Unintended consequences of market designs

The role of inelastic demand and market rules

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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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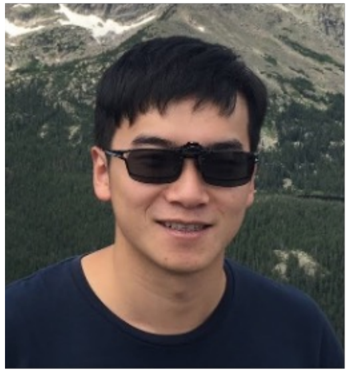

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Two-stage/Sequential Markets

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

ENERGY POLICY ACT OF 1992

TITLE VII—ELECTRICITY

Subtitle A—Exempt Wholesale Generators

Sec. 711. Public Utility Holding Company Act reform.
Sec. 712. State consideration of the effects of power purchases on utility cost of capital; consideration of the effects of leveraged capital structures on the reliability of wholesale power sellers; and consideration of adequate fuel supplies.
Sec. 713. Public utility holding companies to own interests in cogeneration facilities.
Sec. 714. Books and records.
Sec. 715. Investment in foreign utilities.

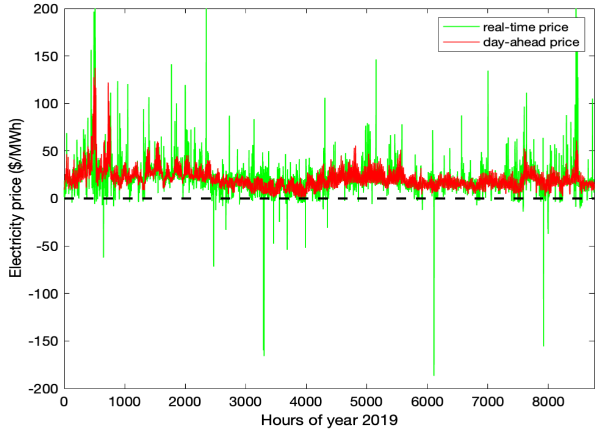
Subtitle B—Federal Power Act; Interstate Commerce in Electricity

Sec. 721. Amendments to section 211 of Federal Power Act.
Sec. 722. Transmission services.
Sec. 723. Information requirements.
Sec. 724. Sales by exempt wholesale generators.
Sec. 725. Penalties.
Sec. 726. Definitions.

Subtitle C—State and Local Authorities

Sec. 731. State authorities.

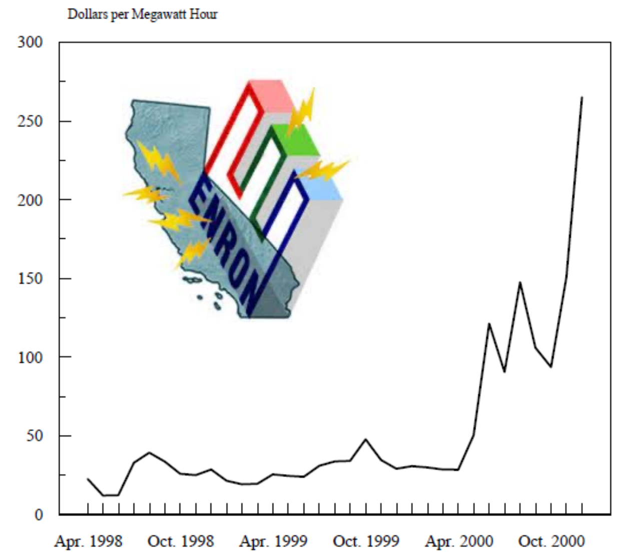
day-ahead vs real-time prices



Source: NYISO

Operational Challenges in Electricity Grids

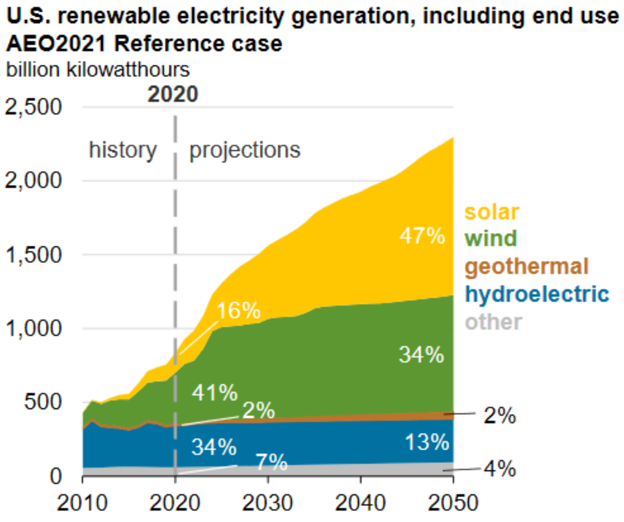
- Undesired price manipulation by market participants
  - California Electricity Crisis – Enron '00-'01
  - Today: ~2% hours with non-competitive bids in the CAISO market (2021)



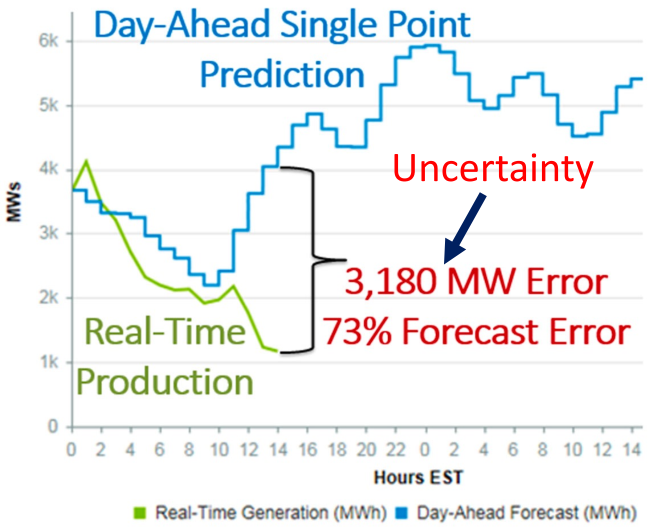
SOURCE: Congressional Budget Office based on data for the northern and southern regions from the California Energy Commission (available at www.energy.ca.gov/electricity/wepr/monthly_day_ahead_prices.html).

- Proliferation of renewable energy sources

Rapid growth in solar and wind energy



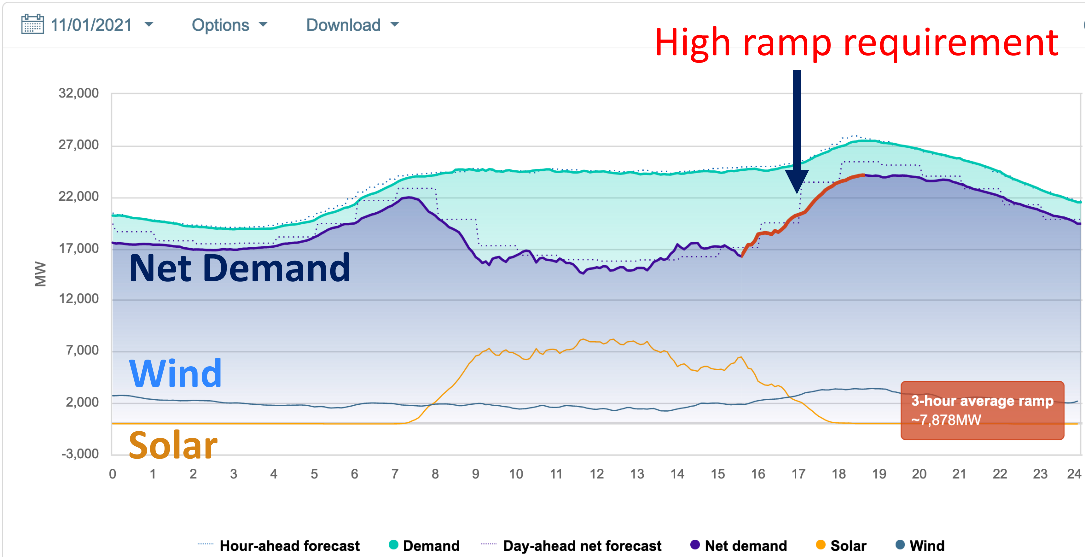
Source: U.S. Energy Information Administration



Source: Midcontinent ISO (Jun 26, 2019)

Net demand trend

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



Source: California ISO

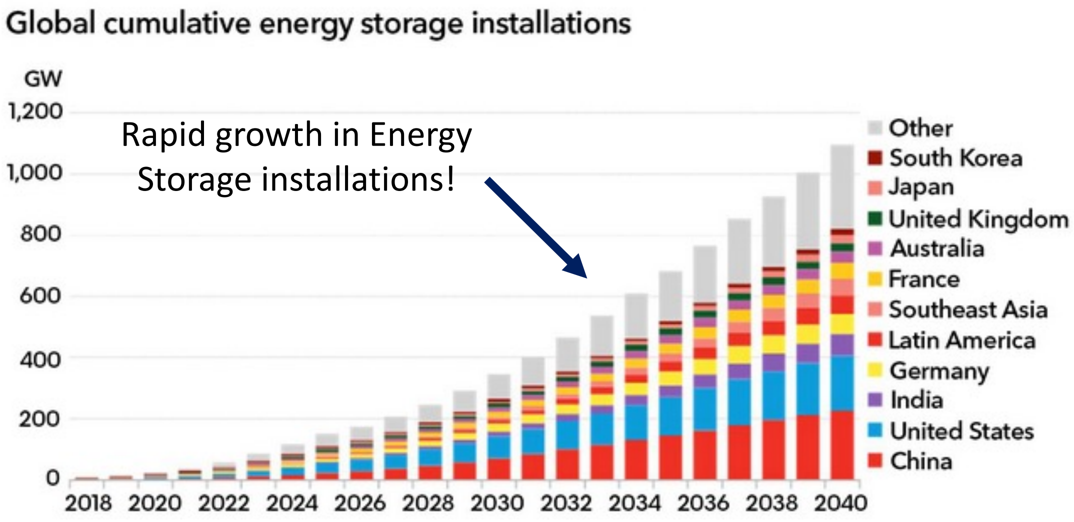
Opportunities

- **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?



Source: BloombergNEF

172 FERC ¶ 61,247
DEPARTMENT OF ENERGY
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 35

[Docket No. RM18-9-000; Order No. 2222]

Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators

(Issued September 17, 2020)

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

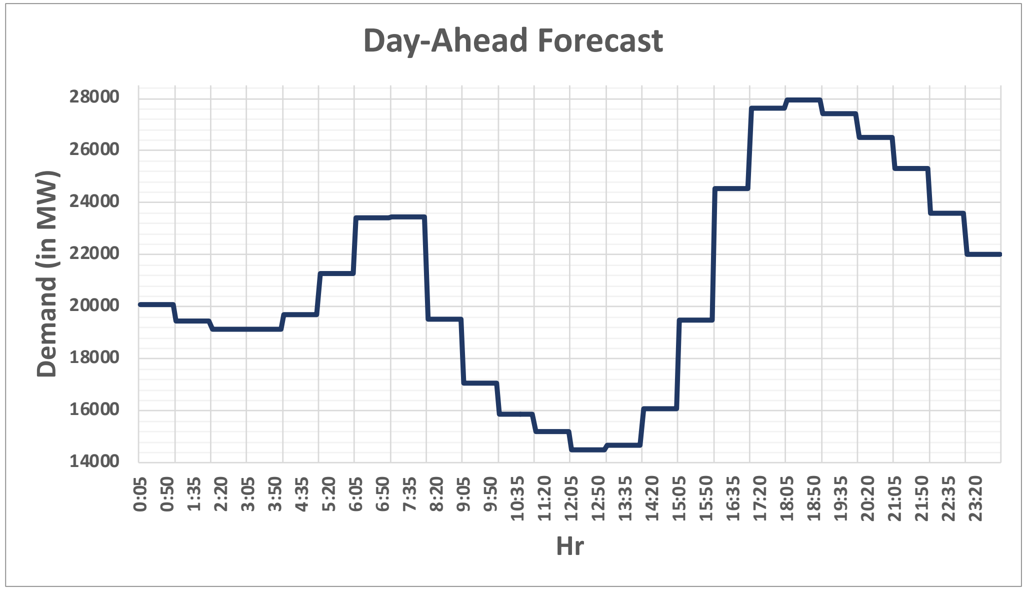
Preprint, August 2022

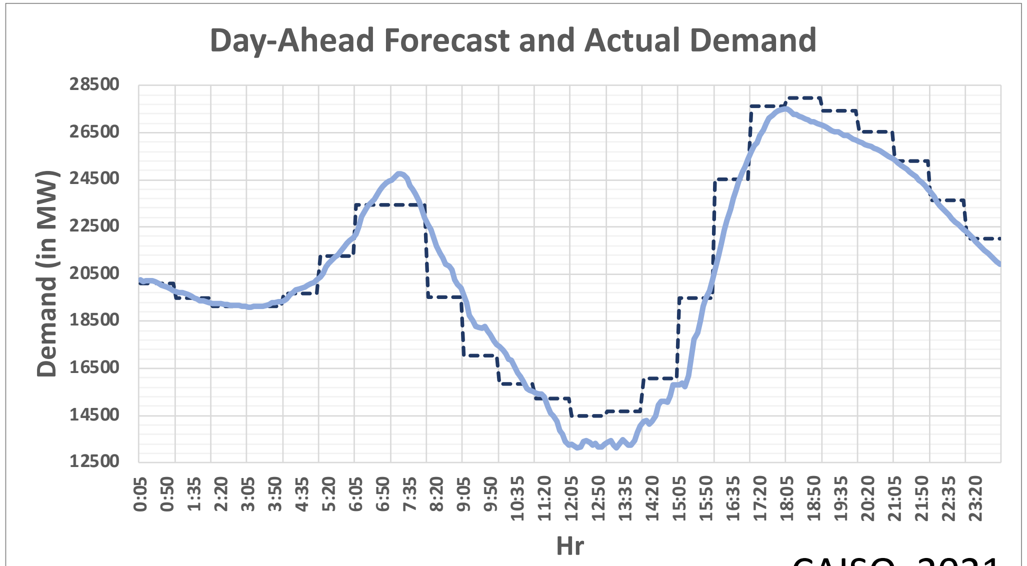
Existing Paradigm - Wholesale Energy Market Design

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**





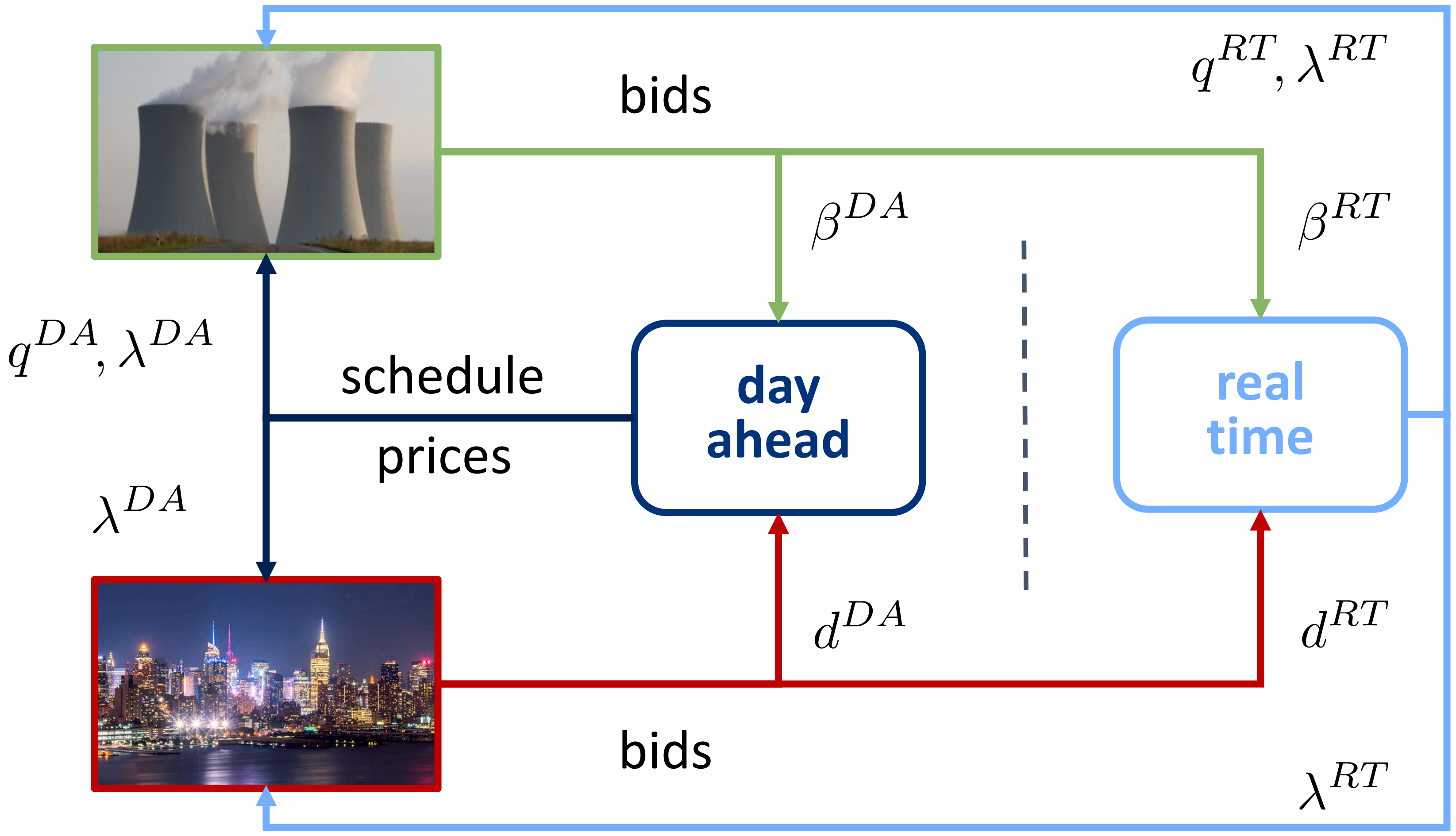
CAISO, 2021

Two-stage Settlement in Electricity Markets

linear supply function

$$q^{?} = \beta^{?} \lambda^{?}$$

[Klemperer, Meyer '89]



total generation

$$q = q^{RT} + q^{DA}$$

total demand

$$d = d^{RT} + d^{DA}$$

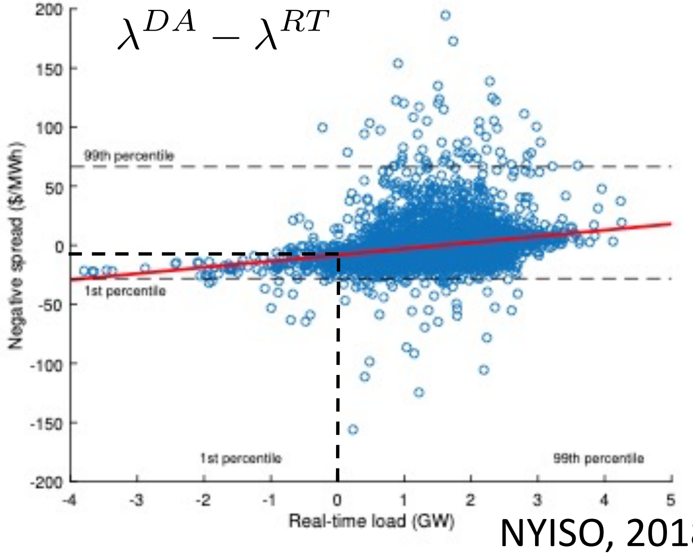
day ahead: forward position

real time: last resort/opportunity

Challenge: Operation Not Fully Understood

Market Power is Major Concern

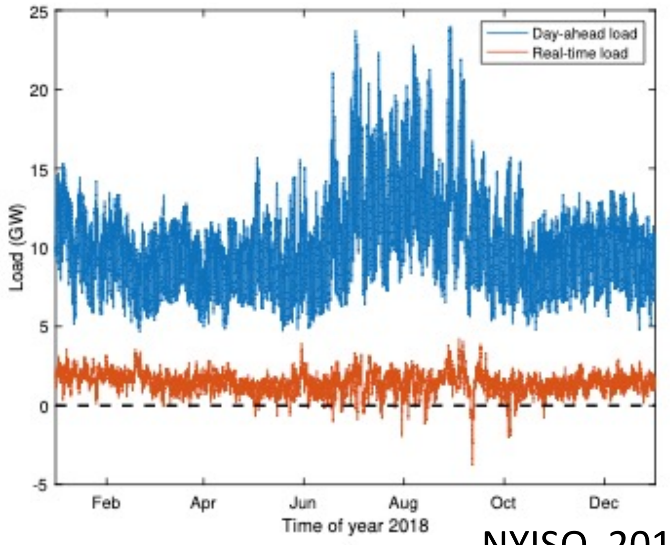
- Competitive Equilibria -> Price Convergence $\lambda^{DA} = \lambda^{RT}$
- Evidence the lack of price convergence
  - MISO [Bowden et al. '09, Birge et al. '18]
  - NYISO [Jha & Wolak '19, You et al. '19]
  - CAISO [Borenstein '08] and more..



NYISO, 2018

Is the Spot Market Operating as Last Resort?

- Systematic bias in real-time demand



NYISO, 2018

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

Individual generator $j \in \mathcal{G}$

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

Day-ahead market clearing

Day-ahead market

$$\sum_{j\in\mathcal{G}} \beta_j^{DA}\lambda^{DA} = \sum_{l\in\mathcal{L}} d_l^{DA}$$

Real-time market

$$\sum_{j\in\mathcal{G}} \beta_j^{RT}\lambda^{RT} = \sum_{l\in\mathcal{L}} d_l^{RT}$$

Real-time market clearing

An Extensive-Form Game

- Between G ***homogeneous*** generators and L ***heterogeneous*** inelastic loads
- Perfect foresight and complete information

Quadratic cost

Individual generator $j \in \mathcal{G}$

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

Linear supply function bid

$$q_j^{DA} = \beta_j^{DA}\lambda^{DA}$$

$$q_j^{RT} = \beta_j^{RT}\lambda^{RT}$$

Day-ahead market clearing

Day-ahead market

$$\sum_{j\in\mathcal{G}} \beta_j^{DA}\lambda^{DA} = \sum_{l\in\mathcal{L}} d_l^{DA}$$

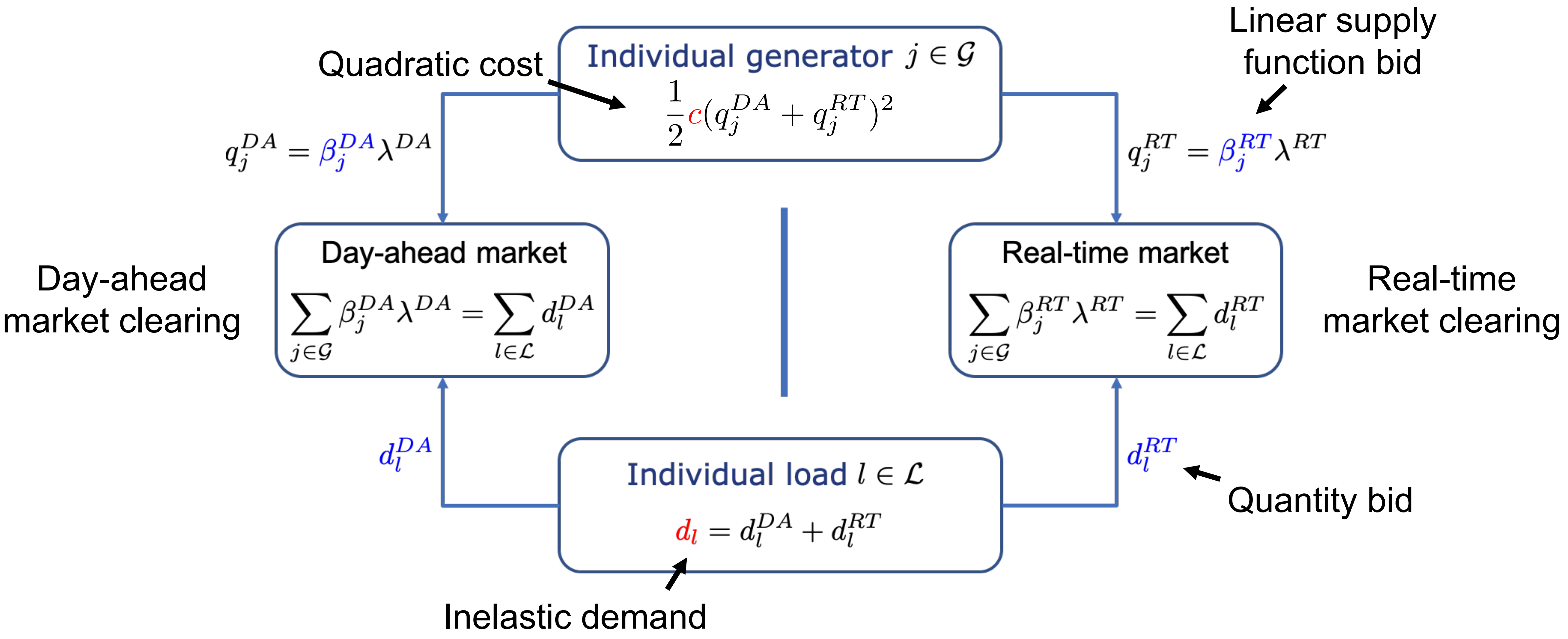
Real-time market clearing

Real-time market

$$\sum_{j\in\mathcal{G}} \beta_j^{RT}\lambda^{RT} = \sum_{l\in\mathcal{L}} d_l^{RT}$$

An Extensive-Form Game

- Between G ***homogeneous*** generators and L ***heterogeneous*** inelastic loads
- Perfect foresight and complete information



An Extensive-Form Game

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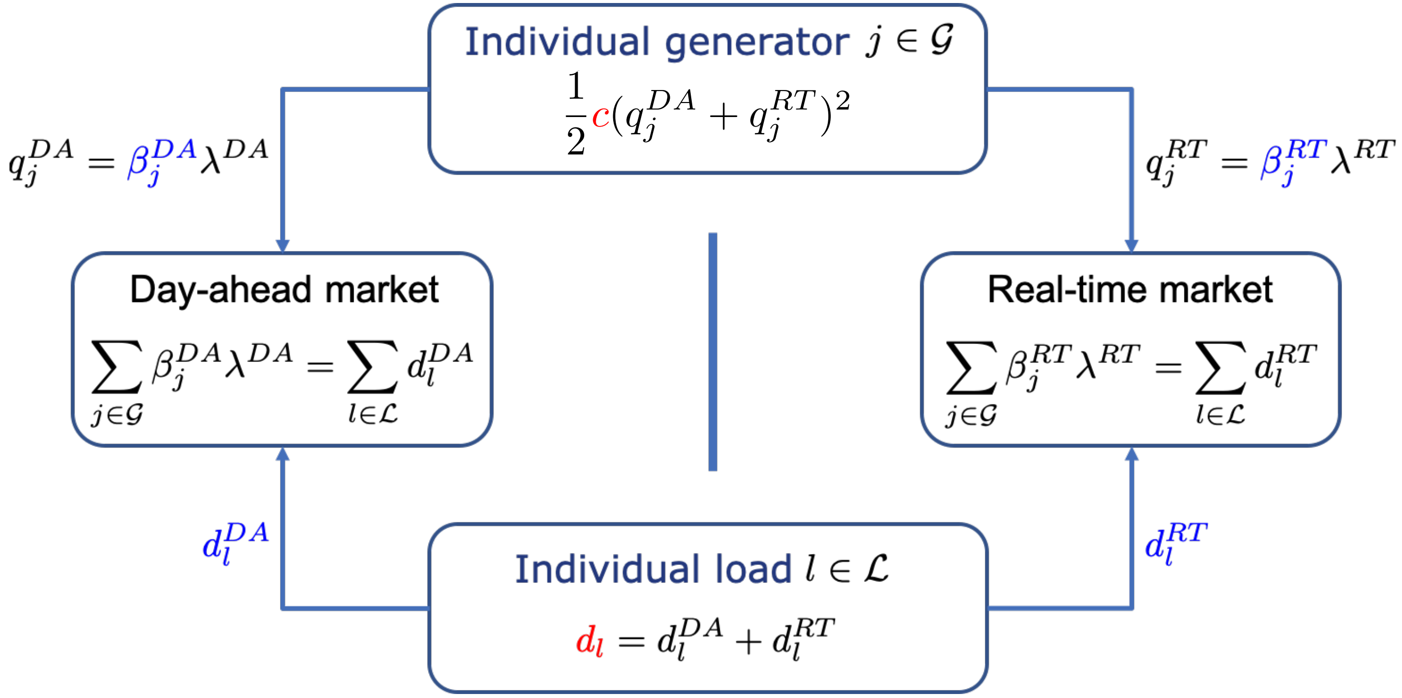


Generation goal

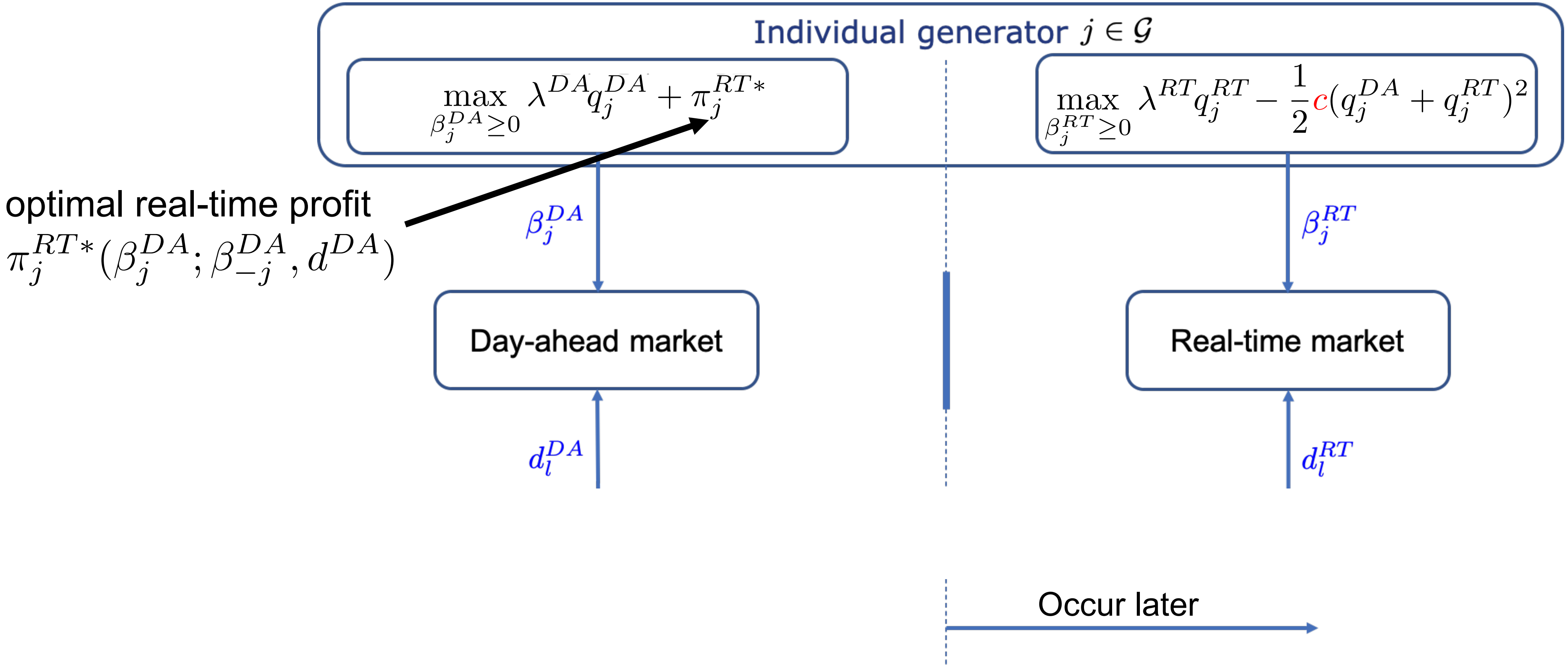
$$\max_{q_j^{DA} q_j^{RT}} \lambda^{DA} q_j^{DA} + \lambda^{RT} q_j^{RT} - \frac{1}{2}c(q_j)^2$$
$$\text{s.t.} \quad q_j = q_j^{DA} + q_j^{RT}$$

Demand goal

$$\max_{d_l^{DA} d_l^{RT}} \lambda^{DA} d_l^{DA} + \lambda^{RT} d_l^{RT}$$
$$\text{s.t.} \quad d_l = d_l^{DA} + d_l^{RT}$$

Model: Nested Game

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



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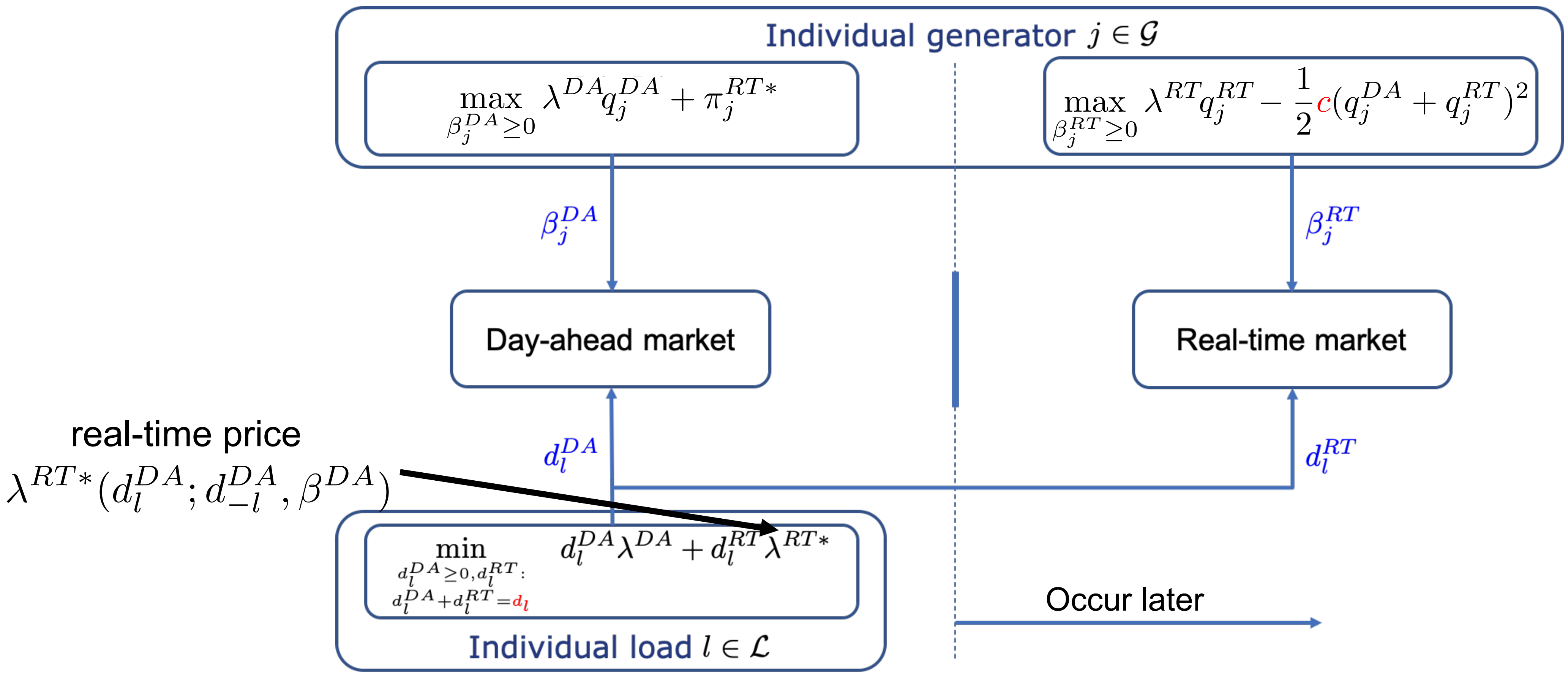


Market Participant Types

- **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

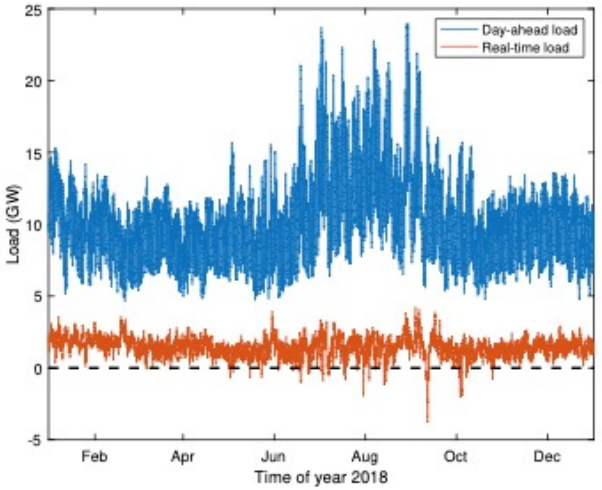
Recall: Homogeneous Generation: $c_j = c$

- **Competitive equilibrium**
  - Equal two-stage prices at marginal cost $\lambda^{DA*} = \lambda^{RT*} = \frac{c}{G}\sum_{l\in\mathcal{L}} d_l$
  - 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 $\lambda^{RT*} = \frac{G-1}{G-2} \cdot \frac{c}{G}\sum_{l\in\mathcal{L}} d_l$
  - Demand allocation:

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



G: num. of gens (*G* >=3 for NE with strategic gens)

Quantification of Market Power

Recall: Homogeneous Generation: $c_j = c$

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

- **Market surplus allocation**

Profit of generators

Surplus: negative total generation cost at equilibrium

$$\sum_{j\in\mathcal{G}} \pi_j - \sum_{l\in\mathcal{L}} \rho_l = -\sum_{j\in\mathcal{G}} \frac{1}{2} c_j (q_j^{DA} + q_j^{RT})^2$$

Payment of loads

Surplus Allocation

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

Generator centric view

Generator profit: $$\frac{1}{2} \cdot \frac{c\left(\sum_{l \in \mathcal{L}} d_l\right)^2}{G^2} \longrightarrow \left(\frac{1}{2} + \frac{1}{G-2}\right) \cdot \frac{c\left(\sum_{l \in \mathcal{L}} d_l\right)^2}{G^2}$$

Competitive equilibrium

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;

Generator centric view

Generator profit: $\frac{1}{2} \cdot \frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)^2}{G^2}$ $\longrightarrow$ $\left(\frac{1}{2} + \frac{1}{G-2}\right) \cdot \frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)^2}{G^2}$

Competitive equilibrium

NE with strategic gens

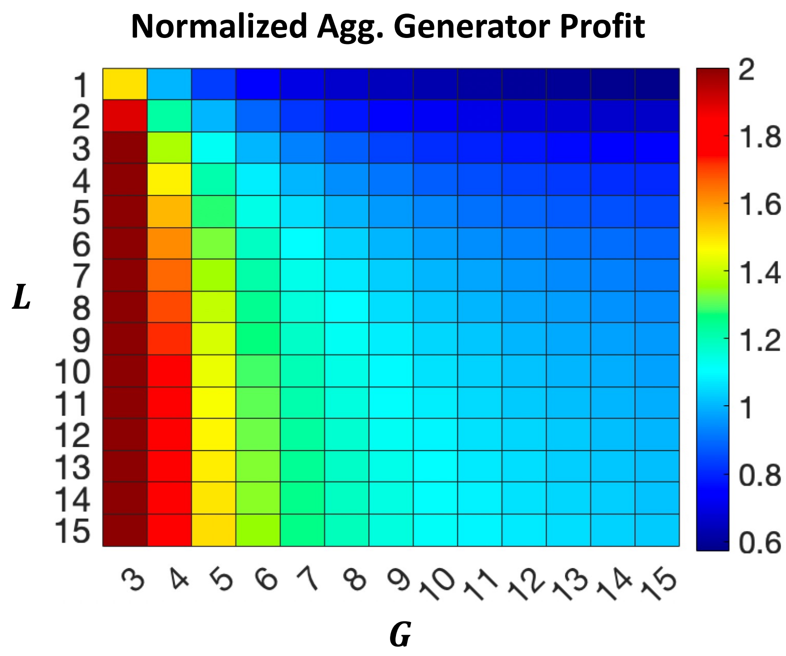
$$\boxed{\left(\frac{1}{2} + \frac{1}{G-2}\right) \cdot \frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)^2}{G^2}} - \frac{L(G-1)+1}{(L+1)^2(G-2)} \cdot \frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)^2}{G^2}$$

NE with strategic gens

NE with strategic gens and loads

Surplus Allocation

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



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Competitive equilibrium

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NE with strategic gens

NE with strategic gens and loads

Surplus Allocation

- ***Inter-group*** market power shift
  - More degree of flexibility for generators;
  - Loads offset generators' market power by
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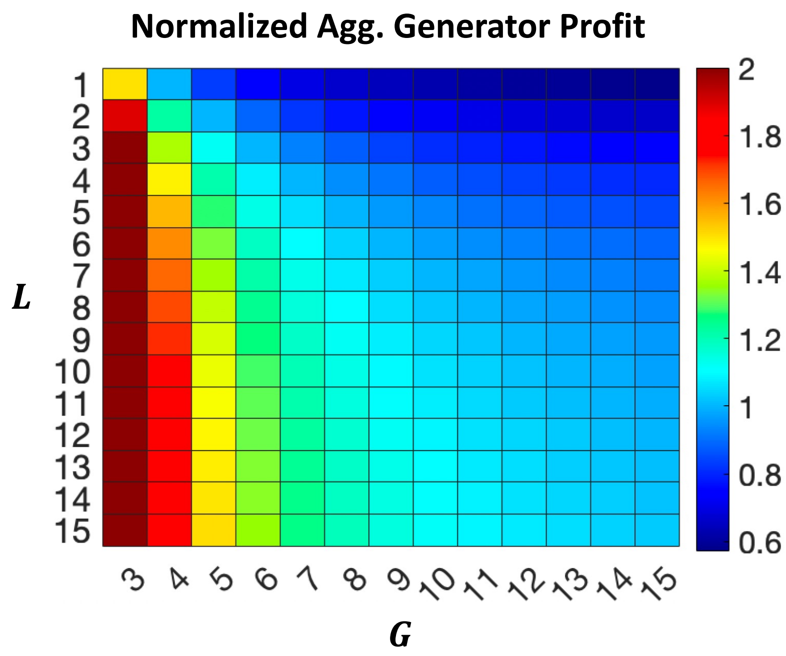
Generator profit: $\frac{1}{2} \cdot \frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)^2}{G^2}$

Competitive equilibrium

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

NE with strategic gens

NE with strategic gens and loads



Reversal of market power: *General Condition*

gen profit NE both strategic	<	**gen profit Comp. Equilibrium**	$\Longleftrightarrow$	$G > L + 3$

Surplus Allocation

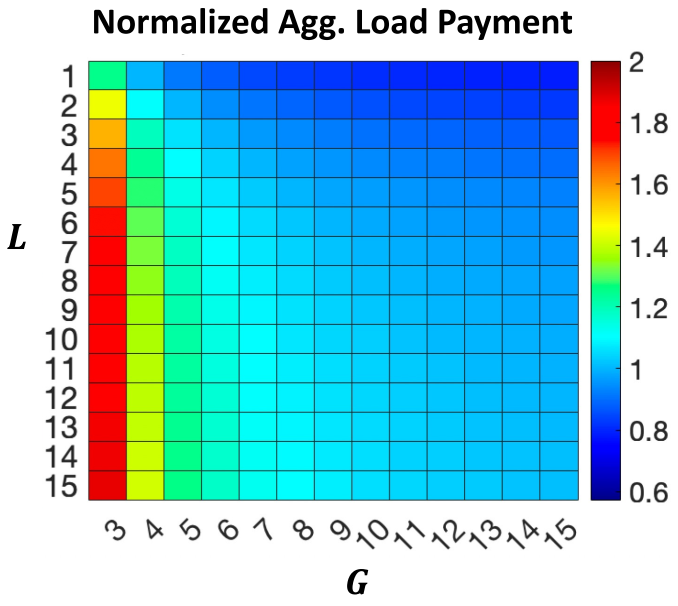
- ***Intra-group*** market power shift
  - Load payment reduced by a fixed amount, regardless of load size;

Load payment

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

NE with strategic gens

NE with strategic gens and loads



- 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):

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

$$\frac{\lambda^{DA*}-\lambda^{RT*}}{\lambda^{DA*}} = \frac{1}{L'} \xrightarrow[L'\to\infty]{} 0$$

L' = *L* + num. of virtual bidder

Unintended consequences of market designs

- The role of inelastic demand in two-stage markets

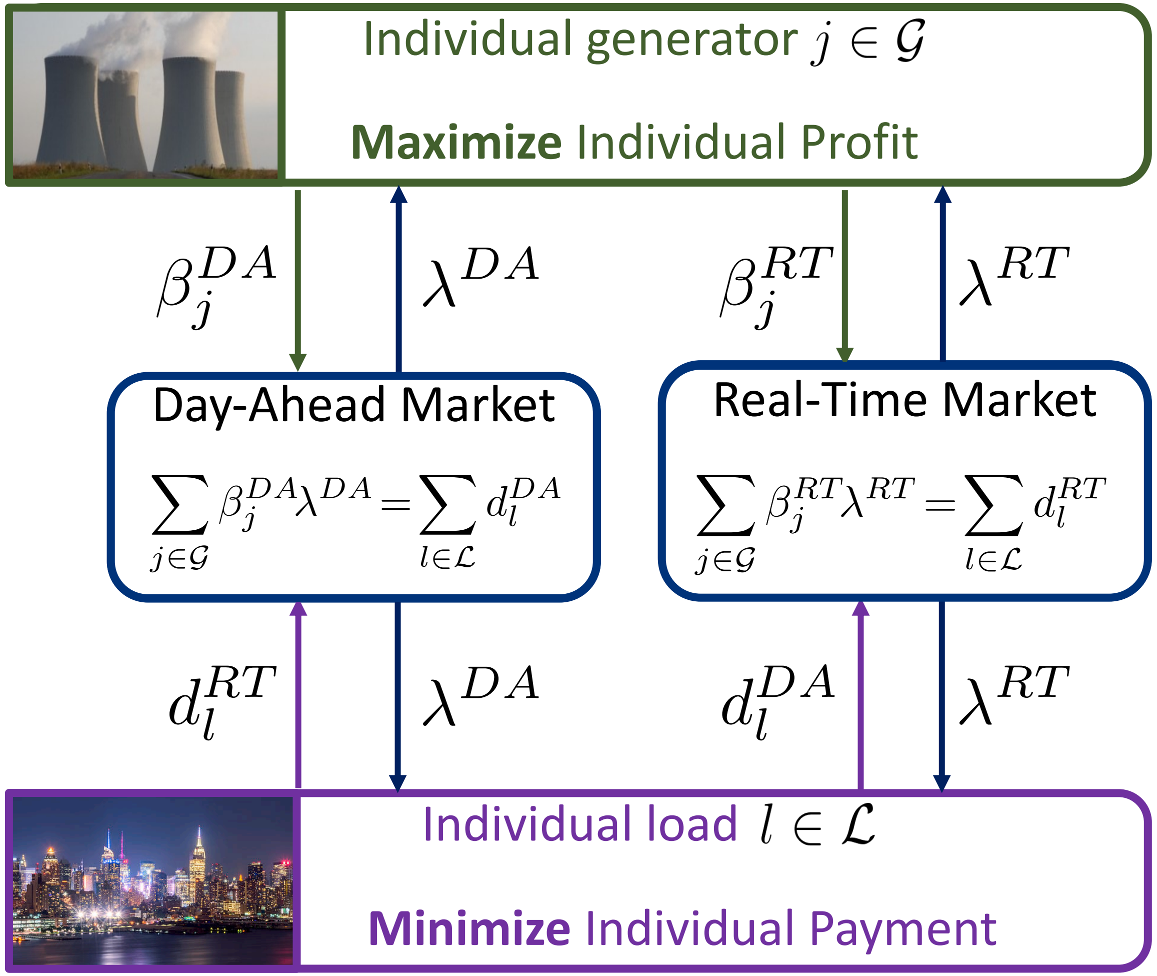
- Market power mitigation via default bids

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



linear supply function

$$q^? = \beta^? \lambda^?$$

[Klemperer, Meyer '89]

generation goal

$$\begin{aligned} \max_{q_j^{DA} q_j^{RT}} \quad & \lambda^{DA} q_j^{DA} + \lambda^{RT} q_j^{RT} - \frac{1}{2} c(q_j)^2 \\ \text{s.t.} \quad & q_j = q_j^{DA} + q_j^{RT} \end{aligned}$$

demand goal

$$\begin{aligned} \max_{d_l^{DA} d_l^{RT}} \quad & \lambda^{DA} d_l^{DA} + \lambda^{RT} d_l^{RT} \\ \text{s.t.} \quad & d_l = d_l^{DA} + d_l^{RT} \end{aligned}$$

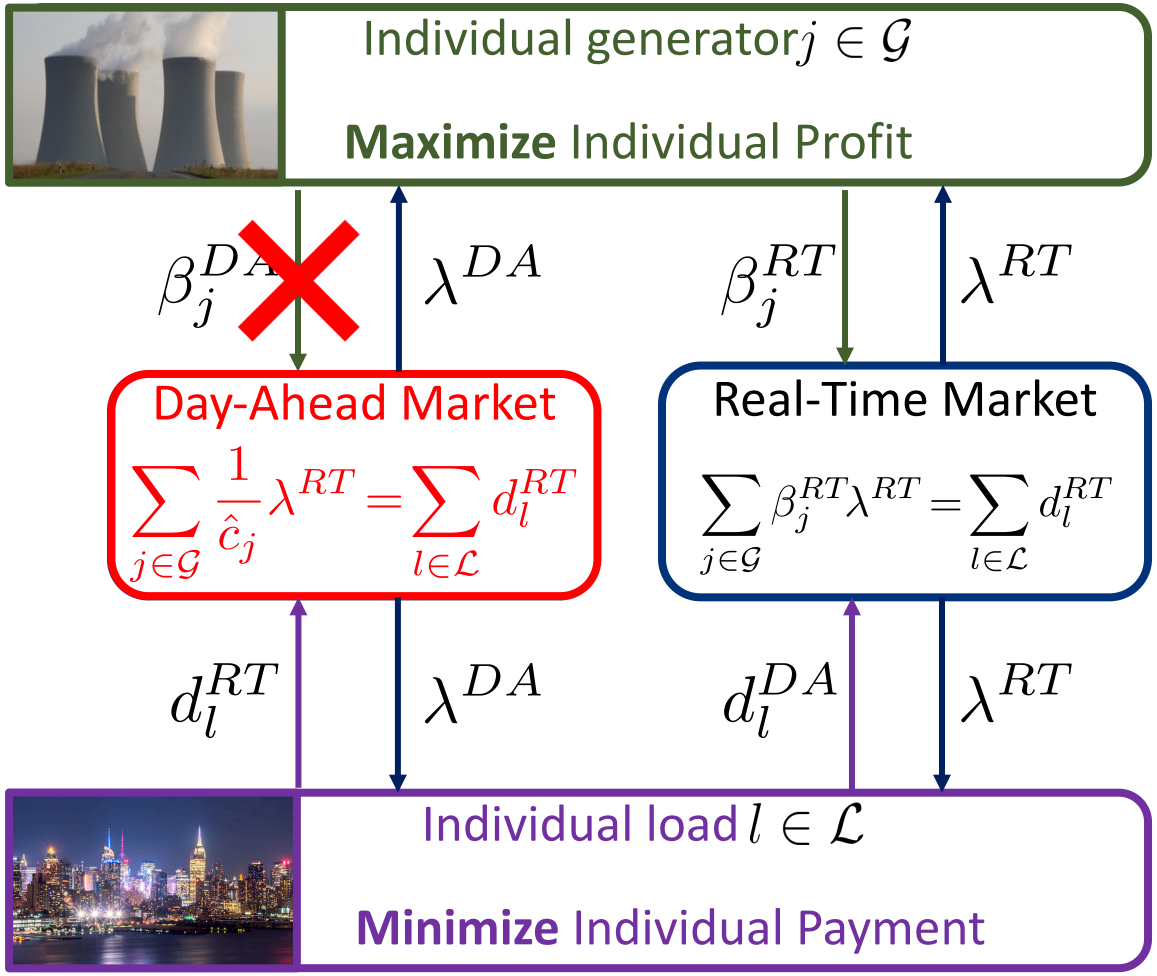
Equilibrium Analysis Summary

d_l^{DA}: Day-ahead allocation of load l
d_l^{RT}: Real-time allocation of load l

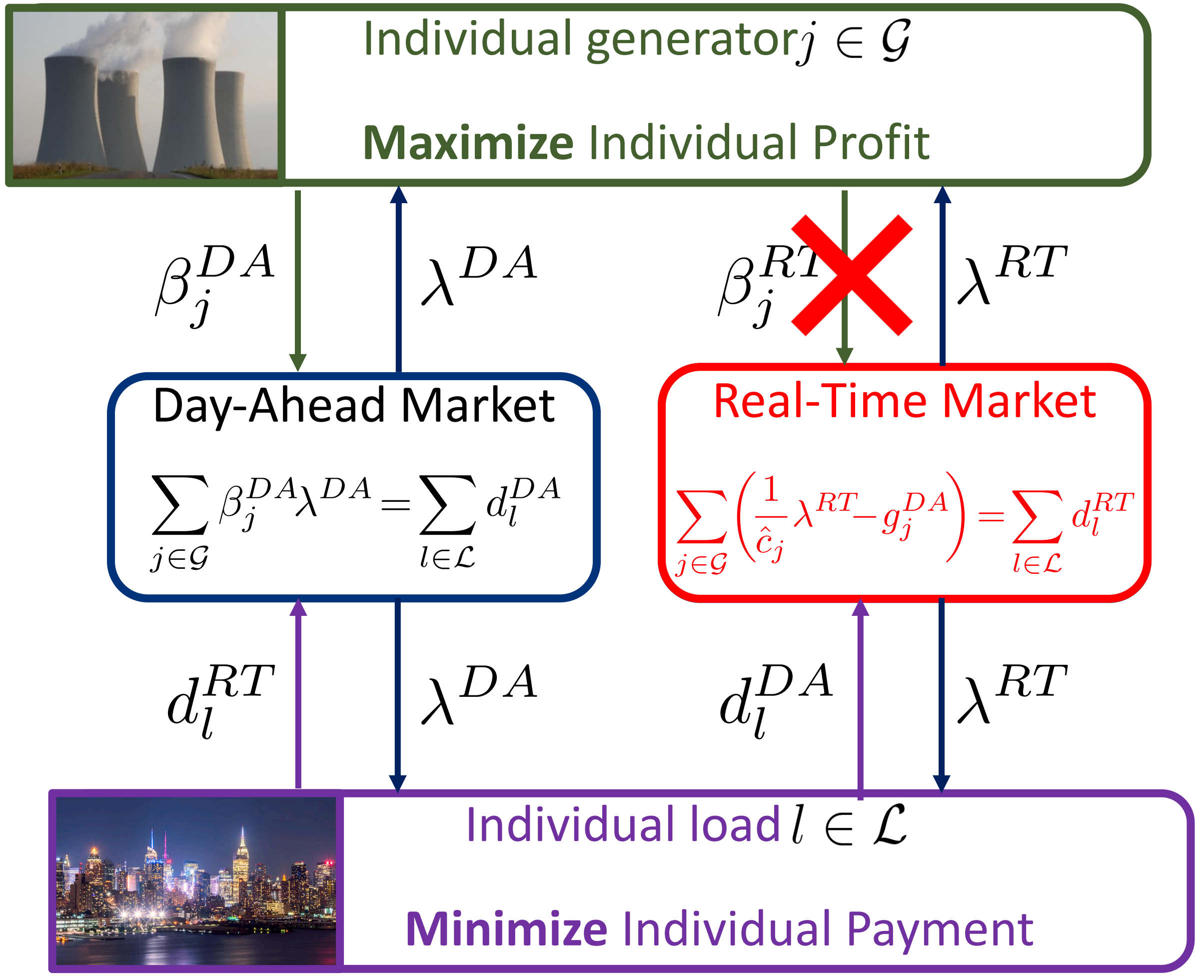
Market	Competitive Equilibrium	Nash Equilibrium
Standard	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j c_j^{-1}}, \qquad d_l^{DA} + d_l^{RT} = d_l$	$\lambda^{DA} = \frac{L}{L+1}\lambda^{RT}, \qquad \frac{\sum_l d_l^{DA}}{\sum_l d_l} < 1$

Market with Market Power Mitigation Policy

Day-Ahead MPM (DA-MPM) Policy



Real-Time MPM (RT-MPM) Policy



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:

$$\lambda^{RT} = \lambda^{DA} = \frac{d}{\sum_{j\in\mathcal{G}} \hat{c}_j^{-1}}$$

  - Load allocation:

$$d_l^{DA} + d_l^{RT} = d_l$$

Nash Equilibrium

- **Does not exist!**
  - Gens and loads incentivize to make bids $\beta_j^{DA} \to 0$ and demand $d^{DA} \to 0$
  - Prices are not clearly defined

$$\lambda^{DA} = \frac{d^{DA}}{\sum_j \beta_j^{DA}} \to ?$$

*R. K. Bansal, Y. Chen, P. You, and E. Mallada, Market Power Mitigation in Two-stage Electricity Market with Supply Function and Quantity Bidding, arXiv:2301.04267
*R. K. Bansal, Y. Chen, P. You, and E. Mallada, Intercept Function Bidding in Two-stage Electricity Market with Market Power Mitigation, arXiv:2308.05570

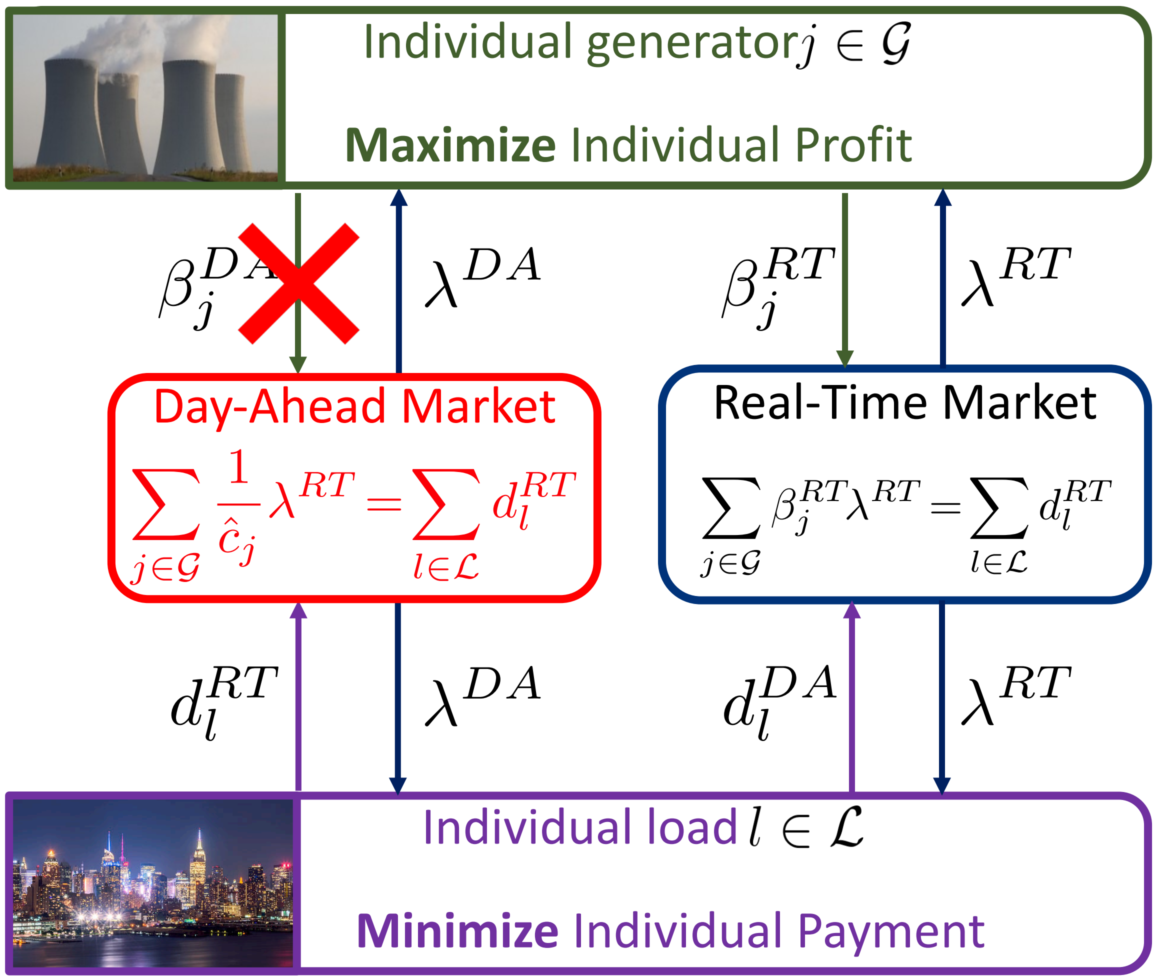
Equilibrium Analysis Summary

d_l^{DA}: Day-ahead allocation of load l
d_l^{RT}: Real-time allocation of load l

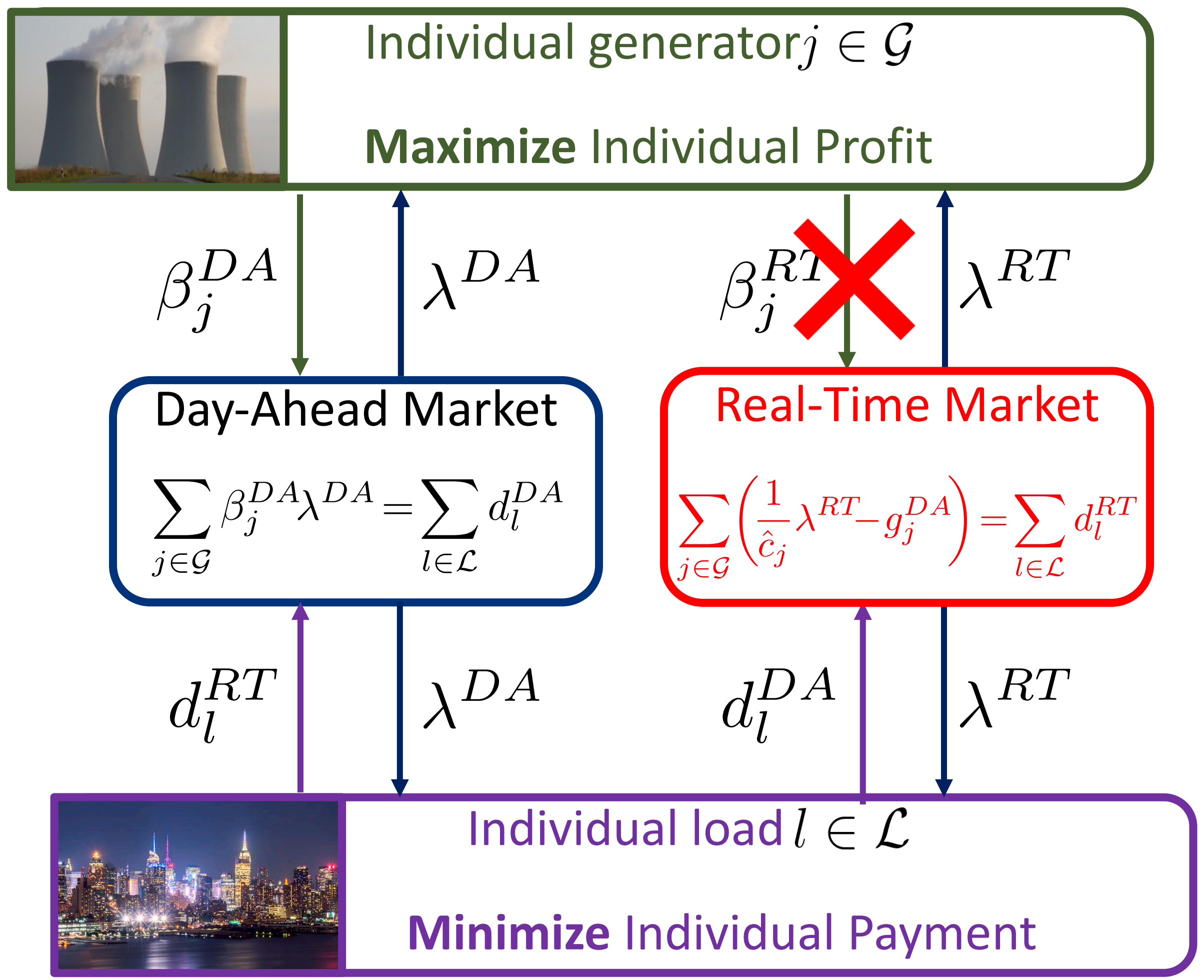
Market	Competitive Equilibrium	Nash Equilibrium
Standard	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j c_j^{-1}}, \qquad d_l^{DA} + d_l^{RT} = d_l$	$\lambda^{DA} = \frac{L}{L+1}\lambda^{RT}, \qquad \frac{\sum_l d_l^{DA}}{\sum_l d_l} < 1$
RT-MPM	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j c_j^{-1}}, \qquad d_l^{DA} + d_l^{RT} = d_l$	**No Equilibrium** $\boldsymbol{d^{DA}} \rightarrow \mathbf{0}$

Market with Market Power Mitigation Policy

Day-Ahead MPM (DA-MPM) Policy



Real-Time MPM (RT-MPM) Policy



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**
  - **Larger prices** than true marginal cost:

$$\lambda^{RT} = \lambda^{DA} = \frac{d}{\sum_{j\in\mathcal{G}} c_j^{-1}}$$

  - Load allocation:

$$\sum_l d_l^{DA} = \frac{\sum_j (c_j+\varepsilon_j)^{-1}}{\sum_j c_j^{-1}} \sum_l d_l$$

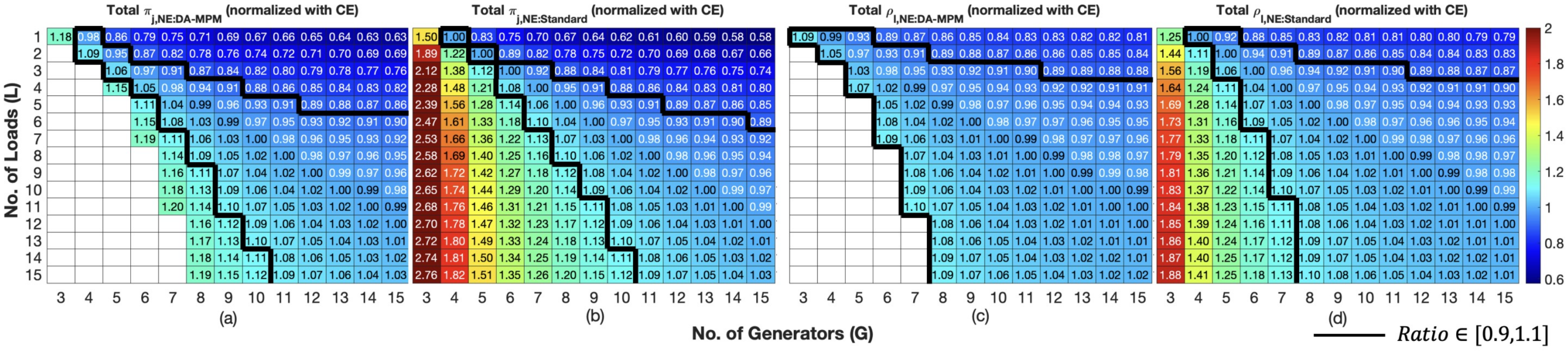
Nash Equilibrium

- **Exists for:** $\boldsymbol{G \geq 3,\ \frac{1}{L} \geq \frac{c-\varepsilon(G-2)}{(c+\varepsilon)(G-2)}}$
- ***Mild reduction in the market power***
  - **Prices as in the standard NE**:

$$\lambda^{DA} = \frac{L}{L+1}\lambda^{RT}$$

  - Load allocation:

$$\sum_l d_l^{DA} = \frac{c}{c+\varepsilon}\frac{L}{L+1}\frac{G-1}{G-2}\sum_l d_l$$



Equilibrium Analysis Summary

d_l^{DA}: Day-ahead allocation of load l
d_l^{RT}: Real-time allocation of load l

Market	Competitive Equilibrium	Nash Equilibrium
Standard	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j c_j^{-1}}, \quad d_l^{DA} + d_l^{RT} = d_l$	$\lambda^{DA} = \frac{L}{L+1}\lambda^{RT}, \quad \frac{\sum_l d_l^{DA}}{\sum_l d_l} < 1$
RT-MPM	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j \hat{c}_j^{-1}}, \quad d_l^{DA} + d_l^{RT} = d_l$	**No Equilibrium** $\boldsymbol{d^{DA} \to 0}$
DA-MPM	$\lambda^{RT} = \lambda^{DA} = \frac{\sum_l d_l}{\sum_j \hat{c}_j^{-1}}, \quad \frac{\sum_l d_l^{DA}}{\sum_l d_l^{DA}} = \frac{\sum_j (c_j + \varepsilon_j)^{-1}}{\sum_j c_j^{-1}}$	$\lambda^{DA} = \frac{L}{L+1}\lambda^{RT}, \quad \frac{\sum_l d_l^{DA}}{\sum_l d_l} < 1$

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

- **P. You**, M. Fernandez, D. Gayme, E. M., “The Role of Strategic Participants in Two-Stage Settlement Markets,” ***Preprint***
- **R. K. Bansal**, Y. Chen, P. You, and E. Mallada, “Equilibrium Analysis of Electricity Markets with Day-Ahead Market Power Mitigation and Real-Time Intercept Bidding,” in e-Energy, Jun. 2022.

Other Related Papers

- **R. K. Bansal**, **P. You**, D. F. Gayme, and E. Mallada, “A Market Mechanism for Truthful Bidding with Energy Storage,” EPSR, Jun 2022.

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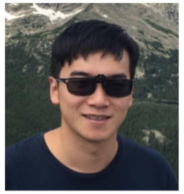

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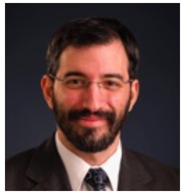

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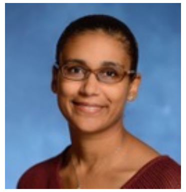

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