Unintended consequences of market designs

The role of inelastic demand and storage

Enrique Mallada

Johns Hopkins University

National Renewable Energy Laboratory

Human Dimensions of Energy Systems Workshop

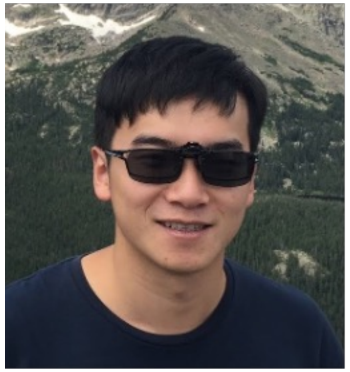
September 7, 2022

Acknowledgements

Rajni K. Bansal

Marcelo Fernandez

Dennice Gayme



Pengcheng You

JOHNS HOPKINS UNIVERSITY

北京大學 PEKING UNIVERSITY

NSF

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

JOHNS HOPKINS RALPH O'CONNOR SUSTAINABLE ENERGY INSTITUTE

Two-stage/Sequential Markets

Two-stage markets are the norm in energy systems!

Designed to incentivize transactions in the presence of uncertainty

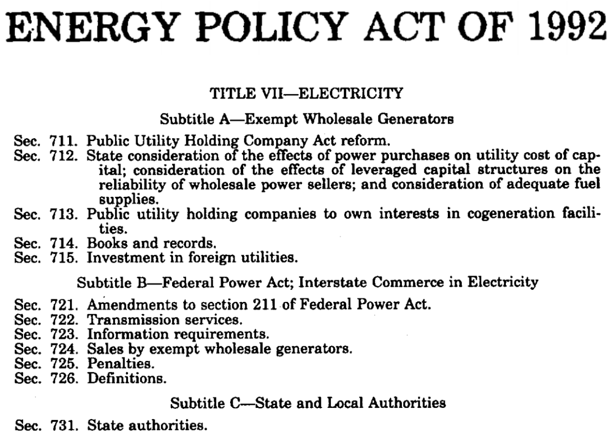
- **Forward Market:** Future contracts
- **Spot Market:** Immediate commitments

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

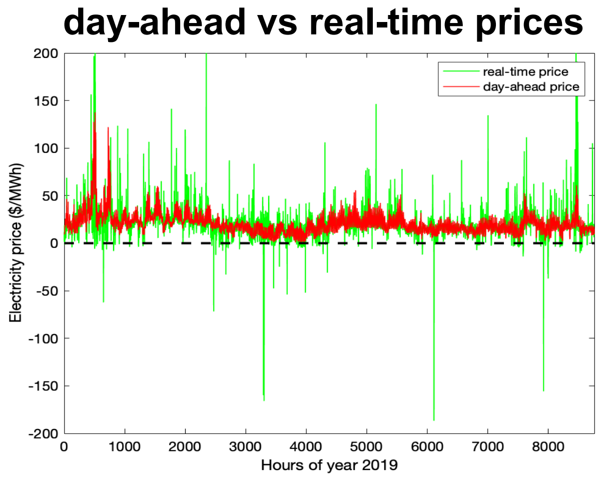
Sec. 711. Public Utility Holding Company Act reform.
Sec. 712. State consideration of the effects of power purchases on utility cost of capital; consideration of the effects of leveraged capital structures on the reliability of wholesale power sellers; and consideration of adequate fuel supplies.
Sec. 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

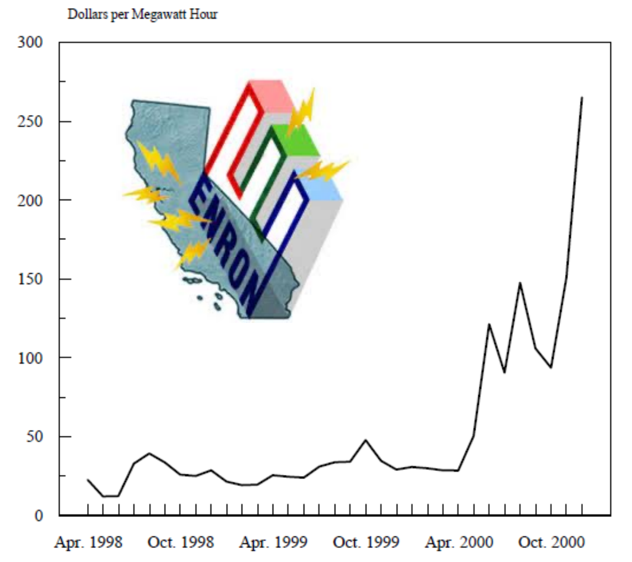
Sec. 731. State authorities.



Source: NYISO

Operational Challenges in Electricity Grids

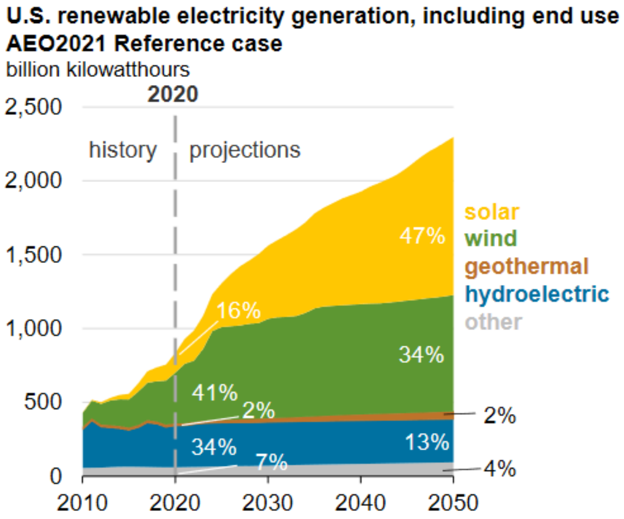
- Undesired price manipulation by market participants
  - California Electricity Crisis – Enron ‘00-’01
  - Today: ~2% hours with non-competitive bids in the CAISO market (2021)



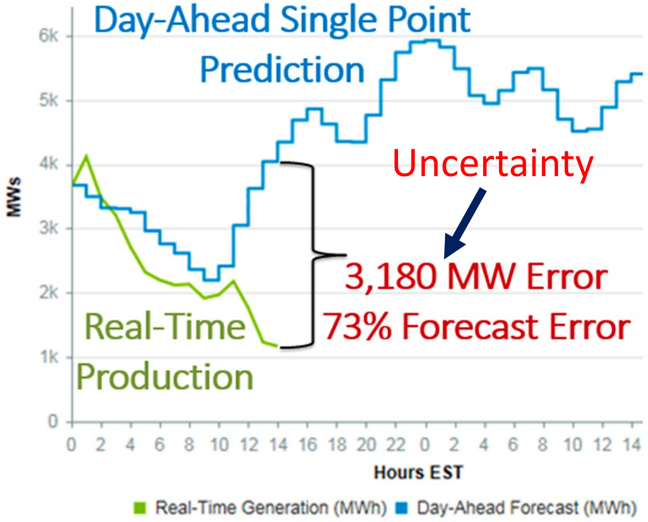
SOURCE: Congressional Budget Office based on data for the northern and southern regions from the California Energy Commission (available at www.energy.ca.gov/electricity/wepr/monthly_day_ahead_prices.html).

- Proliferation of renewable energy sources

Rapid growth in solar and wind energy



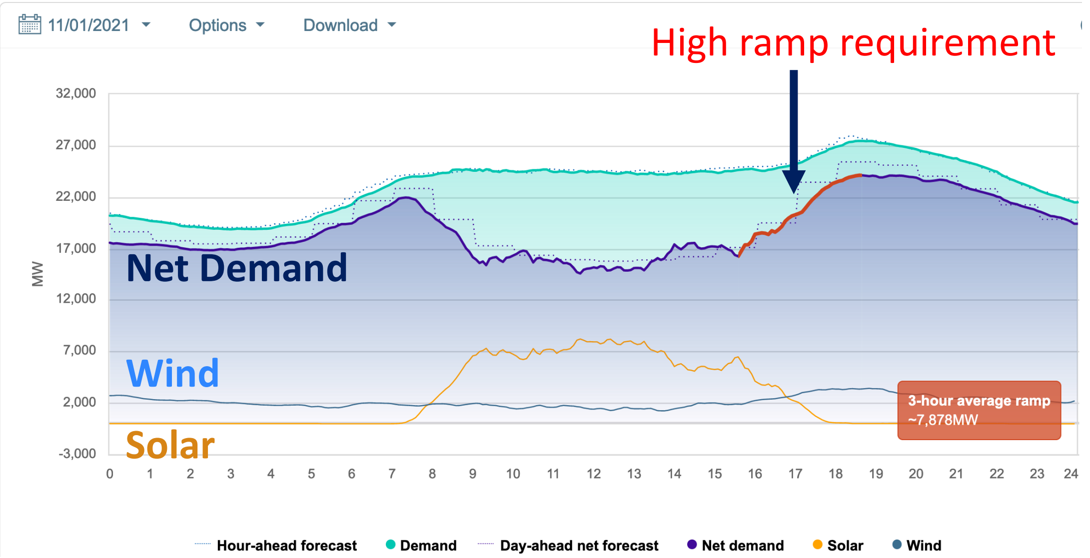
Source: U.S. Energy Information Administration



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

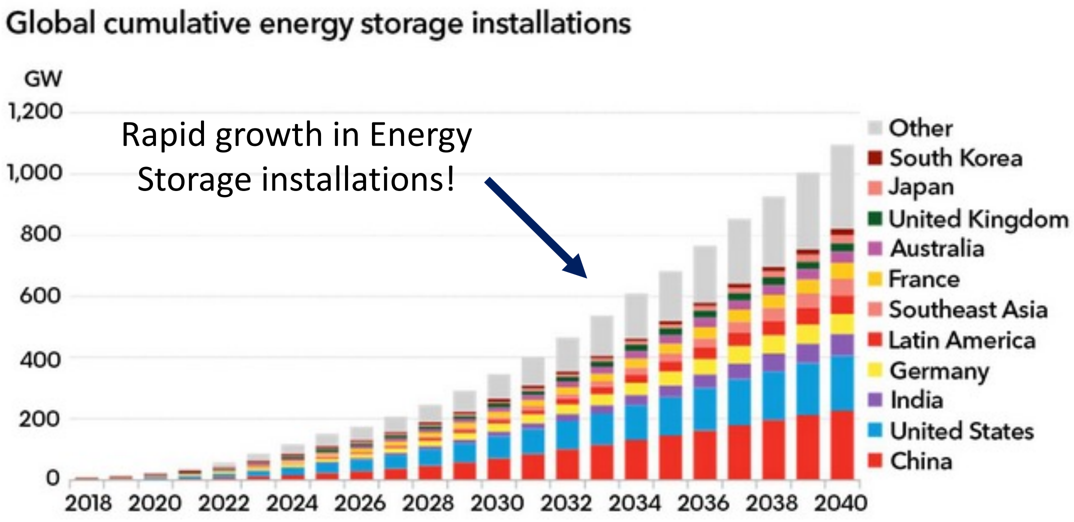
Opportunities

- **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
- Mechanism design for storage participants

The Role of Strategic Participants in Two-Stage Settlement Markets

Pengcheng You, Marcelo A. Fernandez, Dennice F. Gayme, and Enrique Mallada

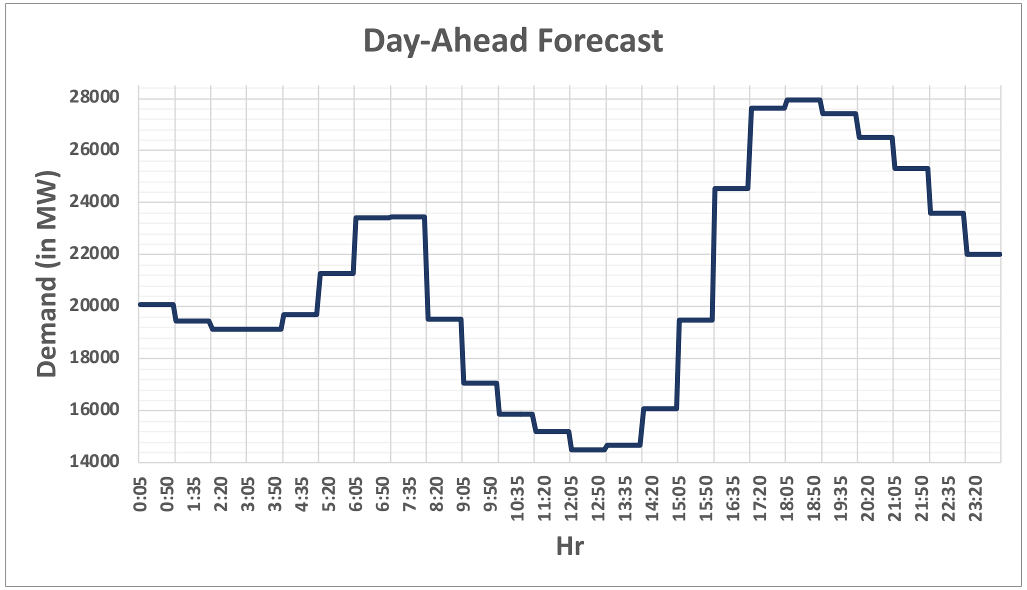
Preprint, August 2022

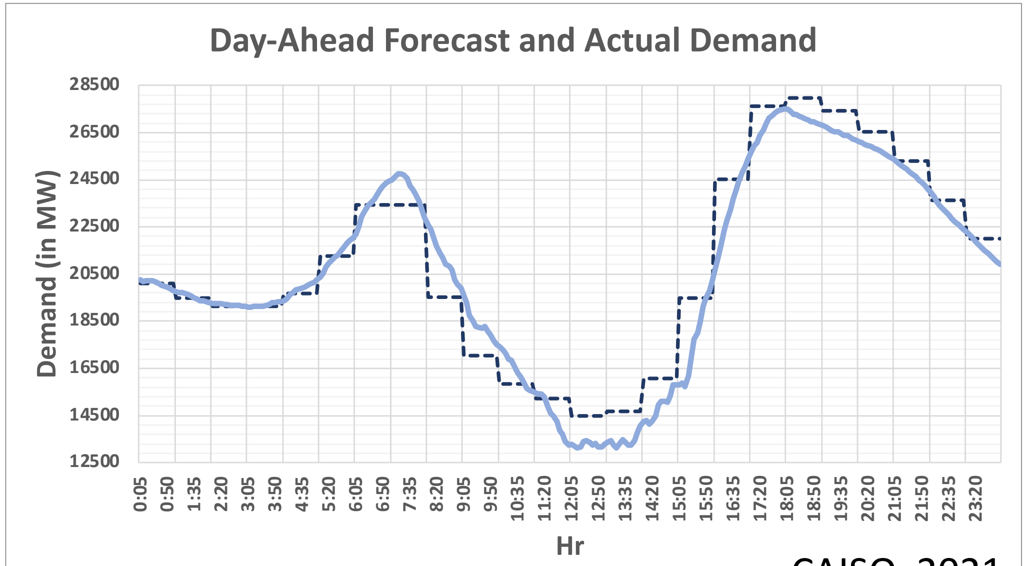
Existing Paradigm - Wholesale Energy Market Design

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**





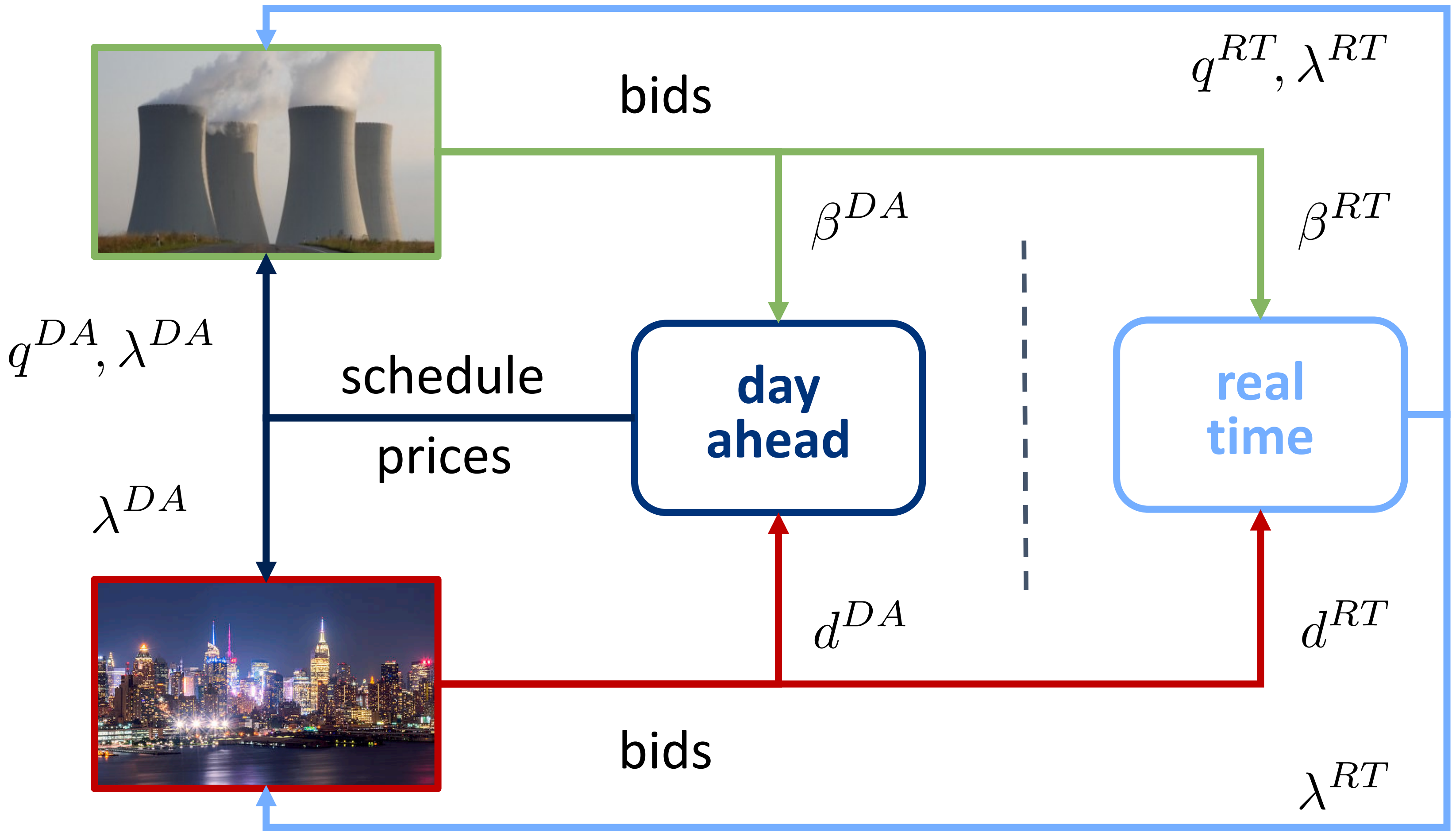
CAISO, 2021

Two-stage Settlement in Electricity Markets

linear supply function

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

[Klemperer, Meyer '89]



total generation

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

total demand

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

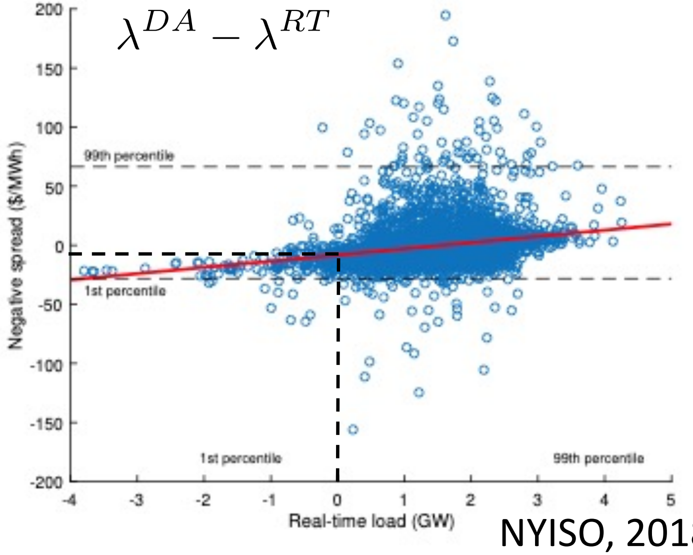
day ahead: forward position

real time: last resort/opportunity

Challenge: Operation Not Fully Understood

Market Power is Major Concern

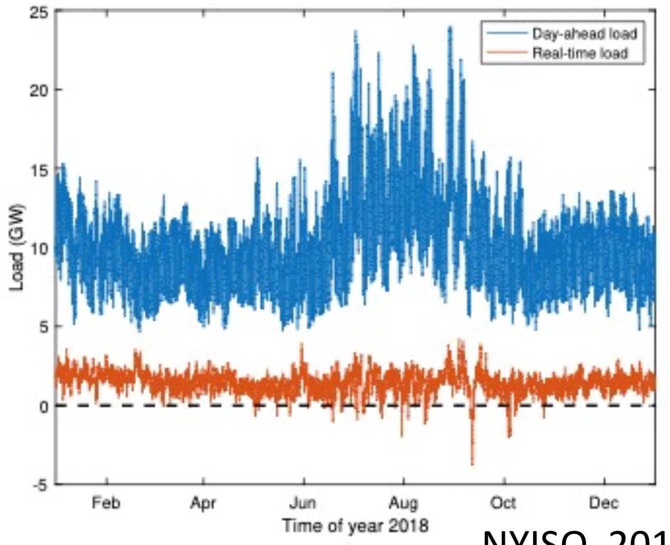
- Competitive Equilibria -> Price Convergence $\lambda^{DA} = \lambda^{RT}$
- Evidence the lack of price convergence
    - MISO [Bowden et al. '09, Birge et al. '18]
    - NYISO [Jha & Wolak '19, You et al. '19]
    - CAISO [Borenstein '08] and more..



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 $j \in \mathcal{G}$**

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

Day-ahead market clearing — **Day-ahead market**

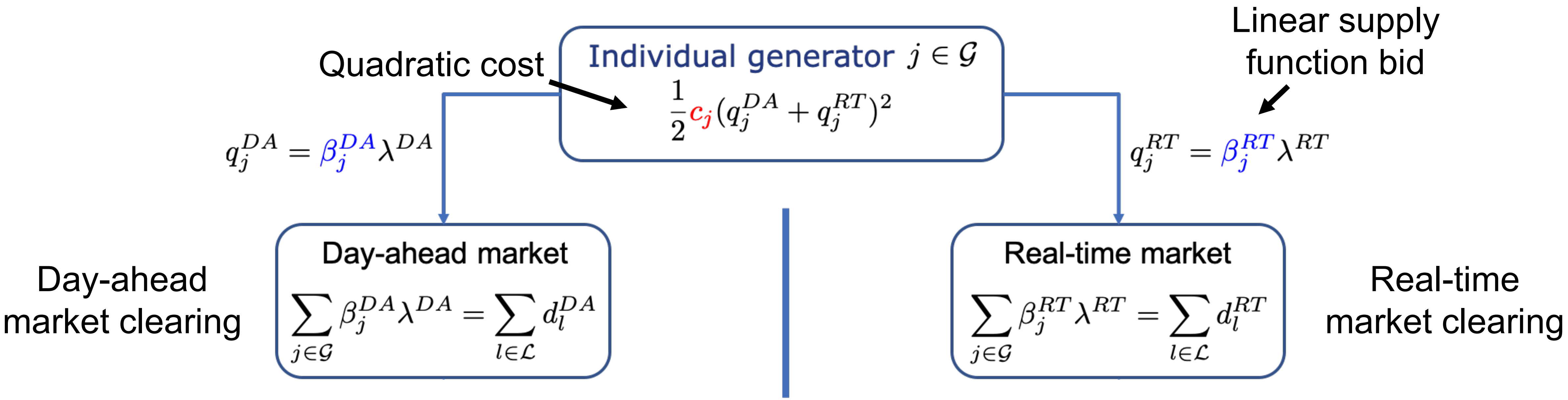
$$\sum_{j\in\mathcal{G}} \beta_j^{DA}\lambda^{DA} = \sum_{l\in\mathcal{L}} d_l^{DA}$$

Real-time market — Real-time market clearing

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

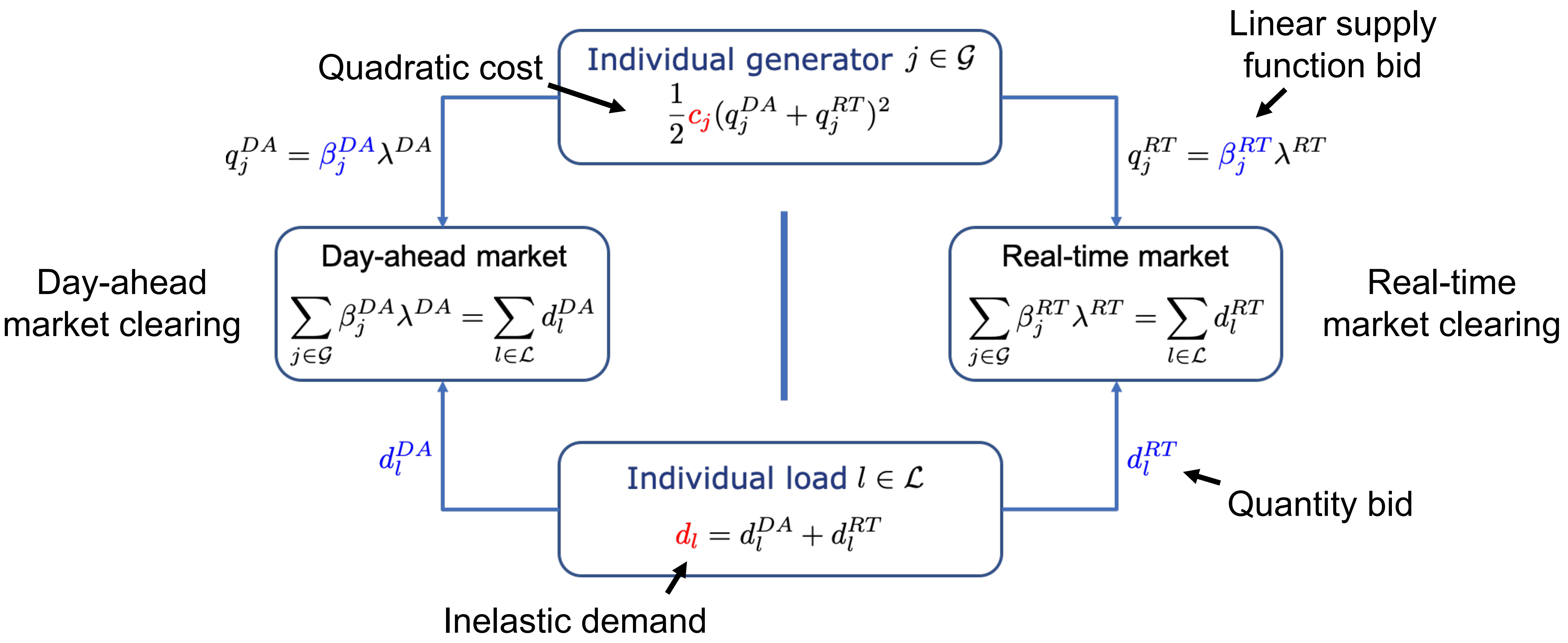
An Extensive-Form Game

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



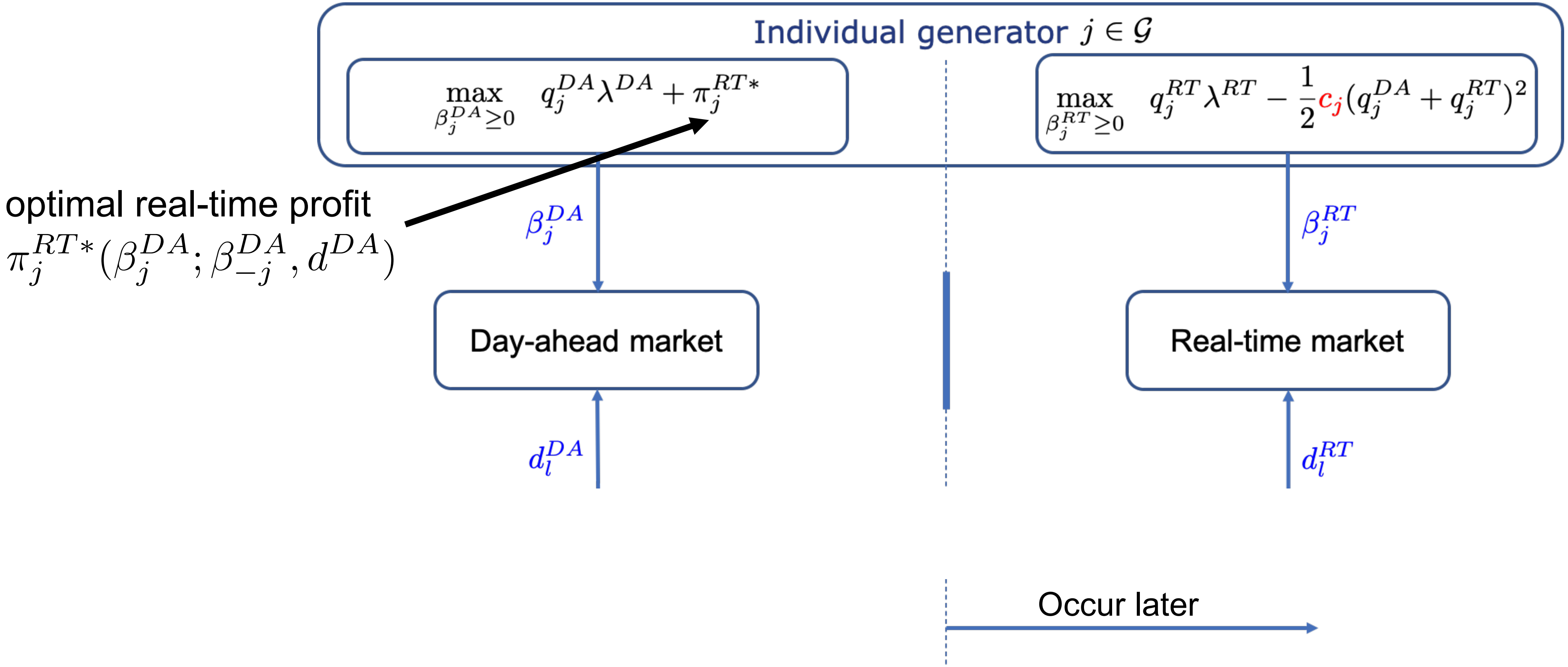
An Extensive-Form Game

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



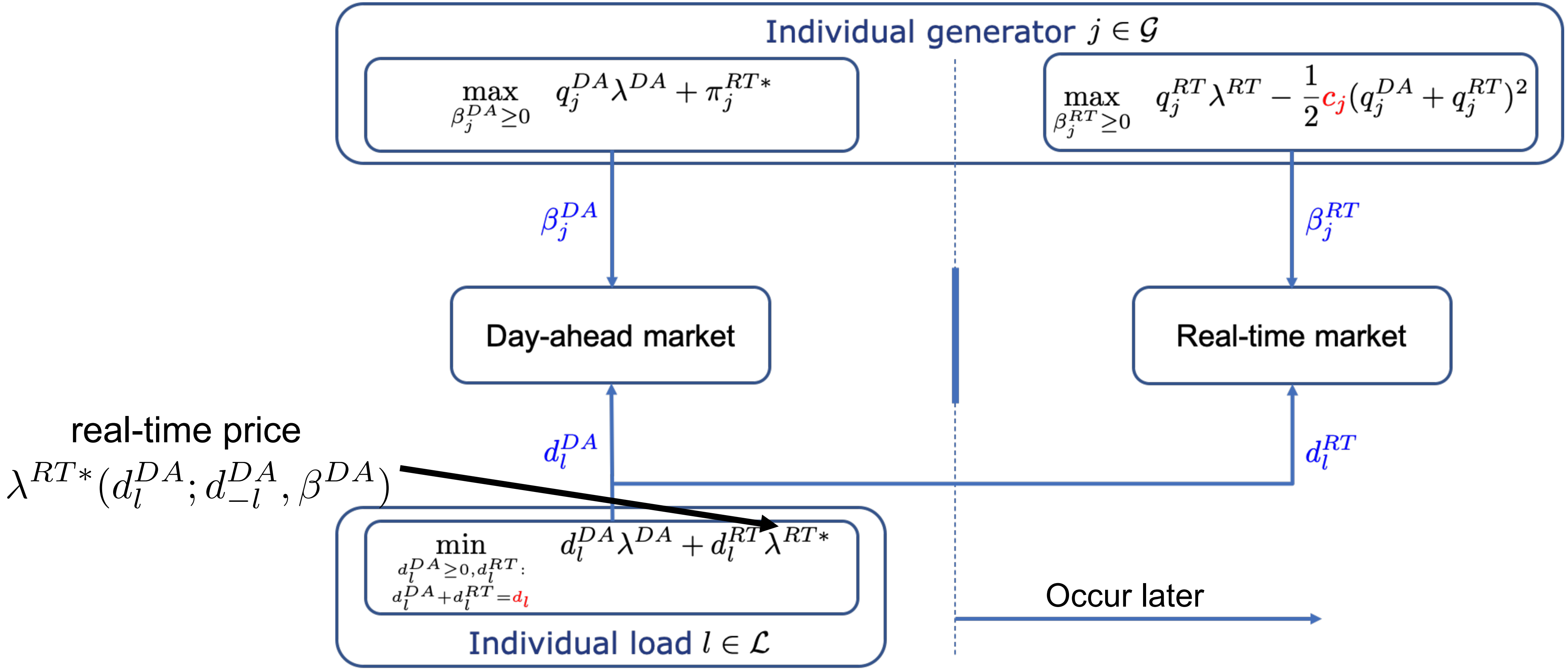
Model: Nested Game

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



Model: Nested Game

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



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

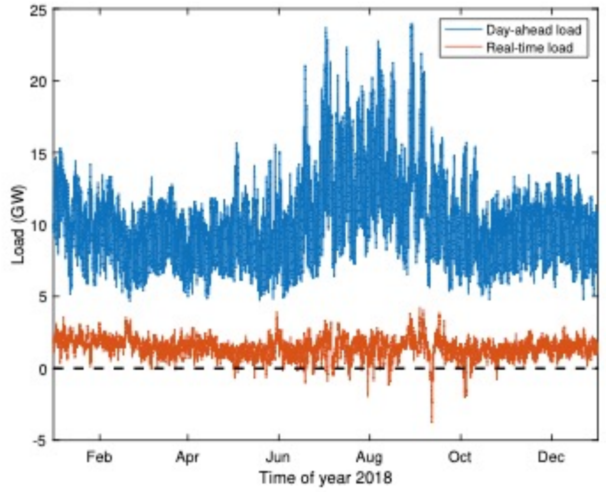
Recall: Homogeneous Generation: $c_j = c$

- **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 equilibrium total generation cost

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

Negative payment of loads

Surplus Allocation

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

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

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 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

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

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;

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

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

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** $\Longleftrightarrow$ $\frac{G}{L} \geq \left(1 + \frac{1}{L}\right)^2$

Surplus Allocation

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

Load payment

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

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

- Mechanism design for storage participants

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A market mechanism for truthful bidding with energy storage☆

Rajni Kant Bansal *, Pengcheng You, Dennice F. Gayme, Enrique Mallada

June 2022

Putting storage in perspective – Related work

?

Market Perspective - minimizing cost of market operation

- Co-optimization of resources including storage in the market [PadManabhan et al. TPS'20]
- Quantify cost of Inter-temporal dispatch (short-term and long-term) [He et al. TPS'21]
- Aggregate energy resources [Qin et al. TSG'19, Elliott et al. TPS'19]

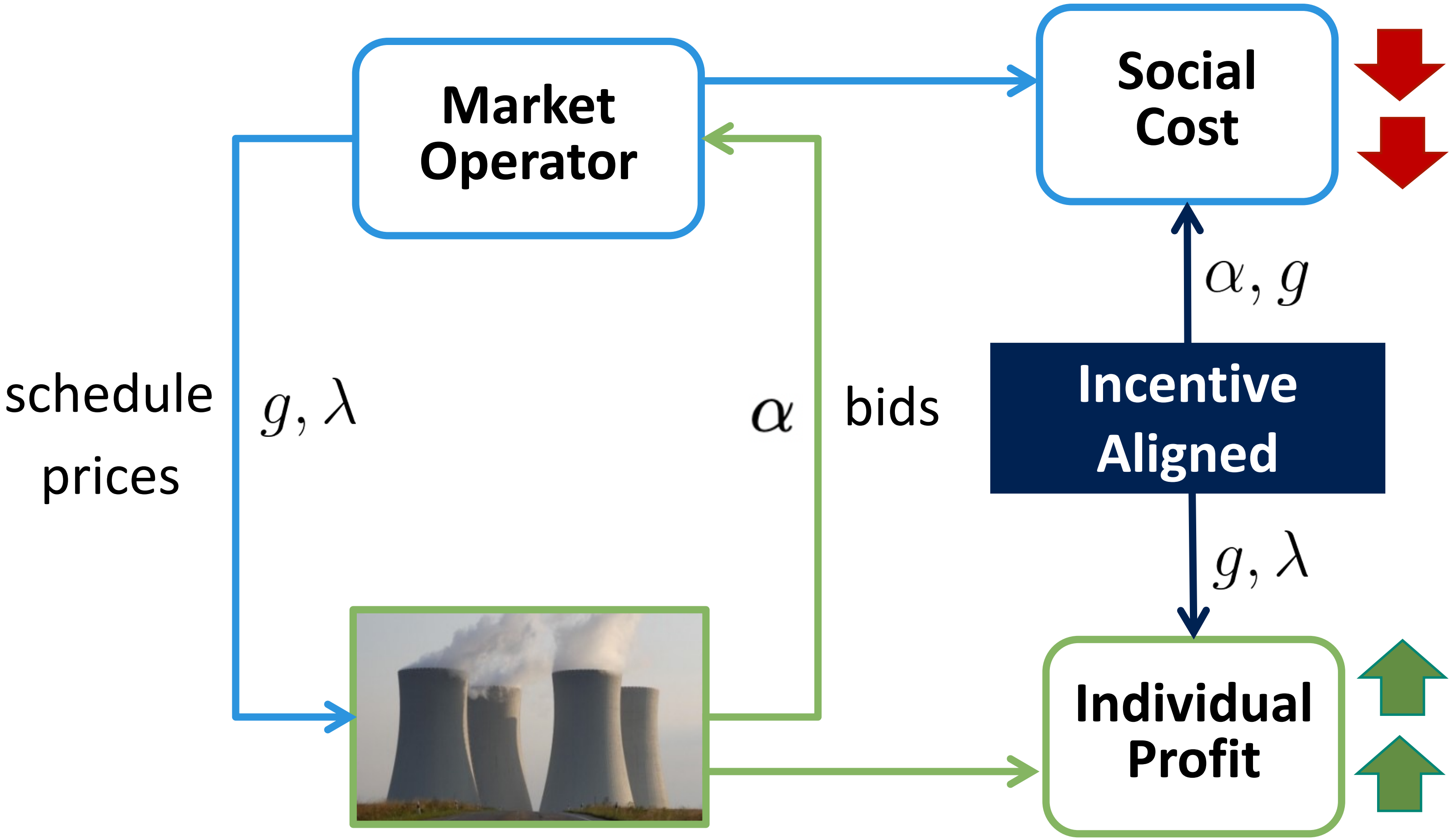
Assumptions :
Storage unwillingly reveal private information
Limit flexibility to seek profit maximization

Individual Perspective - maximizing profit

- Account for cost of operation and co-optimize different markets [He et al. TSG'15, Xu et al. TPS'18, Bhattarai et al. IEEE PES T&D'20, Thatte et al. TSG'13, Shafiee et al. TPS'17]

Assumptions :
Market signals are exogenous

Basic Principles of Market Design



Linear supply function

$$g = \alpha\lambda$$

Economic Dispatch

$$\min_g \frac{1}{2\alpha} g^2$$
$$\text{s.t. } d = g$$

Generator Profit

$$\max_g \lambda g - \frac{c}{2} g^2$$

Power Balance

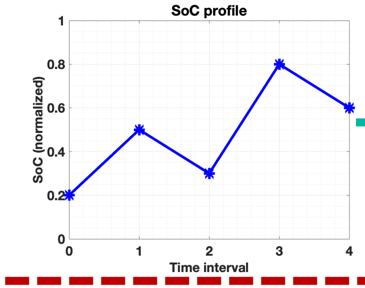
$$d = g$$

Towards a Market Mechanism for Storage

- Cost of dispatching energy storage
- Prosumer based market mechanism
- Cycle aware market mechanism

Storage Cycling Cost

- Consensus on the use cycle-based degradation cost
  - Combine cycle stress function with Rainflow cycle counting



Rainflow Cycle Counting Algorithm

$$\nu = \begin{pmatrix} x_1 - x_2 \\ x_1 - x_2 \\ x_3 - x_0 \\ x_3 - x_4 \end{pmatrix}$$

Cycle stress model $\Phi(\delta)$

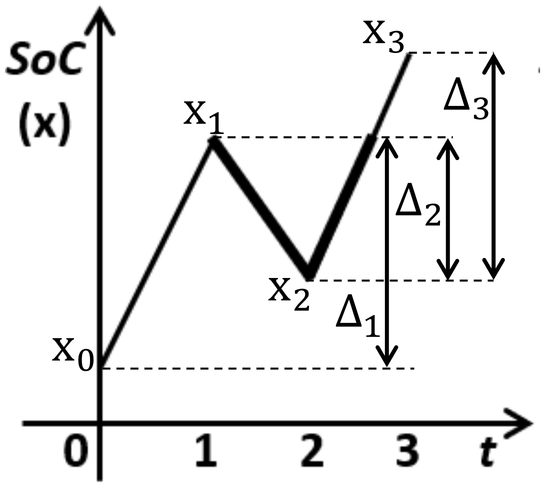
$$C_s(x) = 2\Phi(x_1 - x_2)BE + \Phi(x_3 - x_0)BE + \Phi(x_3 - x_4)BE$$

Cost of replacement of storage

$\Phi(\cdot)$ convex map that quantify the normalized capacity, degradation incurred by each half-cycle δ_i [Shi et al. TAC'19]

Storage Cost Model – Rainflow Algorithm

- To extract half-cycle depths v we use a cycle identification approach based on the $Rainflow$ algorithm [Lee et al. Metal Fatigue Anslysis Handbook '11]



Three consecutive switching points difference:

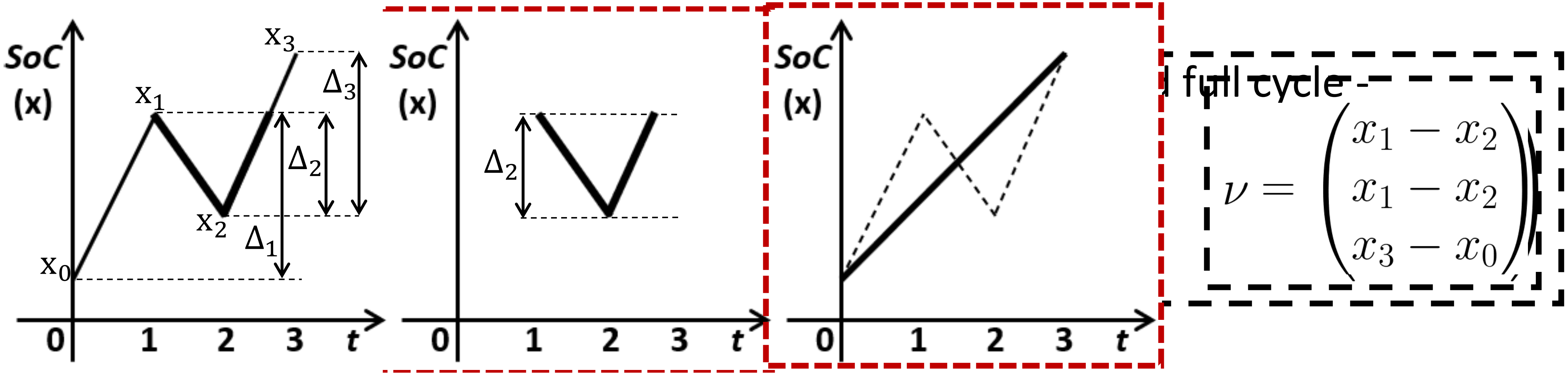
$$\Delta_1 = x_1 - x_0$$
$$\Delta_2 = x_1 - x_2$$
$$\Delta_3 = x_3 - x_2$$

Full cycle if:

$$\Delta_1 \geq \Delta_2 \leq \Delta_3$$

Storage Cost Model – Rainflow Algorithm

- To extract half-cycle depths ν we use a cycle identification approach based on the $Rainflow$ algorithm [Lee et al. Metal Fatigue Anslysis Handbook '11]

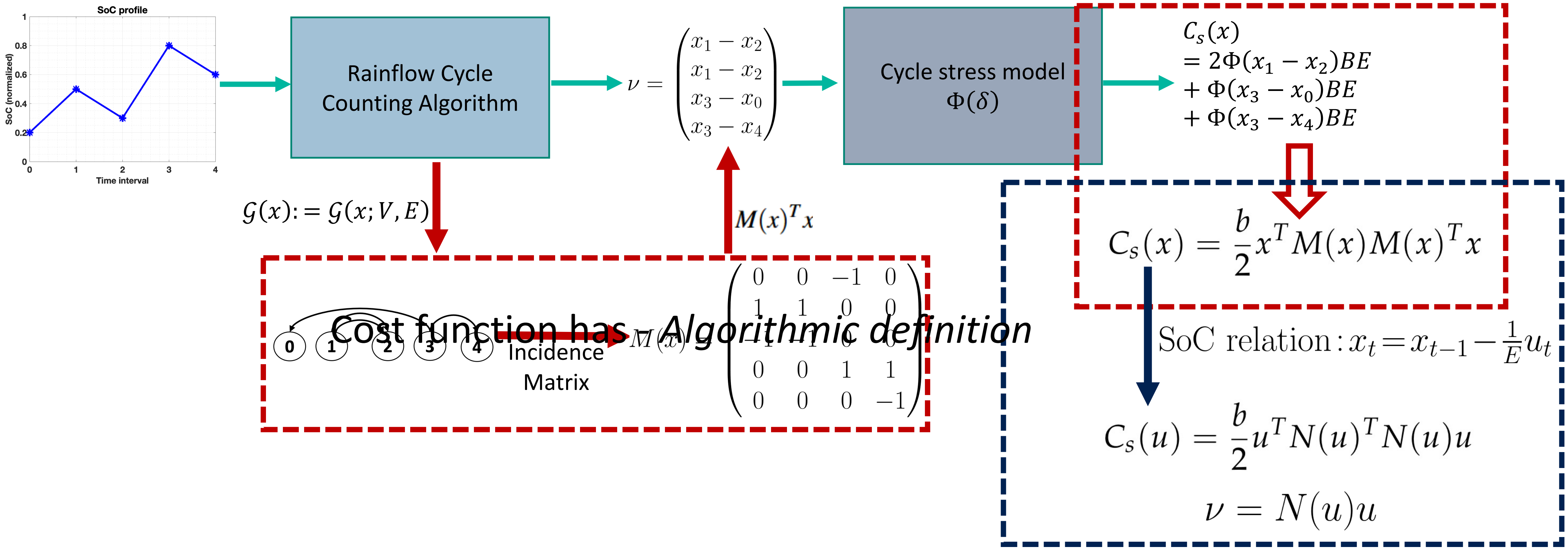


The associated cycling cost:

$$C_s(x) = 2\Phi(x_1 - x_2)BE + \Phi(x_3 - x_0)BE$$

Storage Cycling Cost – Reformulation

- Consensus on the use cycle-based degradation cost
  - Combine cycle stress function with Rainflow cycle counting



Towards a Market Mechanism for Storage

- Cost of dispatching energy storage
- Prosumer based market mechanism
- Cycle aware market mechanism

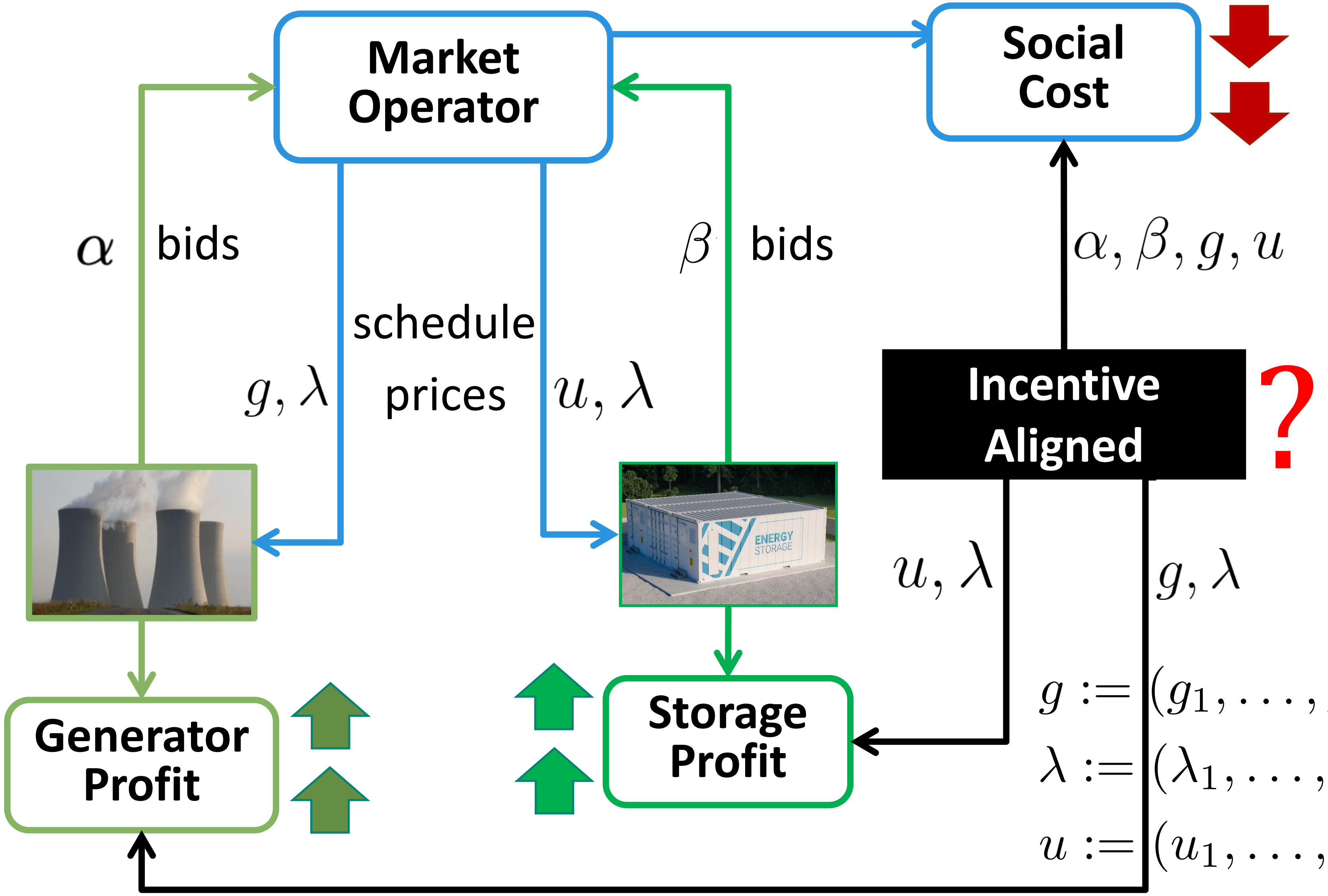
Prosumer-based Market Model

Generalized linear supply function

$$u = \beta\lambda$$

Linear supply function

$$g = \alpha\lambda$$



$$g := (g_1, \ldots, g_H)$$
$$\lambda := (\lambda_1, \ldots, \lambda_H)$$
$$u := (u_1, \ldots, u_H)$$

Power Balance

$$d = g + u$$

Market Model Review

Market Model	Existing	Prosumer Based

Market Interpretation of cost is different

Theorem: The competitive equilibrium is incentive aligned iff $\exists$ convex coefficients $\gamma_k \geq 0, \sum_{k=1}^{m} \gamma_k = 1$ such that for demand d

$$\sum_{k=1}^{m} \gamma_k N_k(d)^T N_k(d) d = \frac{\|N(d)d\|^2}{\|d\|^2} d$$

Towards a Market Mechanism for Storage

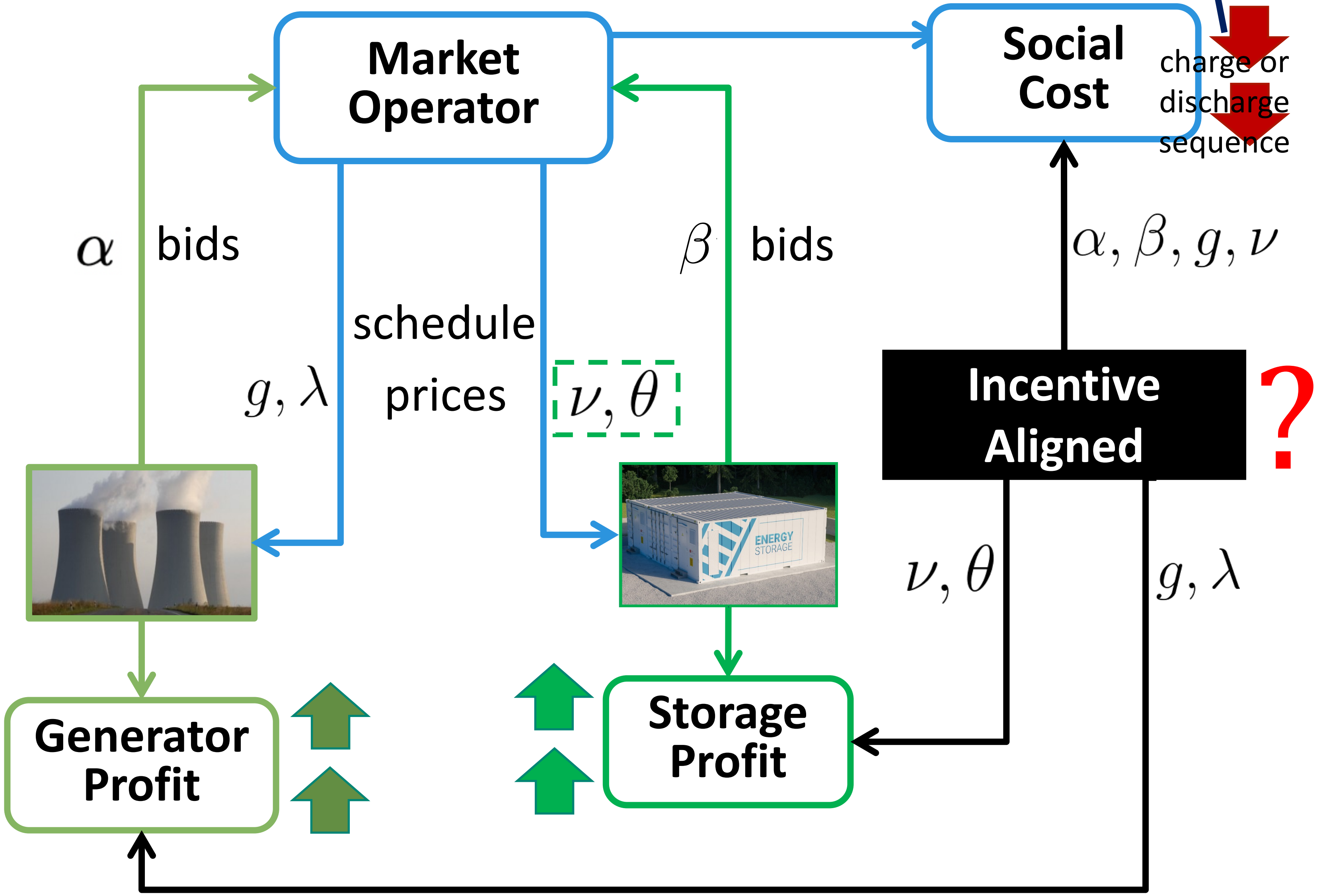
- Cost of dispatching energy storage
- Prosumer based market mechanism
- Cycle aware market mechanism

Time horizon: ***H*** time slots

Cycle Aware Market Model

Generalized supply function / Energy-Cycling function

$u = \beta\lambda$ / $\nu = \beta\theta$



Linear supply function

$$g = \alpha\lambda$$

Energy-Cycling function

$$\nu = \beta\theta$$

cycle-depth vector

$/MWh of Cycle depth

$$\max_{\nu} \theta^T \nu - \frac{b}{2}\|\nu\|^2$$

Power Balance

$$d = g + u$$

Market Model Review

$$\nu = N(u)u$$

Market Model	Existing	Prosumer Based		Cycle Aware
Participants	Generator	Generator	Storage	
Bid Function	$g = \alpha\lambda$	$g = \alpha\lambda$	$u = \beta\lambda$	
Cost to Operator	$\frac{1}{2\alpha}\|g\|^2$	$\frac{1}{2\alpha}\|g\|^2$	$\frac{1}{2\beta}\|u\|^2$	
Actual Cost	$\frac{c}{2}\|g\|^2$	$\frac{c}{2}\|g\|^2$	$\frac{b}{2}\|N(u)u\|^2$	
Optimal Bid	$\alpha^* = \frac{1}{c}$	$\alpha^* = \frac{1}{c}$	$\beta^* = \frac{1}{b}\frac{\|\lambda\|^2}{\|N(\lambda)\lambda\|^2}$	

Numerical Results Metric – Storage Profit

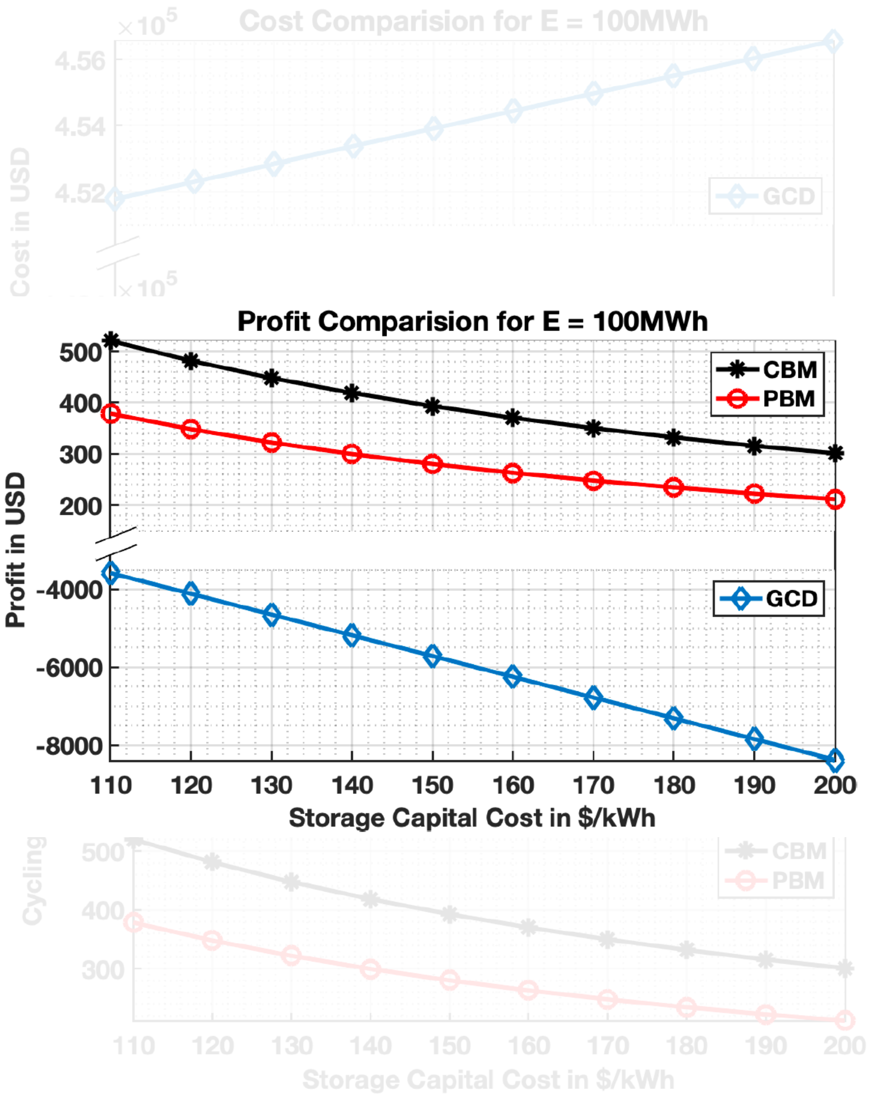
Mechanisms

- *Cycle based* **(CBM) :**
  Generator: power
  Storage : cycle depth

- *Prosumer based* **(PBM)**
  Generator: power
  Storage: power

Current Market

- *Generation Centric Dispatch* ***(GCD)*:**
  Social cost =
  Generation cost
  + *(hidden)* cycling cost



w.r.t Storage Capital Cost

Talk Summary

- The Role of Strategic Load Participants in Two Stage Markets
  - Model and studied the role of strategic load participants in two-stage markets
  - Characterize competitive and Nash equilibria
    - Perfect competition does not lead to all load in day ahead
    - Load strategic behaviour matters! It can even beat generators.
    - Virtual bidders benefit from, and limits only, demand market power

- Market Mechanism for Energy Storage
  - Storage operational cost (cycles) is different from generation cost (power)
    - Bidding mechanisms designed for generators do not apply to storage.
  - Proposed cycle-based market mechanism (bids, prices, clearing)
  - Equilibrium analysis (price takers)
    - Competitive Equilibrium = Social Planner's Optimal

Thanks!

Papers

- **P. You**, M. Fernandez, D. Gayme, E. M., "The Role of Strategic Participants in Two-Stage Settlement Markets," ***Preprint,*** 2022
- **R. K. Bansal**, P. You, D. F. Gayme, and E. Mallada, "A Market Mechanism for Truthful Bidding with Energy Storage," EPSR, Jun 2022.

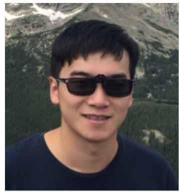
Other Related Work

- **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.

Rajni Bansal

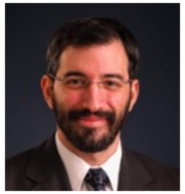
Johns Hopkins University

Enrique Mallada
mallada@jhu.edu
http://mallada.ece.jhu.edu



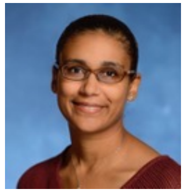
Pengcheng You

北京大学 Peking University



Marcelo Fernandez

Johns Hopkins University



Dennice Gayme

Johns Hopkins University