**: $q'(\lambda)$ to **price maker**: $q''(\lambda)$
- **Capacity withholding** Δq_t leads to price increase from λ_t' to λ_t''





Energy Storage Strategic Bidding

Convex **self-scheduling** model for energy storage units strategic bidding and profit maximization based on price forecasts $\hat{\lambda}_t$ for all $t \in \mathcal{T}$ [4]

$$\underset{p_t, b_t, e_t}{\text{maximize}} \quad \sum_{t \in \mathcal{T}} \hat{\lambda}_t (p_t - b_t)$$

$$\text{s.t.} \quad 0 \leq p_t, \; b_t \leq \bar{P}, \quad \forall t \in \mathcal{T} \qquad \texttt{// charging \& discharging power bounds}$$

$$p_t = 0 \text{ if } \hat{\lambda}_t < 0, \quad \forall t \in \mathcal{T} \qquad \texttt{// no simultaneous charging \& discharging}$$

$$e_t - e_{t-1} = -\frac{p_t}{\eta} + b_t \eta, \quad \forall t \in \mathcal{T} \qquad \texttt{// SoC evolution}$$

$$0 \leq e_t \leq E, \quad \forall t \in \mathcal{T} \qquad \texttt{// energy storage capacity}$$

where at time t

- $p_t, \; b_t$: amount of energy discharge and charge, MW
- e_t: state of charge (SoC), MW
- $\bar{P}$: power capacity, MW
- η: charging and discharging efficiency parameter, $\eta \in (0, 1]$
- E: energy storage capacity, MWh

Energy Storage Strategic Bidding

Simplified bidding model cost functions

- Price taker:

$$\underset{p_t, b_t}{\text{maximize}} \quad \sum_{t \in \mathcal{T}} \hat{\lambda}_t \underbrace{(p_t - b_t)}_{q_t} \tag{1}$$

- Price maker:

$$\underset{p_t, b_t}{\text{maximize}} \quad \sum_{t \in \mathcal{T}} (\bar{\lambda}_t - \alpha_t \underbrace{(p_t - b_t)}_{q_t})(p_t - b_t) \tag{2}$$

Strategic Capacity Withholding Detection

Main Theorem (informal)
– *ex-post* market power monitoring strategy for market operator

Given a series of **observed storage power output profiles** $\{p_t,\ b_t\}$ and **market clearing prices** $\{\lambda_t\}$ for all $t \in \tilde{\mathcal{T}}$, where $\tilde{\mathcal{T}} = \{1, 2, \ldots, NT\}$,

the storage unit **is not evidently exercising market power**, if the following conditions are satisfied:

1. $$\underbrace{\sum_{t\in\tilde{\mathcal{T}}} \mathbb{1}_{\{0<p_t<\bar{P}\}} + \sum_{t\in\tilde{\mathcal{T}}} \mathbb{1}_{\{0<b_t<\bar{P}\}}}_{\#\text{ of withholding intervals}} \leq \underbrace{N'}_{\#\text{ of non-idle periods}} \leq \underbrace{N}_{\#\text{ of total periods}}$$

2. The **price-decision relationship** is satisfied (details omitted).

Two-Interval Bidding

Price taker: p_t^*, b_t^*: optimal solutions to (1) [discharge, charge]

Scenario	Interval 1		Interval 2	
	p_1^*	b_1^*	p_2^*	b_2^*
$\hat{\lambda}_1 > \frac{\hat{\lambda}_2}{\eta^2}$	$\bar{P}\eta^2$	0	0	$\bar{P}$
$\hat{\lambda}_2\eta^2 \leq \hat{\lambda}_1 \leq \frac{\hat{\lambda}_2}{\eta^2}$	0	0	0	0
$\hat{\lambda}_1 < \hat{\lambda}_2\eta^2$	0	$\bar{P}$	$\bar{P}\eta^2$	0

recall problem parameters

- $\hat{\lambda}_t$: price forecast for time t
- $\bar{P}$: power capacity
- η: charging and discharging efficiency parameter, $\eta \in (0, 1]$

Criterion for strategic bidding decision making – scenario distinction

- Sufficient profit to compensate for energy loss during charging and discharging,

Two-Interval Bidding

Price maker: $p_t^*,\ b_t^*$: optimal solutions to (2) [discharge, charge]

Scenario		Interval 1		Interval 2	
		p_1^*	b_1^*	p_2^*	b_2^*
$\bar{\lambda}_1 > \frac{\bar{\lambda}_2}{\eta^2}$	$\bar{\lambda}_1 - 2\alpha_1 \bar{P}\eta^2 \geq \frac{\bar{\lambda}_2 + 2\alpha_2 \bar{P}}{\eta^2}$	$\bar{P}\eta^2$	0	0	$\bar{P}$
	$\bar{\lambda}_1 - 2\alpha_1 \bar{P}\eta^2 < \frac{\bar{\lambda}_2 + 2\alpha_2 \bar{P}}{\eta^2}$	$\frac{\bar{\lambda}_1 - \frac{\bar{\lambda}_2}{\eta^2}}{2(\alpha_1 + \frac{\alpha_2}{\eta^4})}$	0	0	$\frac{\bar{\lambda}_1 - \frac{\bar{\lambda}_2}{\eta^2}}{2(\alpha_1 + \frac{\alpha_2}{\eta^4})\eta^2}$
$\bar{\lambda}_2\eta^2 \leq \bar{\lambda}_1 \leq \frac{\bar{\lambda}_2}{\eta^2}$		0	0	0	0
$\bar{\lambda}_1 < \bar{\lambda}_2\eta^2$	$\frac{\bar{\lambda}_1 + 2\alpha_1 \bar{P}}{\eta^2} > \bar{\lambda}_2 - 2\alpha_2 \bar{P}\eta^2$	0	$\frac{-\bar{\lambda}_1 + \bar{\lambda}_2\eta^2}{2(\alpha_1 + \alpha_2\eta^4)}$	$\frac{(-\bar{\lambda}_1 + \bar{\lambda}_2\eta^2)\eta^2}{2(\alpha_1 + \alpha_2\eta^4)}$	0
	$\frac{\bar{\lambda}_1 + 2\alpha_1 \bar{P}}{\eta^2} \leq \bar{\lambda}_2 - 2\alpha_2 \bar{P}\eta^2$	0	$\bar{P}$	$\bar{P}\eta^2$	0

Criterion for strategic bidding decision making – scenario distinction

- Scenario Col #1: Sufficient profit to compensate for energy loss during charging and discharging,
- Scenario Col #2: If exercising market power, sufficient marginal revenue to compensate for negative impact intervals.

Two-Interval Bidding

- Price **makers** achieve additional profits by exercising market power
- Price **takers** have insufficient incentive to resist the exercise of market power [3]

Scenario	Price Taker ($)	Price Maker ($)
No market power	37.95	–
Low market power	47.50	42.02
High market power	66.66	49.11

$$\lambda_t = \bar{\lambda}_t - \boldsymbol{\alpha_t} q_t$$

Main Takeaways

- mechanism design is essential to ensure social welfare
- reproduced empirical economic observations with a simple model we can understand
- uncertainty in future price predictions

Imperfect Price Forecasting

- Assumed that the price λ_t is provided and accurate – clearly not realistic
- How does uncertainty in price affect bidding?
- We will consider a deterministic/worst case scenario for the **price taker**
- λ_t is unknown but assumed to belong to the set Λ_t

$$\begin{aligned}
\underset{p_t, b_t, e_t}{\text{maximize}} \quad & \sum_{t \in \mathcal{T}} \hat{\lambda}_t (p_t - b_t) \quad \text{for all } \hat{\lambda}_t \in \Lambda_t \\
\text{s.t.} \quad & 0 \leq p_t \; b_t \leq \bar{P} \quad \forall t \in \mathcal{T} \\
& p_t = 0 \text{ if } \hat{\lambda}_t < 0 \quad \forall t \in \mathcal{T} \\
& e_t - e_{t-1} = -\frac{p_t}{\eta} + b_t \eta \quad \forall t \in \mathcal{T} \\
& 0 \leq e_t \leq E \quad \forall t \in \mathcal{T}
\end{aligned}$$

- infinite-dimensional and convex (if Λ_t is convex)
- many approaches to robust stochastic optimization c.f. Roald et al. Electric Power Systems Research, 2023

Finite-Dimensional Reformulation

- w.l.o.g. we rewrite our LP in epigraph form

$$\begin{aligned} \underset{x,\gamma}{\text{maximize}} \quad & \gamma \\ \text{s.t.} \quad & \gamma \leq c^T x \quad \text{for all} \quad c_i \in \mathcal{C}_i \\ & Ax \leq b \end{aligned}$$

- we are considering a **worst case** setting

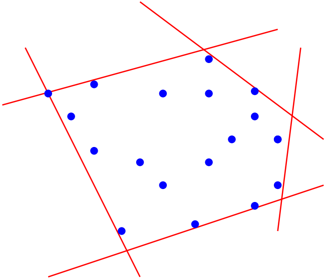
$$\begin{aligned} \underset{x,\gamma}{\text{maximize}} \quad & \gamma \\ \text{s.t.} \quad & \inf_{c_i \in \mathcal{C}_i} \{c^T x\} \geq \gamma \qquad (\dagger) \\ & Ax \leq b \end{aligned}$$

- the representation of $\mathcal{C}_i$ determines if we problem can be solved

Polyhedral Uncertainty

- Let $\mathcal{C} := \mathcal{C}_1 \times \mathcal{C}_2 \times \cdots \times \mathcal{C}_T$ be bounded and non-empty, then

$$\mathcal{C} := \left\{ c \in \mathbb{R}^T \mid Dc \leq d \right\}$$



Polyhedral Uncertainty

- Let $\mathcal{C} := \mathcal{C}_1 \times \mathcal{C}_2 \times \cdots \times \mathcal{C}_T$ be bounded and non-empty, then

$$\mathcal{C} := \left\{ c \in \mathbb{R}^T \mid Dc \leq d \right\}$$

- The lower-level problem of (†) can be written as

$$\underset{c}{\text{minimize}} \quad c^T x \quad \text{s.t.} \quad Dc \leq d \qquad (\mathcal{P})$$

- By strong duality, the optimal cost of $(\mathcal{P})$ can be obtained by solving

$$\underset{y}{\text{maximize}} \quad -y^T d \qquad (\mathcal{D})$$
$$\text{s.t.} \quad x = -D^T y, \quad y \geq 0$$

Polyhedral Uncertainty

- Replace $\inf_{c_i \in \mathcal{C}_i} \{c^T x\}$ from $(\dagger)$ with $(\mathcal{D})$ to get

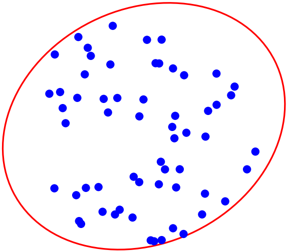
$$\begin{aligned}\underset{x,y,\gamma}{\text{maximize}} \quad & \gamma \\ \text{s.t.} \quad & \underset{y}{\text{maximize}}\ \{-y^T d\} \geq \gamma \\ & x = -D^T y, \quad y \geq 0 \\ & Ax \leq b\end{aligned}$$

- The second "maximize" is redundant, so remove

$$\begin{aligned}\underset{x,y,\gamma}{\text{maximize}} \quad & \gamma \\ \text{s.t.} \quad & -y^T d \geq \gamma \\ & x = -D^T y, \quad y \geq 0 \\ & Ax \leq b\end{aligned}$$

- a finite-dimensional LP!

Ellipsoidal Uncertainty



Representations of an Ellipse

$$\mathcal{E} = \left\{ \bar{\lambda} + Pu \in \mathbb{R}^T \mid \|u\| \le 1 \right\} = \left\{ x \mid (x - x_c)^T P^{-2} (x_c - x) \le 1 \right\}$$

Ellipsoidal Uncertainty

Representations of an Ellipse

$$\mathcal{E} = \left\{ \bar{\lambda} + Pu \in \mathbb{R}^T \mid \|u\| \leq 1 \right\} = \left\{ x \mid (x - x_{\mathrm{c}})^T P^{-2} (x_{\mathrm{c}} - x) \leq 1 \right\}$$

- Minimum-volume ellipsoid that contains all the data:

$$\begin{aligned} \min_{P} \quad & -\log\det\left(P^{-2}\right) \\ \text{s.t.} \quad & (\lambda^s - \lambda_c)^\top P^{-2} (\lambda^s - \lambda_c) \leq 1, \quad \text{for } s = 1, \ldots, N \\ & P \succeq 0, \quad P = P^\top \end{aligned}$$

- Covariance matrix from data:

$$P_{ij} := \mathsf{cov}(X_i, X_j) = \frac{1}{m-1} \sum_{k=1}^{m} (x_{ki} - \bar{x}_i)(x_{kj} - \bar{x}_j)$$

NYISO Data: Polyhedral I

Γ (%)	50	55	60	65	70	75	80	85	90
Robust profit	175.96	117.42	71.60	30.73	5.77	0.00	0.00	0.00	0.00
Actual profit	-15.76	2.19	23.58	26.24	32.48	0.00	0.00	0.00	0.00

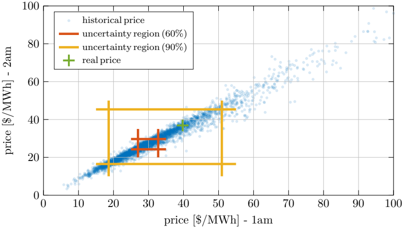


Figure: Polyhedral (box) uncertainty set of electricity prices – i, $\Gamma = 60\%$ and 90%.

$$\mathcal{C}(\Gamma) = \left\{ \boldsymbol{\lambda} \in \mathbb{R}^{N+1} : \ \frac{\lambda_t - \mathbb{E}\lambda_t}{\sigma(\lambda_t)} \ \leq \Gamma, \ t = 0, \ldots, N \right\}$$

NYISO Data: Polyhedral II

Γ	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
Robust profit	223.61	171.21	125.73	89.95	56.90	28.35	8.57	1.25	0.00	0.00	0.00
Actual profit	-17.79	-8.80	-0.28	23.40	24.13	32.02	29.01	16.54	0.00	0.00	0.00

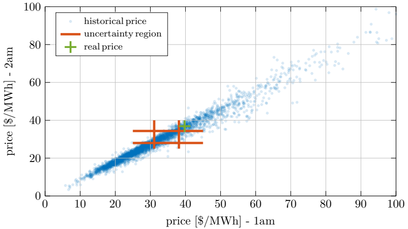


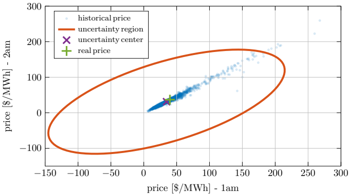
Figure: Polyhedral (box) uncertainty set of electricity prices, quantile $\Gamma = 0.15$.

$$\mathcal{C} = \left\{ \boldsymbol{\lambda} \in \mathbb{R}^{N+1} : \underline{\lambda}_t \leq \lambda_t \leq \overline{\lambda}_t,\ t = 0, \ldots, N \right\}$$

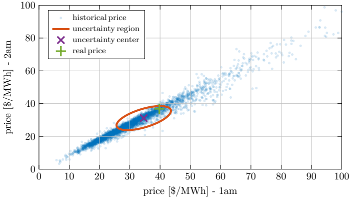
NYISO Data: Ellipsoidal I

Ellipsoidal Uncertainty Set of Electricity Prices — $\mathbf{P}$ fitted from minimum volume problem

Δ	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Robust profit	223.36	195.19	166.77	138.46	110.27	82.63	57.19	35.19	18.48	5.07	0.00
Actual profit	-17.79	-17.79	-17.44	-16.17	-17.08	-23.17	-37.54	-46.03	-30.88	-26.30	0.00



(a) $\Delta = 1$



(b) $\Delta = 0.05$

$$\mathcal{E} = \left\{ \lambda^s \mid (\lambda^s - \lambda_c)^\top P^{-2} (\lambda^s - \lambda_c) \le \Delta, \quad \text{for } s = 1, \dots, N \right\}$$

NYISO Data: Ellipsoidal II

Ellipsoidal Uncertainty Set of Electricity Prices — $\mathbf{P}$ as covariance matrix

Δ (scaled)	0	1	2	3	4	5	6
Robust profit	223.36	141.98	86.33	48.14	25.23	8.38	0.00
Actual profit	-17.79	15.51	10.30	5.98	13.54	6.60	0.00

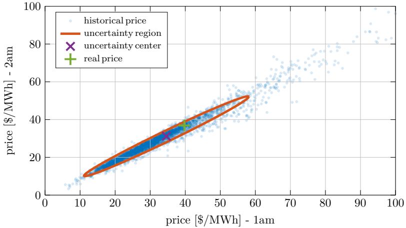


Figure: Ellipsoidal uncertainty set of electricity prices – ii, $\Delta = 2$.

Conclusions

- how do we create incentives to deter market manipulation
- modelling the uncertainty in forecasting data
- presented mostly only partial results

References

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Backup slides

Strategic Capacity Withholding Differentiate

Proposition

Given a series of prices $\hat{\lambda}_t$ throughout the period $\mathcal{T}$, a **strategic price taker** makes bidding decisions $\{p_t^*,\ b_t^*\}$ based on profit-maximization model. Denote the set of discharge withholding intervals $\{u \in \mathcal{T} | \mathbb{1}_{\{0<p_u<\bar{P}\}} = 1\}$ and charge withholding intervals $\{v \in \mathcal{T} | \mathbb{1}_{\{0<b_v<\bar{P}\}} = 1\}$, then the bidding decisions satisfy:

1. if the unit discharges at capacity during interval x, i.e., $p_x^* = \bar{P}$, then $\hat{\lambda}_x > \hat{\lambda}_u$ and $\hat{\lambda}_x > \frac{\hat{\lambda}_v}{\eta^2}$,
2. if the unit charges at capacity during interval y, i.e., $b_y^* = \bar{P}$, then $\hat{\lambda}_u > \frac{\hat{\lambda}_y}{\eta^2}$ and $\hat{\lambda}_v > \hat{\lambda}_y$,
3. if the unit is idle during interval z, i.e., $p_z^* = b_z^* = 0$, then $\frac{\hat{\lambda}_z}{\eta^2} > \hat{\lambda}_u > \hat{\lambda}_z$ and $\hat{\lambda}_z > \hat{\lambda}_v > \hat{\lambda}_z \eta^2$.