Unintended consequences of market designs
The role of inelastic demand and market rules

Enrique Mallada

Agency for Science, Technology and Research
IHPC's Workshop on Power and Energy Systems of the (near) Future

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Acknowledgements

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UC San Diego  北京大学  CUHK  JOHNS HOPKINS UNIVERSITY

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Two-stage/Sequential Markets

Two-stage markets are the norm in energy systems!

Designed to incentivize transactions in the presence of uncertainty

• **Forward Market**: Future contracts
• **Spot Market**: Immediate commitments

Benefits of forward contracting

• **Hedge** against future risks
• Increased **efficiency** [Allaz & Vila ‘93]

Natural solution to electricity markets

• Day-ahead: Forward Market
  • Hedge via a forward position
• Real-time: Spot Market
  • Correct: Last-resort/realized uncertainty
Operational Challenges in Electricity Grids

• Undesired price manipulation by market participants
  • California Electricity Crisis – Enron ‘00-’01
  • Today: ~2% hours with non-competitive bids in the CAISO market (2021)

• Proliferation of renewable energy sources

Rapid growth in solar and wind energy

Source: U.S. Energy Information Administration

Day-Ahead Single Point Prediction

Uncertainty

3,180 MW Error
73% Forecast Error

Source: Midcontinent ISO (Jun 26, 2019)

High ramp requirement

Net demand trend

System demand minus wind and solar, in 5-minute increments, compared to total system and forecasted demand.

Source: California ISO
Opportunities

• Utility-Scale Storage
  • Rapidly growing technology
  • Can be used across all grid services (regulation, ramping, volt/var, etc.)
  • High cost, complex to quantify

• Distributed Energy Resources (DERs)
  • FERC 2222 opens the door for democratized participation in Markets
  • Multiple types: solar, wind, batteries, smart meters, demand response, EVs, etc.
  • Heterogeneous functionalities/incentives

Q1: How does participants' behavior affect market outcomes? What are their incentives?

Q2: How should new types of participants bid in energy markets?
Unintended consequences of market designs

• The role of inelastic demand in two-stage markets

• Market power mitigation via default bids
The Role of Strategic Participants in Two-Stage Settlement Markets

Pengcheng You, Marcelo A. Fernandez, Dennice F. Gayme, and Enrique Mallada
**Existing Paradigm - Wholesale Energy Market Design**

**Generator centric view:**

- **Day-Ahead Market (Forward Market)**
  - Market clears based on demand forecasts
  - Account for majority of trading in market
  - Hedge against uncertainty via a forward position

- **Real-Time Market (Spot Market)**
  - Market clears at faster timescale, typically 5 min
  - Participants buy or sell to adjust commitments
  - Correct: Last-resort/realized uncertainty

CAISO, 2021
Two-stage Settlement in Electricity Markets

- **q** = **q**<sub>RT</sub> + **q**<sub>DA</sub> (total generation)
- **d** = **d**<sub>RT</sub> + **d**<sub>DA</sub> (total demand)
- Linear supply function: 
  \[ q^? = \beta^? \cdot \lambda^? \]  
  [Klemperer, Meyer '89]

### Diagram:
- **Day ahead**
  - **q**<sub>DA</sub>, **λ**<sub>DA</sub>
  - **β**<sub>DA</sub>
  - **d**<sub>DA</sub>
  - **q**<sub>DA</sub>, **λ**<sub>DA</sub>

- **Real time**
  - **q**<sub>RT</sub>, **λ**<sub>RT</sub>
  - **β**<sub>RT</sub>
  - **d**<sub>RT</sub>
  - **q**<sub>RT</sub>, **λ**<sub>RT</sub>

**Day ahead**: forward position

**Real time**: last resort/opportunity
Challenge: Operation Not Fully Understood

Market Power is Major Concern
- Competitive Equilibria -> Price Convergence $\lambda^{DA} = \lambda^{RT}$
- Evidence the lack of price convergence
  - MISO [Bowden et al. ‘09, Birge et al. ‘18]
  - NYISO [Jha & Wolak ’19, You et al. ‘19]
  - CAISO [Borenstein ‘08] and more..

Is the Spot Market Operating as Last Resort?
- Systematic bias in real-time demand

Our focus: Understanding the role of strategic load participants
An Extensive-Form Game

• Between \( G \) homogeneous generators and \( L \) heterogeneous inelastic loads
• Perfect foresight and complete information

Quadratic cost

\[
\frac{1}{2}c(q_j^{DA} + q_j^{RT})^2
\]

Individual generator \( j \in G \)

Day-ahead market clearing

\[
\sum_{j \in G} \beta_j^{DA} \lambda^{DA} = \sum_{l \in L} d_l^{DA}
\]

Real-time market clearing

\[
\sum_{j \in G} \beta_j^{RT} \lambda^{RT} = \sum_{l \in L} d_l^{RT}
\]
An Extensive-Form Game

- Between \textit{G homogeneous} generators and \textit{L heterogeneous} inelastic loads
- Perfect foresight and complete information

\[
\begin{align*}
q_j^{DA} &= \beta_j^{DA} \lambda^{DA} \\
q_j^{RT} &= \beta_j^{RT} \lambda^{RT}
\end{align*}
\]

Day-ahead market clearing

\[
\sum_{j \in G} \beta_j^{DA} \lambda^{DA} = \sum_{i \in L} d_i^{DA}
\]

Real-time market clearing

\[
\sum_{j \in G} \beta_j^{RT} \lambda^{RT} = \sum_{i \in L} d_i^{RT}
\]
An Extensive-Form Game

- Between \( G \) \textit{homogeneous} generators and \( L \) \textit{heterogeneous} inelastic loads
- Perfect foresight and complete information

Day-ahead market clearing:

\[
\sum_{j \in G} \beta_j^{DA} \lambda^{DA} = \sum_{l \in L} d_l^{DA}
\]

Individual generator \( j \in G \):

\[
\frac{1}{2} c (q_j^{DA} + q_j^{RT})^2
\]

Real-time market clearing:

\[
\sum_{j \in G} \beta_j^{RT} \lambda^{RT} = \sum_{l \in L} d_l^{RT}
\]

Individual load \( l \in L \):

\[
d_l = d_l^{DA} + d_l^{RT}
\]

Linear supply function bid:

\[
q_j^{RT} = \beta_j^{RT} \lambda^{RT}
\]

Quadratic cost:

\[
q_j^{DA} = \beta_j^{DA} \lambda^{DA}
\]

Inelastic demand:

\[
d_l^{RT} = \text{Quantity bid}
\]

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An Extensive-Form Game

• Between \( G \) homogeneous generators and \( L \) heterogeneous inelastic loads
• Perfect foresight and complete information

Generation goal

\[
\max \quad \lambda^{DA} q^{DA}_j + \lambda^{RT} q^{RT}_j - \frac{1}{2} c(q_j)^2 \\
\text{s.t.} \quad q_j = q^{DA}_j + q^{RT}_j
\]

Demand goal

\[
\max \quad \lambda^{DA} d^{DA}_l + \lambda^{RT} d^{RT}_l \\
\text{s.t.} \quad d_l = d^{DA}_l + d^{RT}_l
\]
Model: Nested Game

- Real-time subgame: given day-ahead market outcome
- Day-ahead competition: anticipate real-time market outcome (global view)

\[
\begin{align*}
\max_{\beta_{j}^{DA} \geq 0} & \quad \lambda^{DA} q_{j}^{DA} + \pi_{j}^{RT}\star \\
\max_{\beta_{j}^{RT} \geq 0} & \quad \lambda^{RT} q_{j}^{RT} - \frac{1}{2} c(q_{j}^{DA} + q_{j}^{RT})^2
\end{align*}
\]

Optimal real-time profit

\[
\pi_{j}^{RT}\star (\beta_{j}^{DA} ; \beta_{-j}^{DA}, d^{DA})
\]

Occur later
Model: Nested Game

- Real-time subgame: given day-ahead market outcome
- Day-ahead competition: anticipate real-time market outcome (global view)

\[
\begin{align*}
\max_{\beta_j^{DA} \geq 0} & \quad \lambda^{DA} q_j^{DA} + \pi_j^{RT*} \\
\max_{\beta_j^{RT} \geq 0} & \quad \lambda^{RT} q_j^{RT} - \frac{1}{2} c (q_j^{DA} + q_j^{RT})^2
\end{align*}
\]

Individual generator \( j \in \mathcal{G} \)

\[
\begin{align*}
\beta_j^{DA} \quad \text{Day-ahead market} \\
\beta_j^{RT} \quad \text{Real-time market}
\end{align*}
\]

real-time price
\[
\lambda^{RT*}(d_l^{DA}, d_l^{DA}, \beta^{DA})
\]

Individual load \( l \in \mathcal{L} \)

Occur later
Market Participant Types

• **Price taker participants:** respond (bid) optimally to given prices

• **Competitive equilibrium**
  - A set of two-stage bids \((\beta^{DA}, \beta^{RT}, d^{DA}, d^{RT})\) and prices \((\lambda^{DA}, \lambda^{RT})\) s.t.
    - Bids are optimal for individual participants, *given the prices*;
    - Supply matches demand in both stages.

• **Strategic participants:** anticipate
  - Bidding impacts on clearing prices (through power balance);
  - Day-ahead bidding impact on real-time market outcome;

• **Nash equilibrium**
  - A set of two-stage bids \((\beta^{DA}, \beta^{RT}, d^{DA}, d^{RT})\) and prices \((\lambda^{DA}, \lambda^{RT})\) s.t.
    - Bids are optimal for individual participants, *given others’ bids*;
    - *Symmetric decisions* for homogeneous generators:
    - Supply matches demand in both stages.
Market Equilibria Characterization

• **Competitive equilibrium**
  • Equal two-stage prices at marginal cost \( \lambda^{DA*} = \lambda^{RT*} = \frac{c}{G} \sum_{l \in L} d_l \)
  • Any combination of bids with two-stage power balance

Generator: \( \beta_j^{DA*} + \beta_j^{RT*} = \frac{1}{c} \)

Load: \( d_l^{DA*} + d_l^{RT*} = d_l \)

• **Nash equilibrium**
  • No price convergence: \( \lambda^{DA*} = \frac{L}{L+1} \cdot \lambda^{RT*} \), with

\[
\lambda^{RT*} = \frac{G-1}{G-2} \cdot \frac{c}{G} \sum_{l \in L} d_l
\]

• Demand allocation:

\[
\frac{\sum_{l \in L} d_l^{DA*}}{\sum_{l \in L} d_l} = \frac{L(G-1) + 1}{(L+1)(G-1)} \in (0, 1)
\]

\( G \): num. of gens (\( G \geq 3 \) for NE with strategic gens)
Quantification of Market Power

- **Total generation cost**: optimal and fixed at all equilibria
  - *Reason*: Generator symmetry and load inelasticity

- **Market surplus allocation**

\[
\sum_{j \in G} \pi_j - \sum_{l \in L} \rho_l = - \sum_{j \in G} \frac{1}{2} c_j \left(q_{jDA}^A + q_{jRT}^R\right)^2
\]

**Profit of generators**

**Payment of loads**

**Surplus**: negative total generation cost at equilibrium

Recall: Homogeneous Generation: \(c_j = c\)

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Surplus Allocation

- **Inter-group** market power shift
  - More degree of flexibility for generators;

Generator profit:
\[
\frac{1}{2} \cdot \frac{c \left( \sum_{l \in L} d_l \right)^2}{G^2}
\]

Competitive equilibrium

\[
\left( \frac{1}{2} + \frac{1}{G - 2} \right) \cdot \frac{c \left( \sum_{l \in L} d_l \right)^2}{G^2}
\]

Generator centric view

NE with strategic gens
**Surplus Allocation**

- **Inter-group** market power shift
  - More degree of flexibility for generators;
  - Loads offset generators’ market power by
  - allocating demand strategically;

\[
\text{Generator profit: } \frac{1}{2} \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{G^2}
\]

**Competitive equilibrium**

\[
\left( \frac{1}{2} + \frac{1}{G - 2} \right) \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{G^2}
\]

**NE with strategic gens**

\[
\left( \frac{1}{2} + \frac{1}{G - 2} \right) \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{G^2}
\]

**NE with strategic gens and loads**

\[
\frac{L(G - 1) + 1}{(L + 1)^2(G - 2)} \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{G^2}
\]

Generators centric view
Surplus Allocation

- **Inter-group** market power shift
  - More degree of flexibility for generators;
  - Loads offset generators’ market power by
  - allocating demand strategically;

Generator profit:

\[
\frac{1}{2} \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{G^2}
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Competitive equilibrium

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\]

NE with strategic gens

\[
L(G - 1) + 1 \cdot \frac{c \left( \sum_{l \in \mathcal{L}} d_l \right)^2}{(L + 1)^2(G - 2)}
\]

NE with strategic gens and loads

Normalized Agg. Generator Profit

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Surplus Allocation

• **Inter-group** market power shift
  - More degree of flexibility for generators;
  - Loads offset generators’ market power by
  - allocating demand strategically;

Generator profit:
\[
\frac{1}{2} \cdot \frac{c \left( \sum_{l \in L} d_l \right)^2}{G^2}
\]

Competitive equilibrium

\[
\left( \frac{1}{2} + \frac{1}{G - 2} \right) \cdot \frac{c \left( \sum_{l \in L} d_l \right)^2}{G^2}
\]

NE with strategic gens

\[
\frac{L(G - 1) + 1}{(L + 1)^2(G - 2)} \cdot \frac{c \left( \sum_{l \in L} d_l \right)^2}{G^2}
\]

NE with strategic gens and loads

**Reversal of market power**: *General Condition*

\[
\text{gen profit}_{\text{NE both strategic}} < \text{gen profit}_{\text{Comp. Equilibrium}} \iff G > L + 3
\]
**Surplus Allocation**

- **Intra-group** market power shift
  - Load payment reduced by a fixed amount, regardless of load size;

Load payment

\[ \frac{G - 1}{G - 2} \cdot \frac{c \sum_{l \in \mathcal{L}} d_l}{G} \cdot d_l - \frac{L(G - 1) + 1}{L(L + 1)^2(G - 2)} \cdot \frac{c \sum_{l \in \mathcal{L}} d_l}{G} \]

- Relatively, small loads are favored;
  - Incentive to split instead of aggregation

- **Special Case: virtual bidding**
  - a load bidder with \( d_l = 0 \), its payment (negative profit):

\[ \frac{L'(G - 1) + 1}{L'(L' + 1)^2(G - 2)} \cdot \frac{c \sum_{l \in \mathcal{L}} d_l}{G} \]

\[ \frac{\lambda^{DA*} - \lambda^{RT*}}{\lambda^{DA*}} = \frac{1}{L'} \quad \text{as} \quad L' \to \infty \]

\( L' = L + \text{num. of virtual bidder} \)
Unintended consequences of market designs

• The role of inelastic demand in two-stage markets

• Market power mitigation via default bids
Market Power Mitigation in Two-stage Electricity Markets with Supply Function and Quantity Bidding

Rajni Kant Bansal, Yue Chen, Pengcheng You, Enrique Mallada

IEEE TEMPR, September 2023
Recall: Two-Stage Standard Market

**Day-Ahead Market**

- **Individual generator** $j \in \mathcal{G}$
- **Maximize** Individual Profit
  
  \[
  \beta_j^{DA} \quad \Rightarrow \quad \lambda^{DA} \quad \Rightarrow \quad \sum_{j \in \mathcal{G}} \beta_j^{DA} \lambda^{DA} = \sum_{i \in \mathcal{L}} d_i^{DA}
  \]

**Real-Time Market**

- **Minimize** Individual Payment
  
  \[
  \beta_j^{RT} \quad \Rightarrow \quad \lambda^{RT} \quad \Rightarrow \quad \sum_{j \in \mathcal{G}} \beta_j^{RT} \lambda^{RT} = \sum_{i \in \mathcal{L}} d_i^{RT}
  \]

- Linear supply function
  
  \[
  q_j = \beta_j \lambda
  \]

  [Klemperer, Meyer ‘89]

- **Generation goal**
  
  \[
  \max_{q_j^{DA}, q_j^{RT}} \quad \lambda^{DA} q_j^{DA} + \lambda^{RT} q_j^{RT} - \frac{1}{2} c(q_j)^2 \quad \text{s.t.} \quad q_j = q_j^{DA} + q_j^{RT}
  \]

- **Demand goal**
  
  \[
  \max_{d_i^{DA}, d_i^{RT}} \quad \lambda^{DA} d_i^{DA} + \lambda^{RT} d_i^{RT} \quad \text{s.t.} \quad d_i = d_i^{DA} + d_i^{RT}
  \]
# Equilibrium Analysis Summary

<table>
<thead>
<tr>
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<td>( \lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j c_j^{-1}} ), ( d_l^{DA} + d_l^{RT} = d_l )</td>
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\( d_l^{DA} \): Day-ahead allocation of load \( l \)

\( d_l^{RT} \): Real-time allocation of load \( l \)
Market with Market Power Mitigation Policy

Day-Ahead MPM (DA-MPM) Policy

Maximize Individual Profit

\[ \sum_{j \in \mathcal{G}} \beta_j^D A \lambda^D A = \sum_{l \in \mathcal{L}} d_l^D A \]

Minimize Individual Payment

\[ \sum_{j \in \mathcal{G}} \frac{1}{\hat{c}_j} \lambda^R T = \sum_{l \in \mathcal{L}} d_l^R T \]

Real-Time MPM (RT-MPM) Policy

Maximize Individual Profit

\[ \sum_{j \in \mathcal{G}} \beta_j^R T \lambda^R T = \sum_{l \in \mathcal{L}} d_l^R T \]

Minimize Individual Payment

\[ \sum_{j \in \mathcal{G}} \left( \frac{1}{\hat{c}_j} \lambda^R T - g_j^D A \right) = \sum_{l \in \mathcal{L}} d_l^R T \]

*Assumption: Substituting with default bids – market estimates \( \hat{c}_j = c_j + \varepsilon_j > c_j \)
**Main Results: Real-Time Market Power Mitigation (RT-MPM)**

**Competitive Equilibrium**
- **Same** as the standard market
- **Approximately efficient** but **non-unique**
  - Equal Prices at approx. marginal cost:
    \[ \lambda^{RT} = \lambda^{DA} = \frac{d}{\sum_{j \in G} \hat{c}_j^{-1}} \]
  - Load allocation:
    \[ d_l^{DA} + d_l^{RT} = d_l \]

**Nash Equilibrium**
- **Does not exist!**
  - Gens and loads incentivize to make bids
    \[ \beta_j^{DA} \rightarrow 0 \text{ and demand } d^{DA} \rightarrow 0 \]
  - Prices are not clearly defined
    \[ \lambda^{DA} = \frac{d^{DA}}{\sum_j \beta_j^{DA}} \rightarrow ? \]

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<td><strong>No Equilibrium</strong> [ d_l^{DA} \rightarrow 0 ]</td>
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\( d_l^{DA} \): Day-ahead allocation of load \( l \)  
\( d_l^{RT} \): Real-time allocation of load \( l \)
Market with Market Power Mitigation Policy

**Day-Ahead MPM (DA-MPM) Policy**

- **Individual generator** $j \in G$
- **Maximize** Individual Profit
  \[ \beta^D_{j} \]
  \[ \sum_{j \in G} \frac{1}{\hat{c}_j} \lambda^R T = \sum_{l \in L} d^R_{l} \]
- **Minimize** Individual Payment
  \[ d^D_{l} \]

**Real-Time MPM (RT-MPM) Policy**

- **Individual generator** $j \in G$
- **Maximize** Individual Profit
  \[ \beta^R_{j} \]
  \[ \sum_{j \in G} \beta^R_{j} \lambda^R T = \sum_{l \in L} d^R_{l} \]
- **Minimize** Individual Payment
  \[ d^R_{l} \]

*Assumption: Substituting with default bids – market estimates $\hat{c}_j = c_j + \varepsilon_j > c_j$*

---

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Main Results: Real-Time Market Power Mitigation (RT-MPM)

Competitive Equilibrium
- **Same** as the standard market
- **Approximately efficient** but non-unique
  - Larger prices than true marginal cost:
    \[
    \lambda_{RT}^{DA} = \lambda_{DA} = \frac{d}{\sum_{j \in G} c_j^{-1}}
    \]
  - Load allocation:
    \[
    \sum_l d_l^{DA} = \frac{\sum_{j}(c_j + \varepsilon_j)^{-1}}{\sum_j c_j^{-1}} \sum_l d_l
    \]

Nash Equilibrium
- **Exists for:** \( G \geq 3, \quad \frac{1}{L} \geq \frac{c - \varepsilon(G-2)}{(c+\varepsilon)(G-2)} \)
- **Mild reduction in the market power**
  - Prices as in the standard NE:
    \[
    \lambda_{DA} = \frac{L}{L + 1} \lambda_{RT}
    \]
  - Load allocation:
    \[
    \sum_l d_l^{DA} = \frac{c}{c + \varepsilon L + 1 G - 2} \sum_l d_l
    \]
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**Remarks:**
- **CE** is efficient, **unique** and aligns with the standard market
- **NE** does not always exist
- **DA-MPM** results in mild market power mitigation, while **RT-MPM** leads to undesirable market outcome
Summary

• The role of strategic load participants in two-stage markets
  • Modeling framework that accounts for gen and loads’ strategic behavior.
  • Existence and uniqueness of Nash equilibrium
  • Quantification of market power shift among participants

• Take-away messages:
  • Accounting for load behavior is critical
  • Competitive two-stage markets do not incentive clearing all the demand in day ahead
  • Loads can only manipulate prices if generators are strategic!
  • Generator’s profit can be below the competitive eq. profit

• Analysis further allows characterization of the impact of many policies, e.g.,
  • Virtual bidding -> benefits from load market power
  • Default-bid market power mitigation policies
  • Real-time transaction charges
Thanks!

**Papers**


**Other Related Papers**


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