Incentive Analysis and Coordination Design for Multi-Timescale Electricity Markets

Enrique Mallada

JOHNS HOPKINS UNIVERSITY

University of Southern California
Epstein Institute Seminar Series

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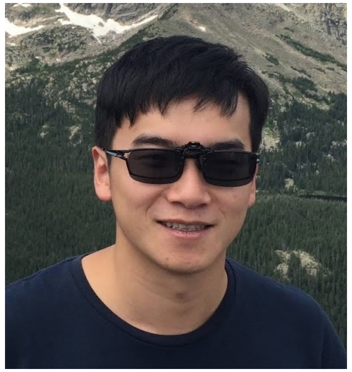
Acknowledgements


Pengcheng You


Marcelo Fernandez


Dennice Gayme


Desmond Cai


Adam Wierman

JOHNS HOPKINS UNIVERSITY

A*STAR Institute of High Performance Computing

Caltech

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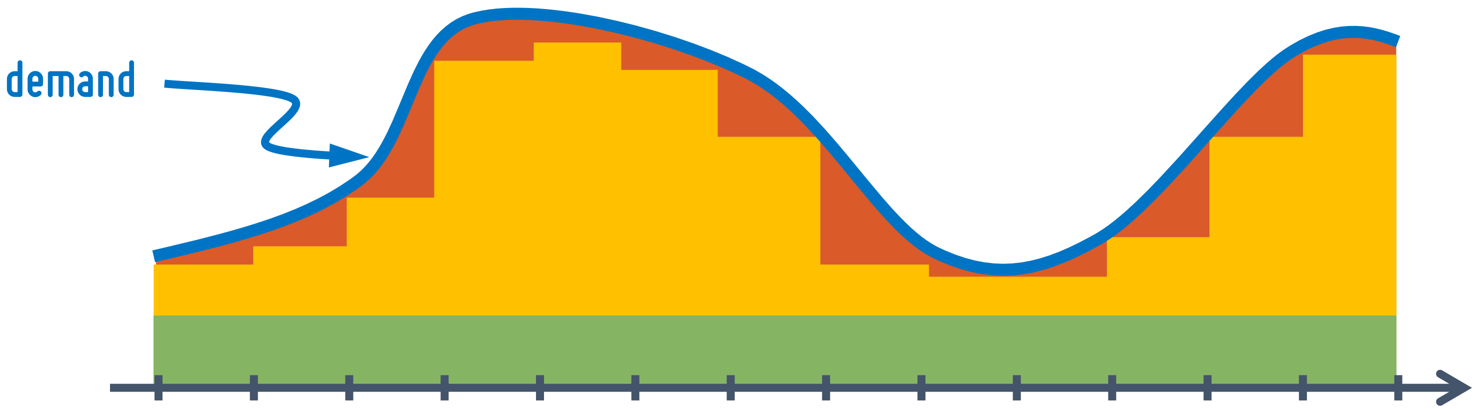
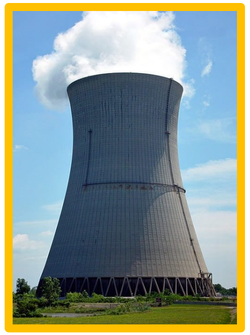
Supply-demand Balance: A Multi-timescale Undertaking



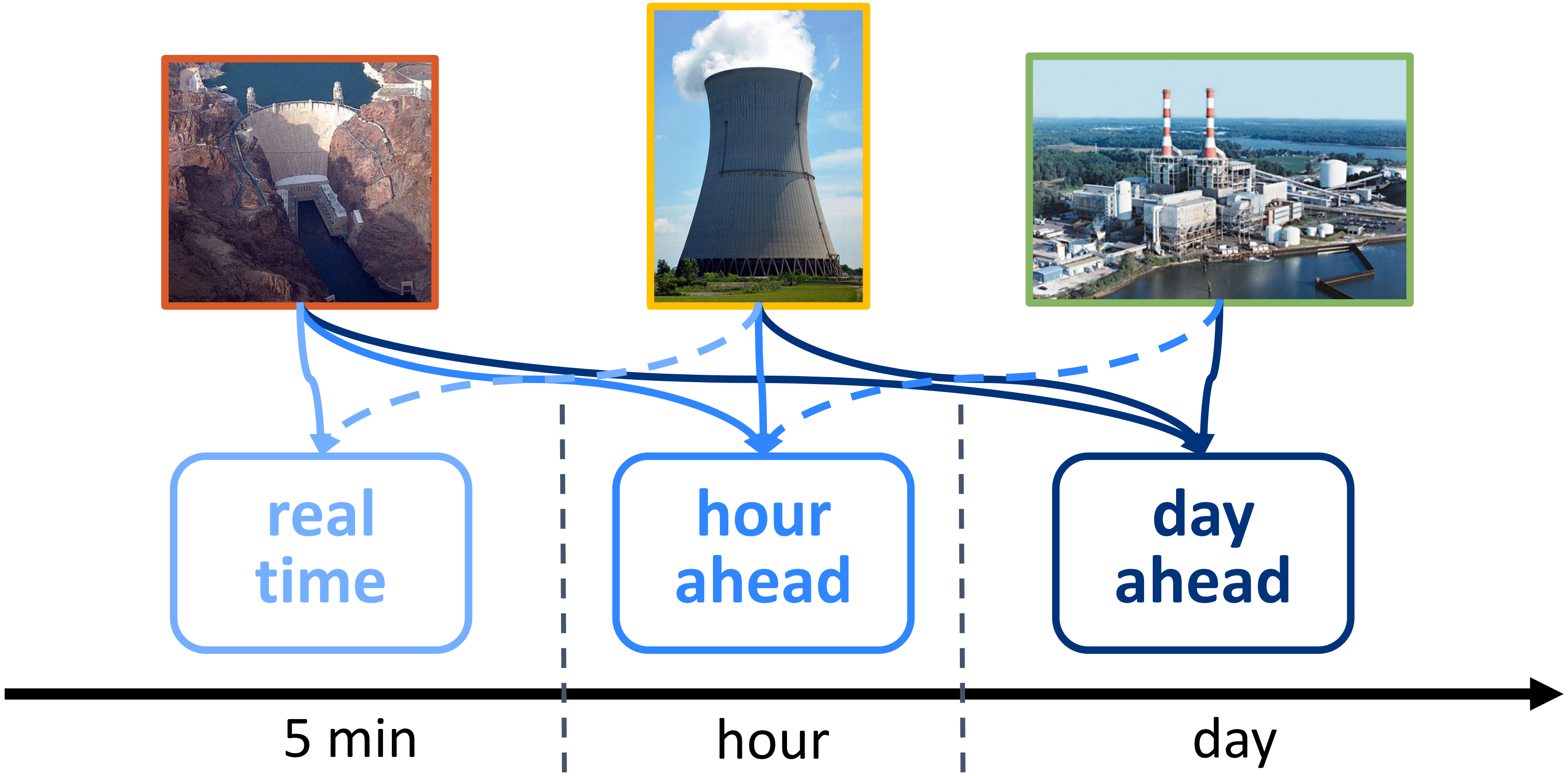


100 MW/min 10 MW/min 1 Mw/min

ramp rates

Goal: supply-demand balance while seeking efficiency and security

Existing Architecture: 'Siloed' Markets



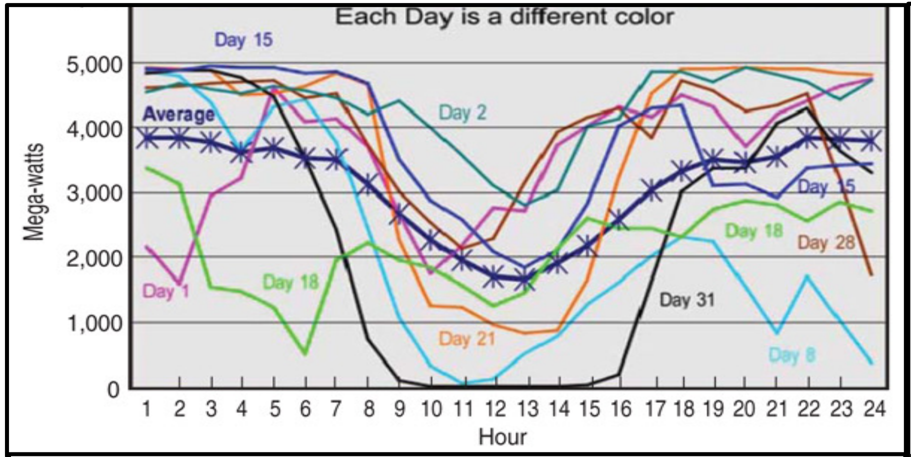
Limitations:

- Faster resources forced to schedule energy very early (unnecessary errors)
- Market are agnostic to faster timescale markets (inefficient)
- Energy allocation decreases as timescale decreases (reduced flexibility)
- Need for robust mechanisms (N-1) to enforce security (inefficient)

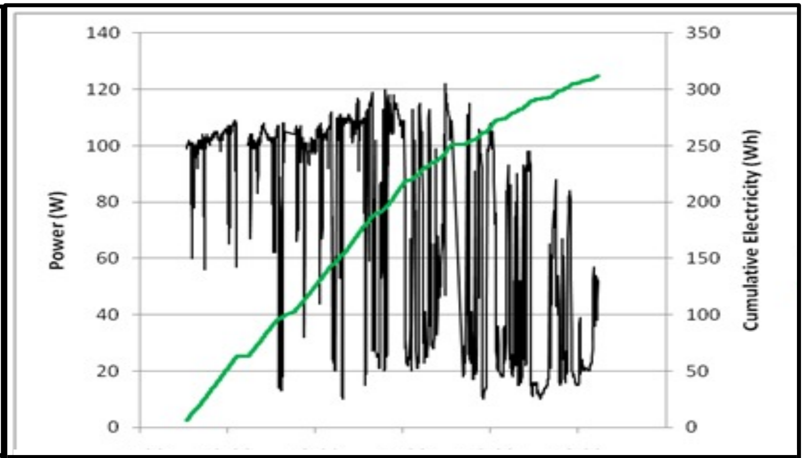
What’s coming

1000 MW/min 100 MW/min 10 MW/min 1 Mw/min
ramp rates

Challenges: Volatility + Uncertainty



Daily **wind** generation [Tehachapi, CA]



5-hour **solar** generation [Columbia Univ.]

What we should prevent

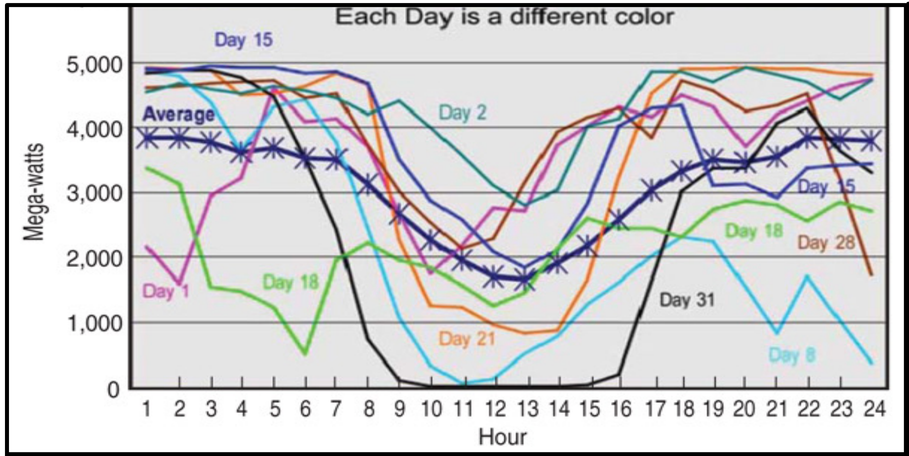
↓ flexibility

↑ conservative

↓ optimal

sub min (DSO)	real time	hour ahead	day ahead
min	5 min	hour	day

Challenges: Volatility + Uncertainty



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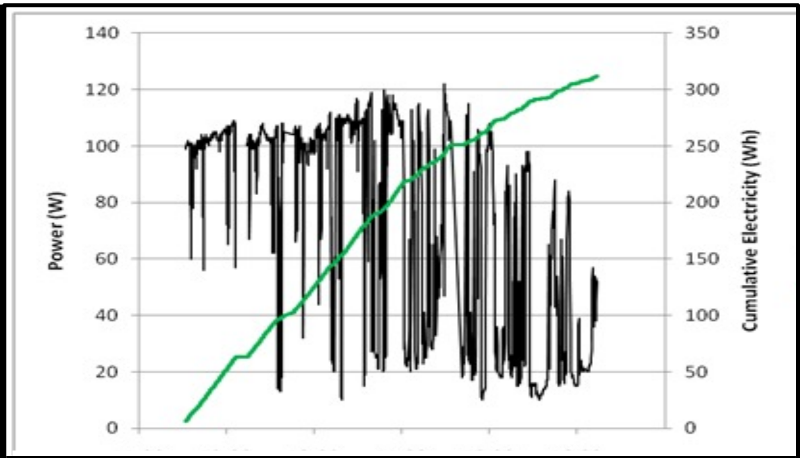
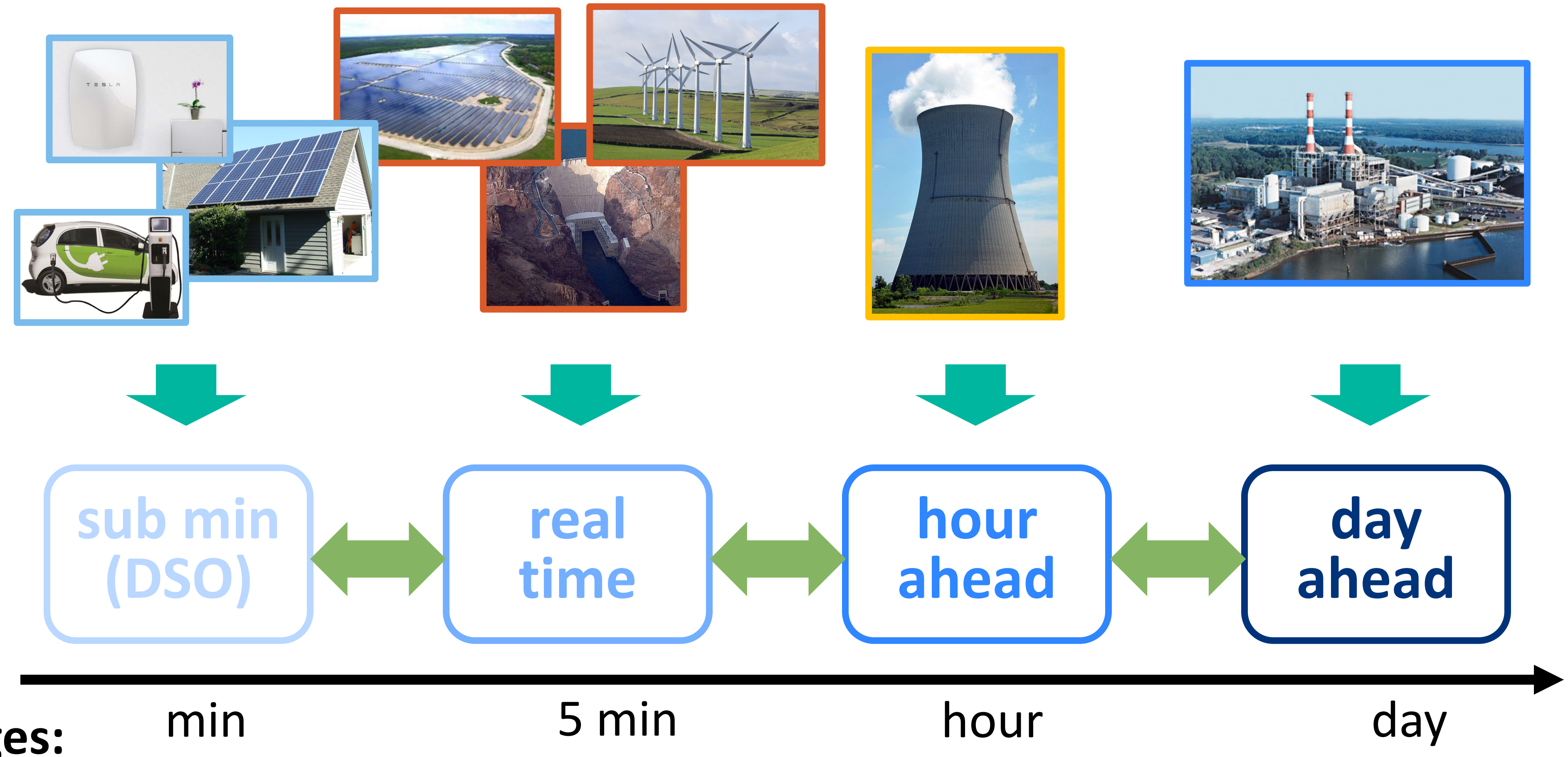


5-hour **solar** generation [Columbia Univ.]

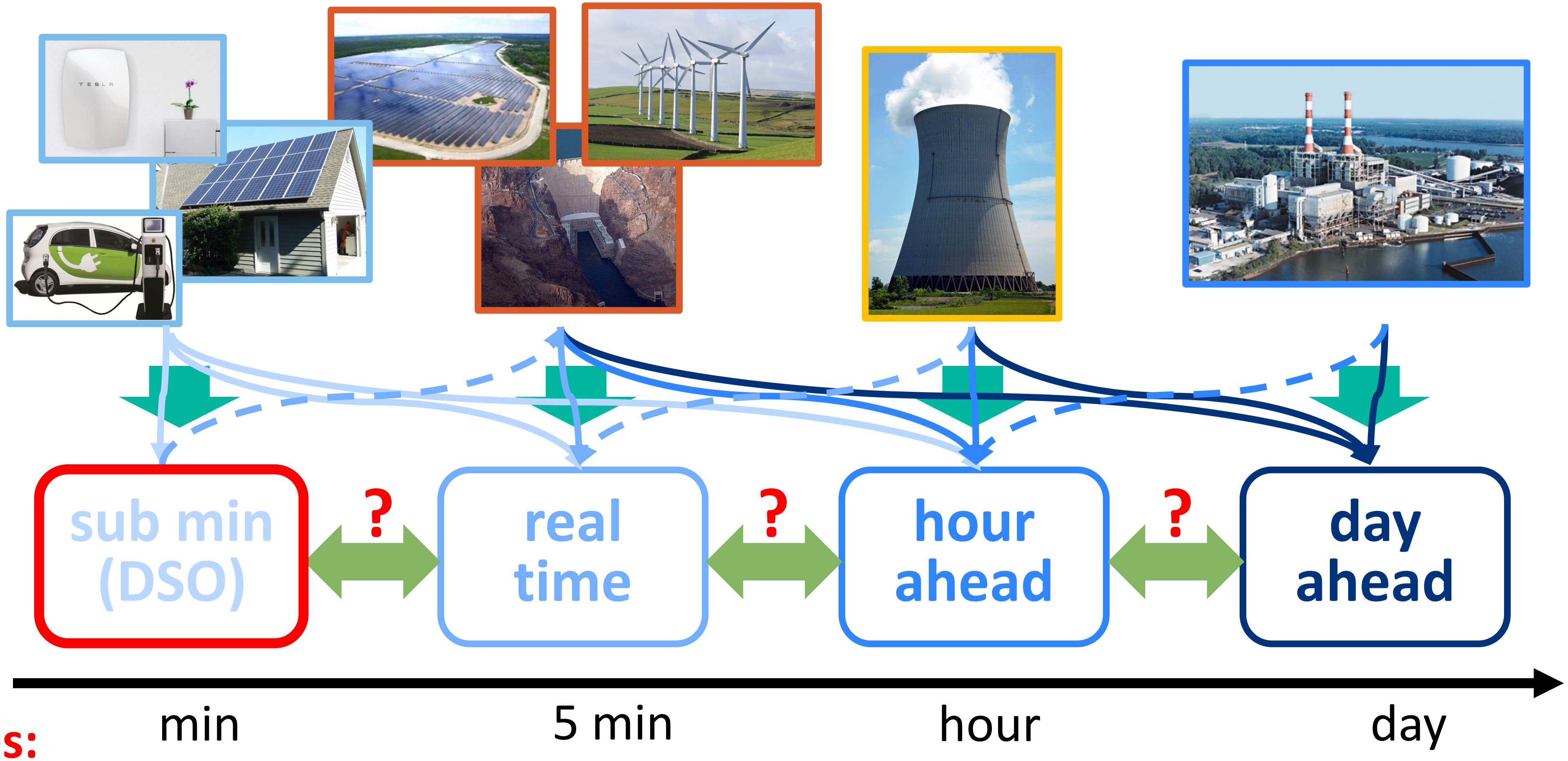
Multi-timescale Market Co-optimization (Ideal World)



Advantages:

- Flexibility: Increase allocation at faster timescales allows to handle more drastic demand variations
- Efficiency: Remove the need of several N-1 constraints. (e.g., congestion)
- Reliability: Prevent cascading failures by fast re-dispatch

Multi-timescale Market Co-optimization (Real World)



Challenges:

- Resources have (coupled) incentives to participate in multiple markets
- It is not (always) clear how markets should coordinate their clearing mechanisms
- Faster timescales can interfere with grid stability!

The Role of Strategic Participants in Two-Stage Settlement Markets

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

Preprint, April 2021

Distributed optimization decomposition for joint economic dispatch and frequency regulation

Desmond Cai[*], Enrique Mallada[†] and Adam Wierman[††]

IEEE Transactions on Power Systems, November 2017

Towards Multi-timescale Market Design

- Coupled Incentives in Two-stage Markets

- Co-optimizing Economic Dispatch and Freq. Regulation

Two-stage/Sequential Markets

Designed to incentivize transactions in the presence of uncertainty

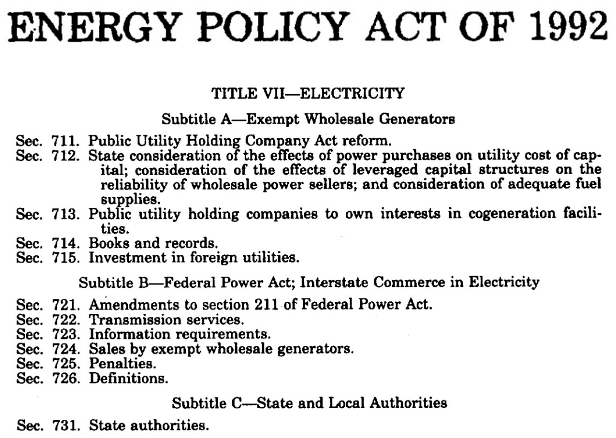
- **Forward Market:** Future contracts
- **Spot Market:** Immediate commitments

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

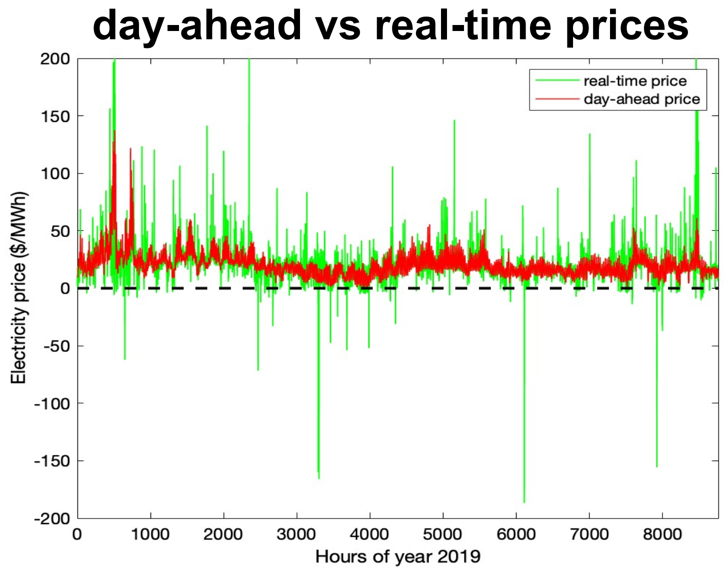
Sec. 711. Public Utility Holding Company Act reform.
Sec. 712. State consideration of the effects of power purchases on utility cost of capital; consideration of the effects of leveraged capital structures on the reliability of wholesale power sellers; and consideration of adequate fuel supplies.
Sec.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



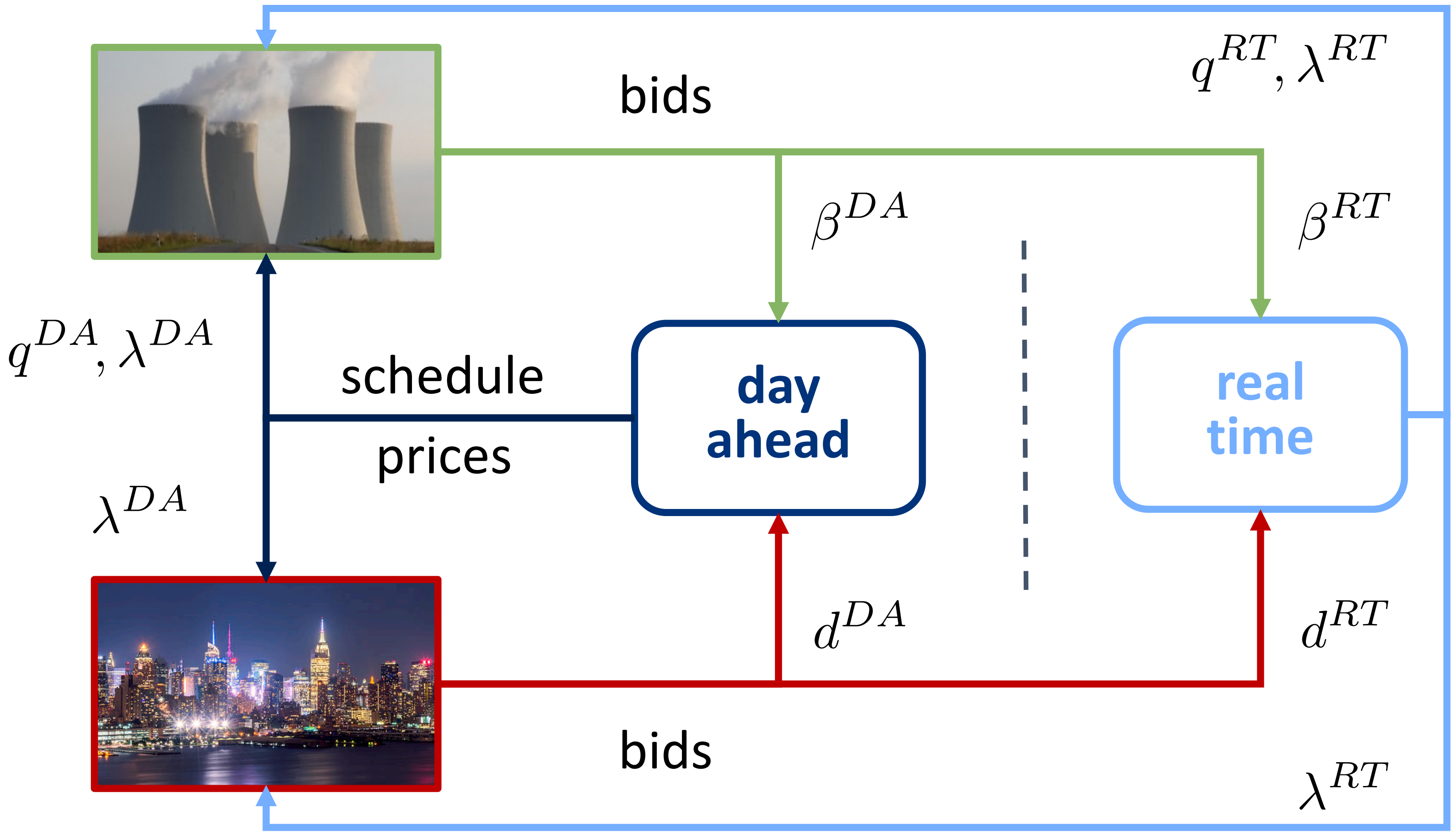
Source: NYISO

Two-stage Settlement in Electricity Markets

linear supply function

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

[Klemperer, Meyer '89]



total generation

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

total demand

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

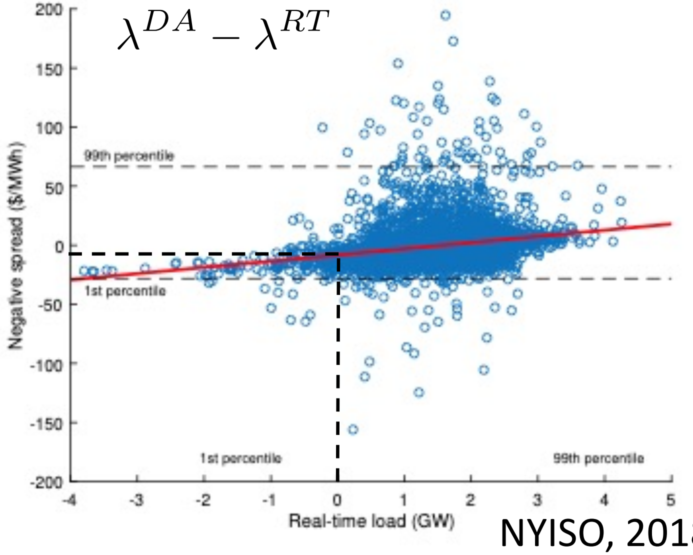
day ahead: forward position

real time: last resort/opportunity

Challenge: Operation Not Fully Understood

Market Power is Major Concern

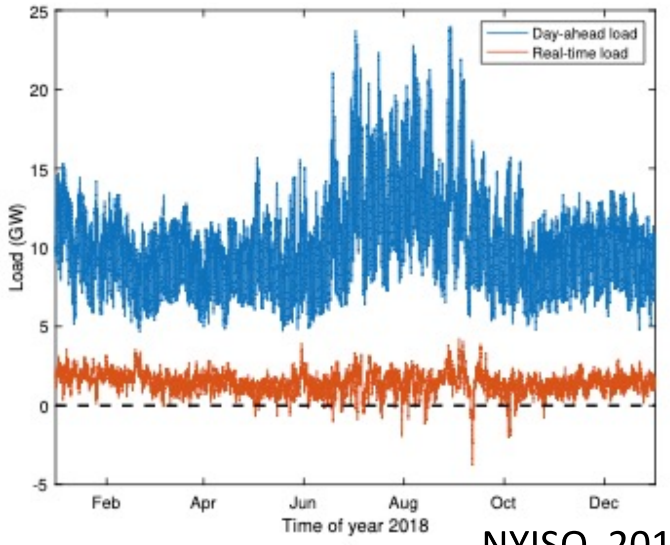
- Competitive Equilibria -> Price Convergence $\lambda^{DA} = \lambda^{RT}$
- Evidence the lack of price convergence
  - MISO [Bowden et al. '09, Birge et al. '18]
  - NYISO [Jha & Wolak '19, You et al. '19]
  - CAISO [Borenstein '08] and more..



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

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

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 $j \in \mathcal{G}$

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

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

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

Real-time market clearing

An Extensive-Form Game

- Between G ***homogeneous*** generators and L ***heterogeneous*** inelastic loads
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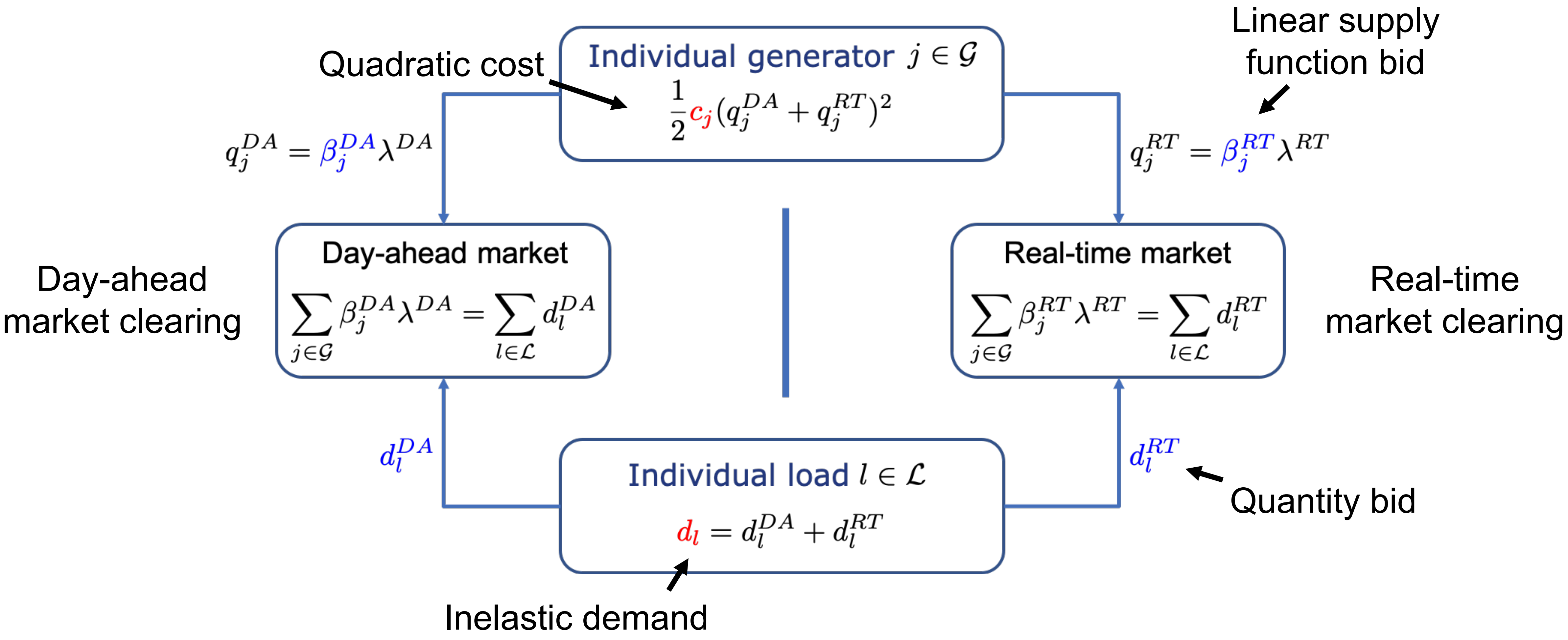
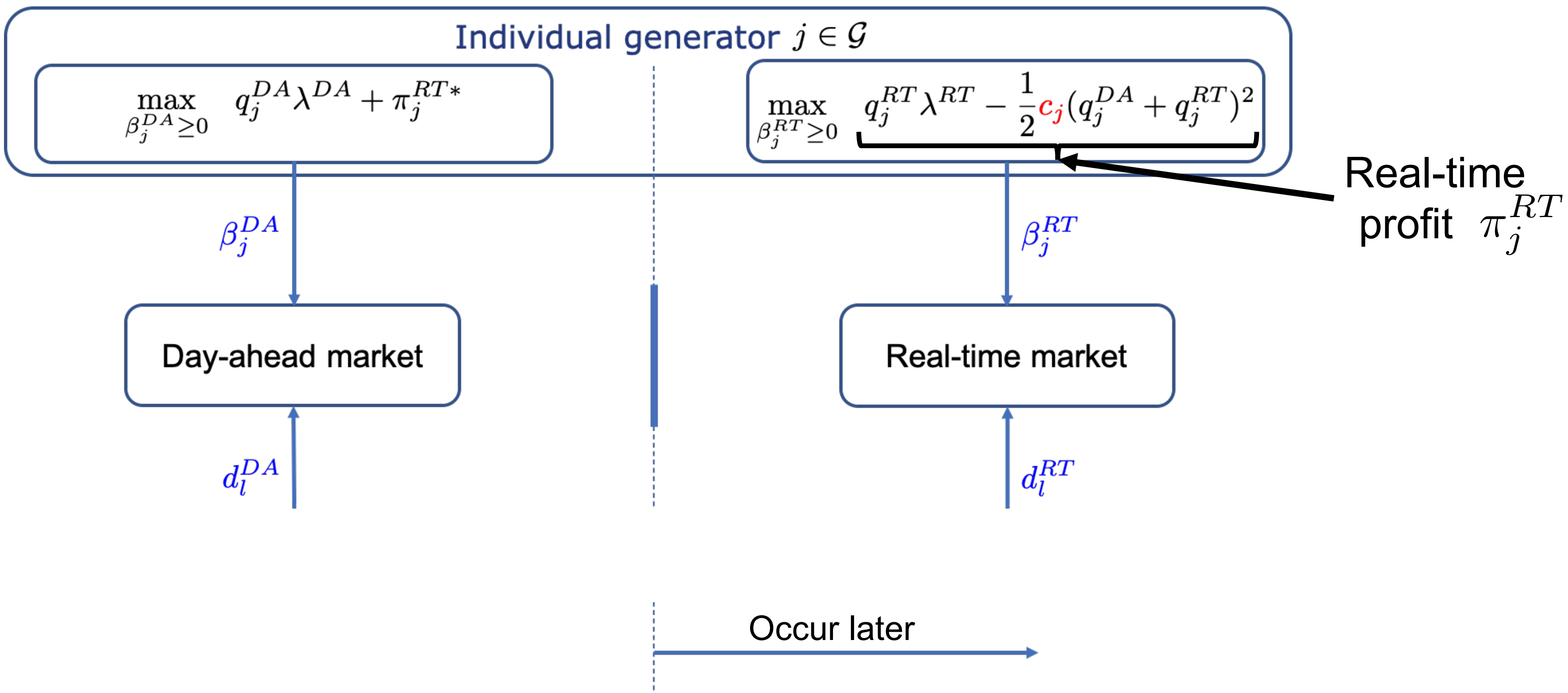


Model: Nested Game

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



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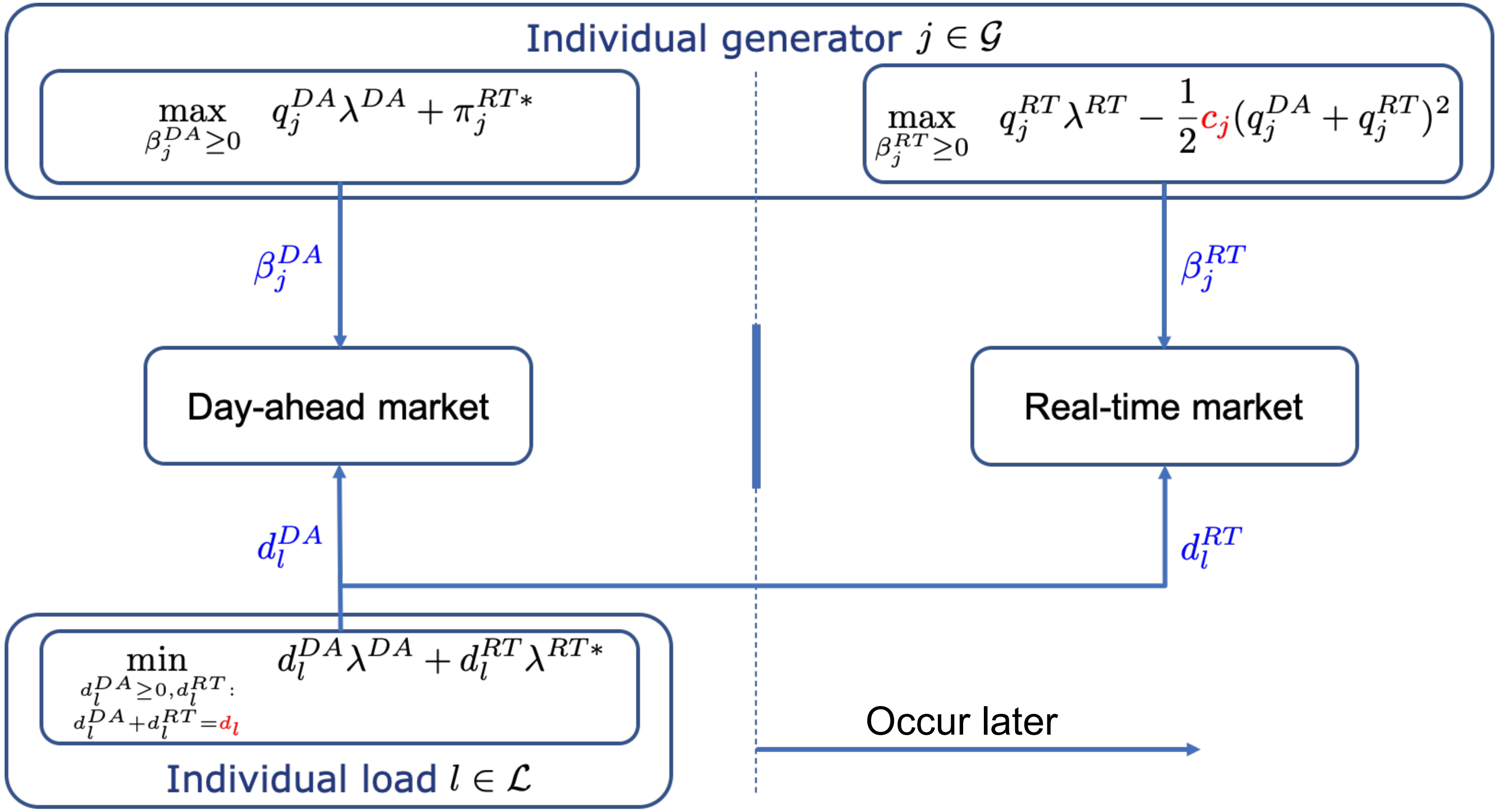

Market Participant Types

- **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: $\beta_j^{DA*} = \beta^{DA*}, \ \beta_j^{RT*} = \beta^{RT*}, \ \forall j \in \mathcal{G}$
    - Supply matches demand in both stages.

- **Approach**
  - build intuition by looking at cases where, **neither, either or both,** gen and load, are strategic.

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 with **strategic loads only**
  - Same as competitive equilibrium

- Nash equilibrium with **strategic generators only**
  - Equal two-stage prices higher than marginal cost $\lambda^{DA*} = \lambda^{RT*} = \boxed{\frac{G-1}{G-2}} \cdot \frac{c}{G} \sum_{l \in \mathcal{L}} d_l$
  - Any combination of bids with two-stage power balance

$\frac{G-1}{G-2} > 1$

Generator: $\beta_j^{DA*} + \beta_j^{RT*} = \boxed{\frac{G-2}{G-1}} \cdot \frac{1}{c}$ Load: $d_l^{DA*} + d_l^{RT*} = d_l$

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

Market Equilibria Characterization

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- **Competitive equilibrium**
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$$\text{Generator: } \beta_j^{DA*} + \beta_j^{RT*} = \frac{1}{c} \qquad \text{Load: } d_l^{DA*} + d_l^{RT*} = d_l$$

- Nash equilibrium with **strategic loads only**
  - Same as competitive equilibrium

Remark 1: *If generators are truthful, load cannot exercise market power!*

- Nash equilibrium with **strategic generators only**
  - Equal two-stage prices higher than marginal cost $\lambda^{DA*} = \lambda^{RT*} = \frac{G-1}{G-2} \cdot \frac{c}{G}\sum_{l\in\mathcal{L}} d_l$
  - Any combination of bids with two-stage power balance

$$\frac{G-1}{G-2} > 1$$

$$\text{Generator: } \beta_j^{DA*} + \beta_j^{RT*} = \frac{G-2}{G-1} \cdot \frac{1}{c} \qquad \text{Load: } d_l^{DA*} + d_l^{RT*} = d_l$$

Remark 2: *No apparent incentive for full allocation of demand in day ahead!*

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

NE with Strategic Generators and Loads

- **Demand allocation**
  - Strategic loads in total allocate the portion

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

  of demand in the day-ahead market;

- **Real-time price higher than day-ahead price**
  - Real-time price same as only strategic gens case

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

  - Day-ahead price is a fraction $\frac{L}{L+1}$ of real-time price.

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

G >=3: num. of gens, *L*: num. of loads

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 loads

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 loads

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

Reversal of market power: *G*=5 and *L*=1

NE gen profit $$\frac{1}{60}\cdot c\left(\sum_{l\in\mathcal{L}} d_l\right)^2 < \frac{1}{50}\cdot c\left(\sum_{l\in\mathcal{L}} d_l\right)^2$$ **Comp. E gen profit**

Surplus Allocation

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

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

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

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

Surplus Allocation

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

Load payment

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

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):

$$-\frac{L'(G-1)+1}{L'(L'+1)^2(G-2)}\cdot\frac{c\left(\sum_{l\in\mathcal{L}} d_l\right)}{G} \qquad \frac{\lambda^{DA*}-\lambda^{RT*}}{\lambda^{DA*}} = \frac{1}{L'} \xrightarrow[L'\to\infty]{} 0$$

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

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

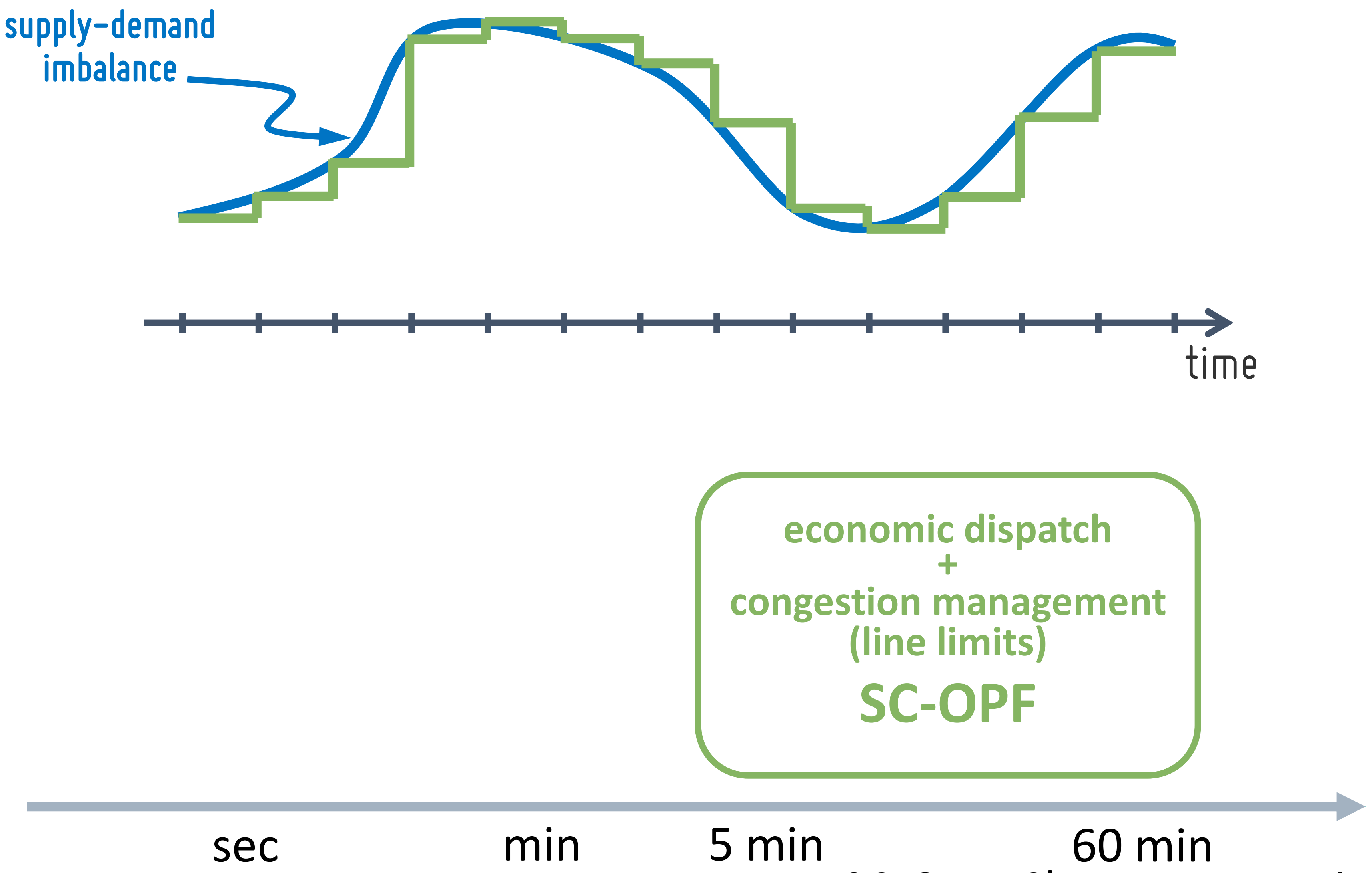
- Analysis further allows characterization of the impact of many policies, e.g.,
  - Virtual bidding -> *benefits from load market power*
  - Uniform supply function bidding by generators
  - Real-time transaction charges

Towards Multi-timescale Market Design

- Coupled Incentives in Two-stage Markets

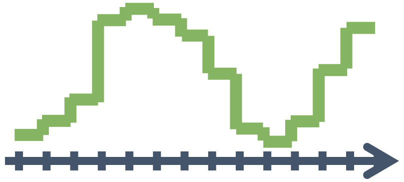
- Co-optimizing Economic Dispatch and Freq. Regulation

Multi-timescale Approach Supply-Demand Balance



SC-OPF: Chance constrained; N-1 secure

Economic Dispatch



Seeks **efficiency** through a **market**:

Generators

bids $\hat{\theta}$

ISO

$$ED$$

ISO's Economic Dispatch

supply function

$$\text{power} = f(\hat{\theta}, \text{price})$$

cost function

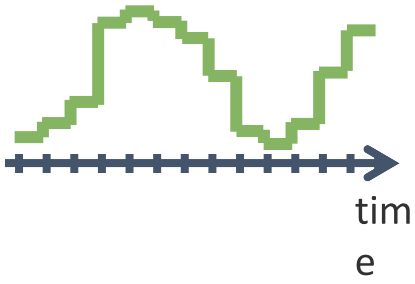
$$\text{cost} = \int_0^{\text{power}} f^{-1}(\hat{\theta}, p)\,dp$$

optimization

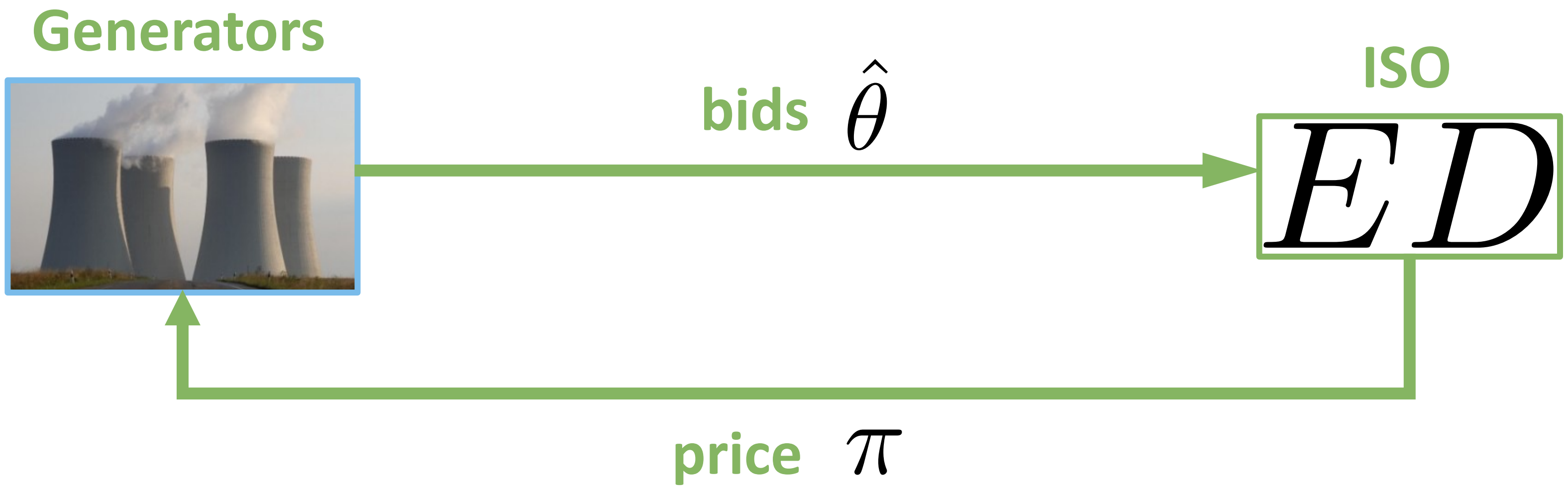
$$\begin{aligned} \text{min.}\ \ & \text{cost} \\ \text{s.t.}\ \ & \text{constraints} \end{aligned}$$

price π

Economic Dispatch



Seeks **efficiency** through a **market**:

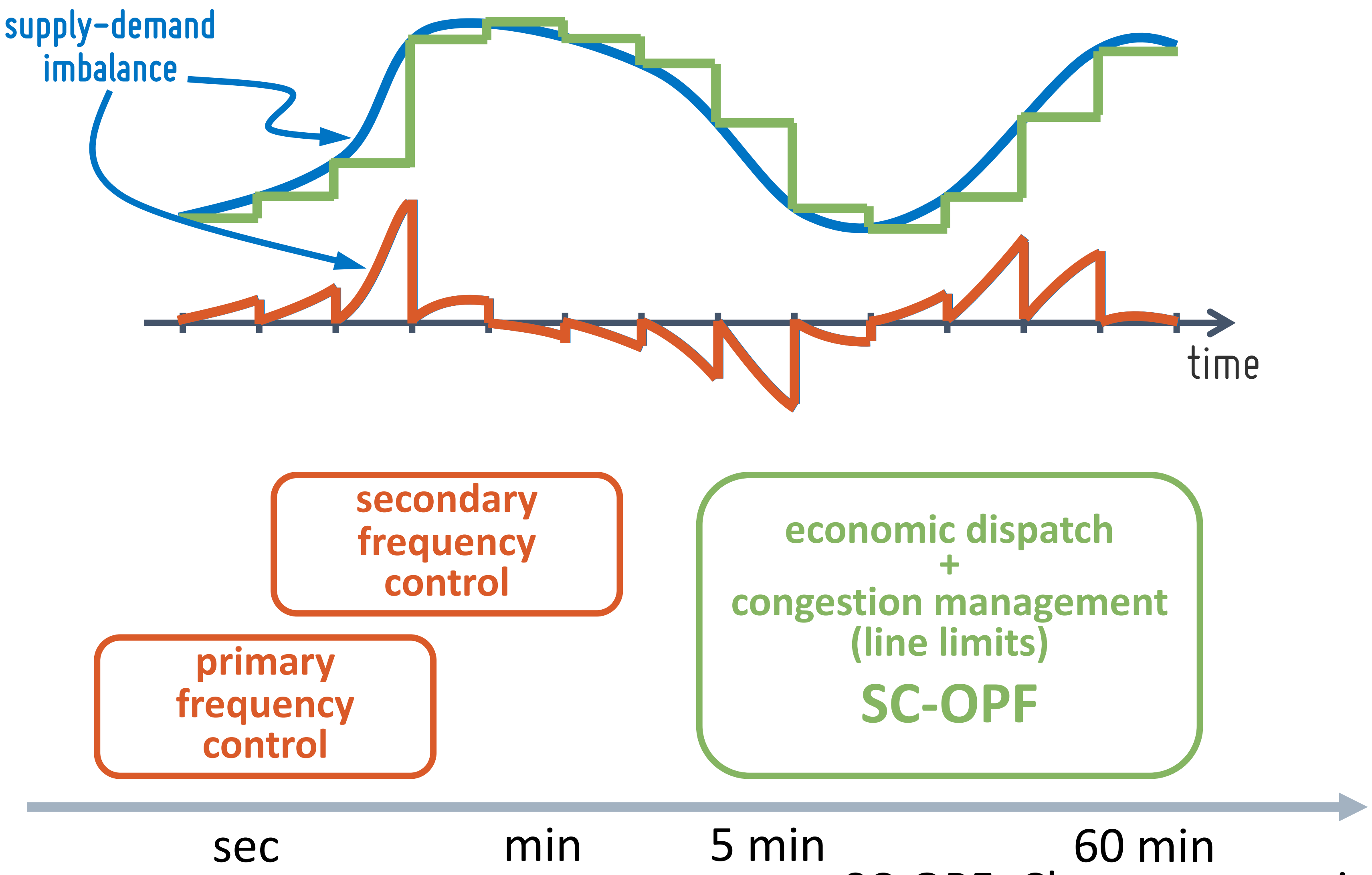


Gen objective: Maximize profit

$$\max_{\hat{\theta}} \left(\pi f(\hat{\theta}, \pi) - c(f(\hat{\theta}, \pi)) \right)$$

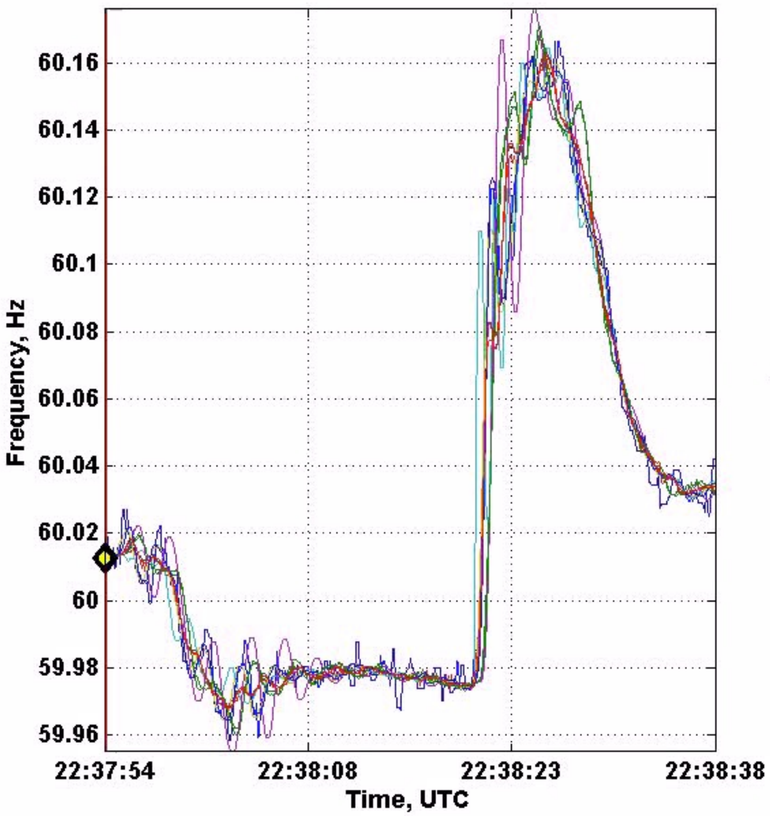
revenue **true cost**

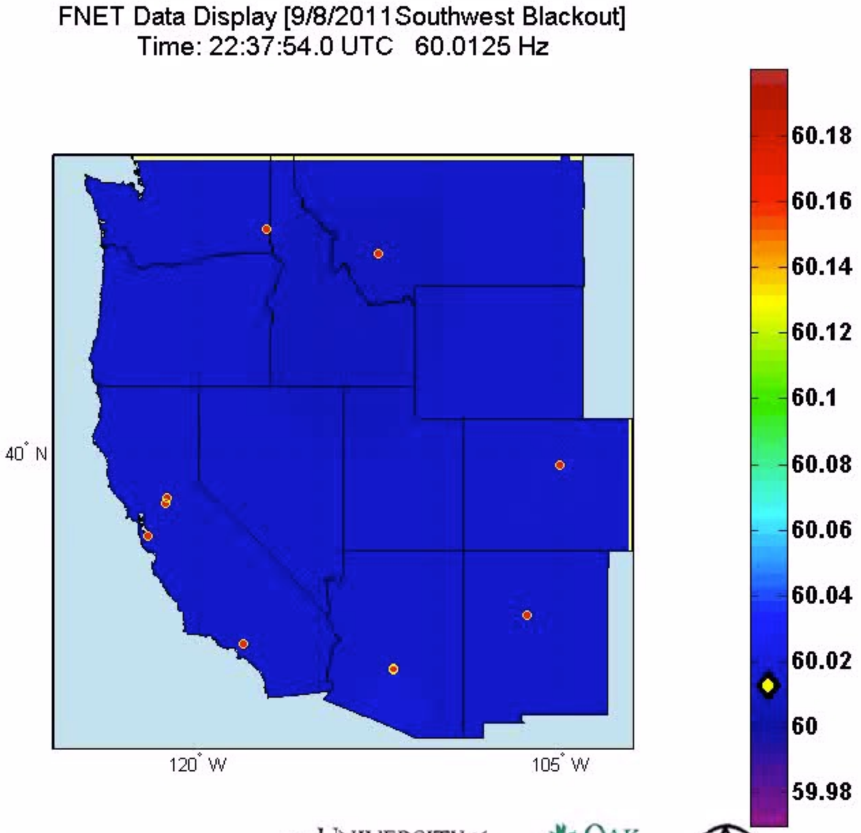
Multi-timescale Approach Supply-Demand Balance

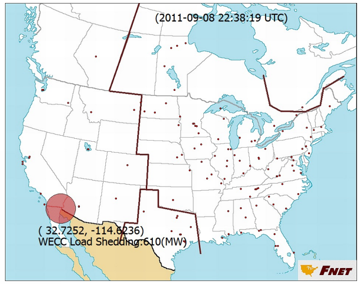


SC-OPF: Chance constrained; N-1 secure

Frequency Control







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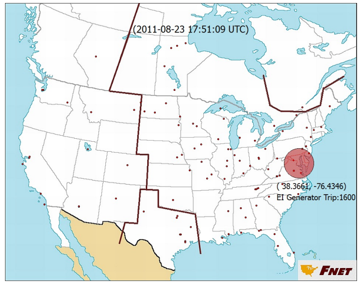
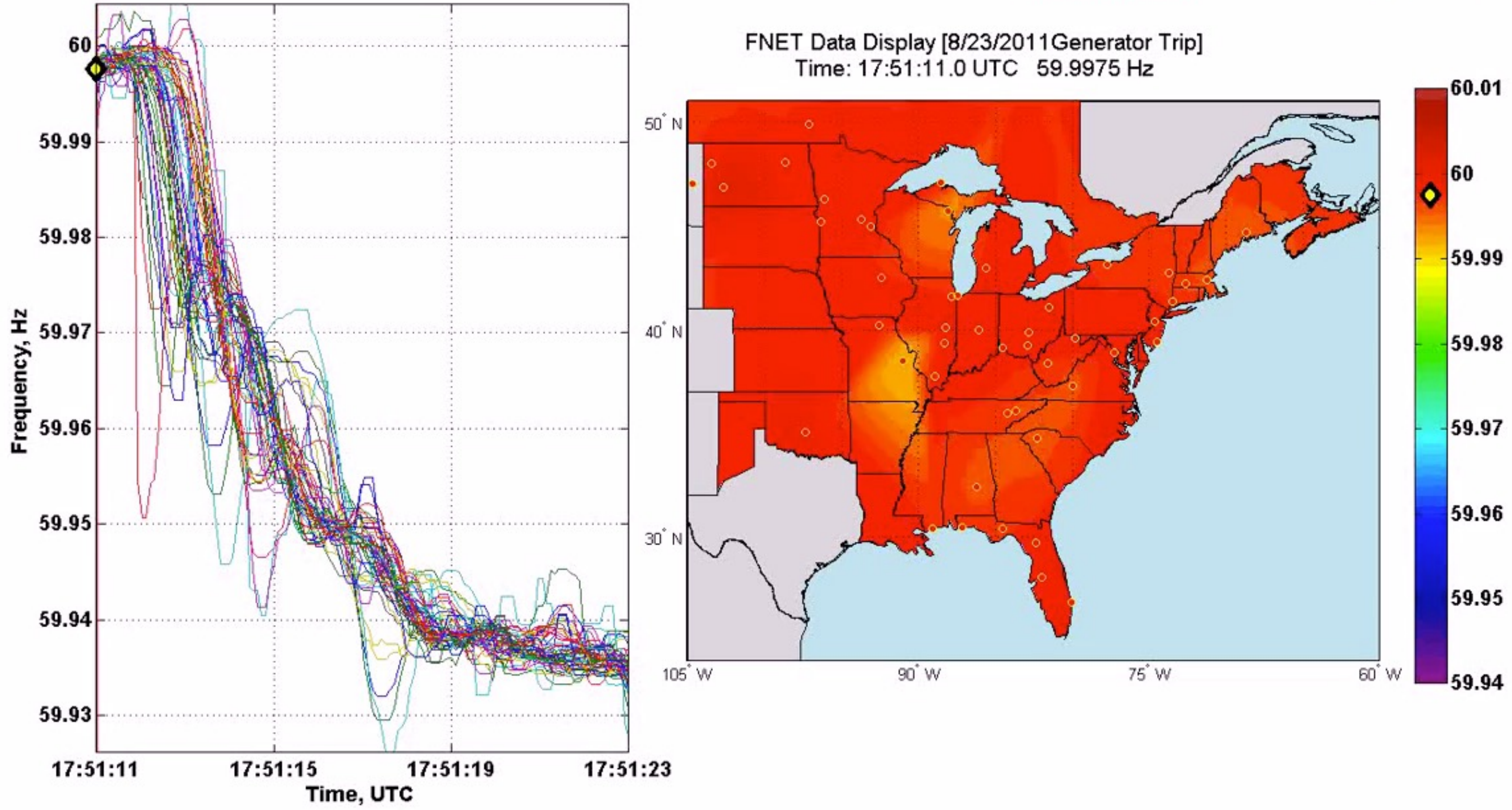
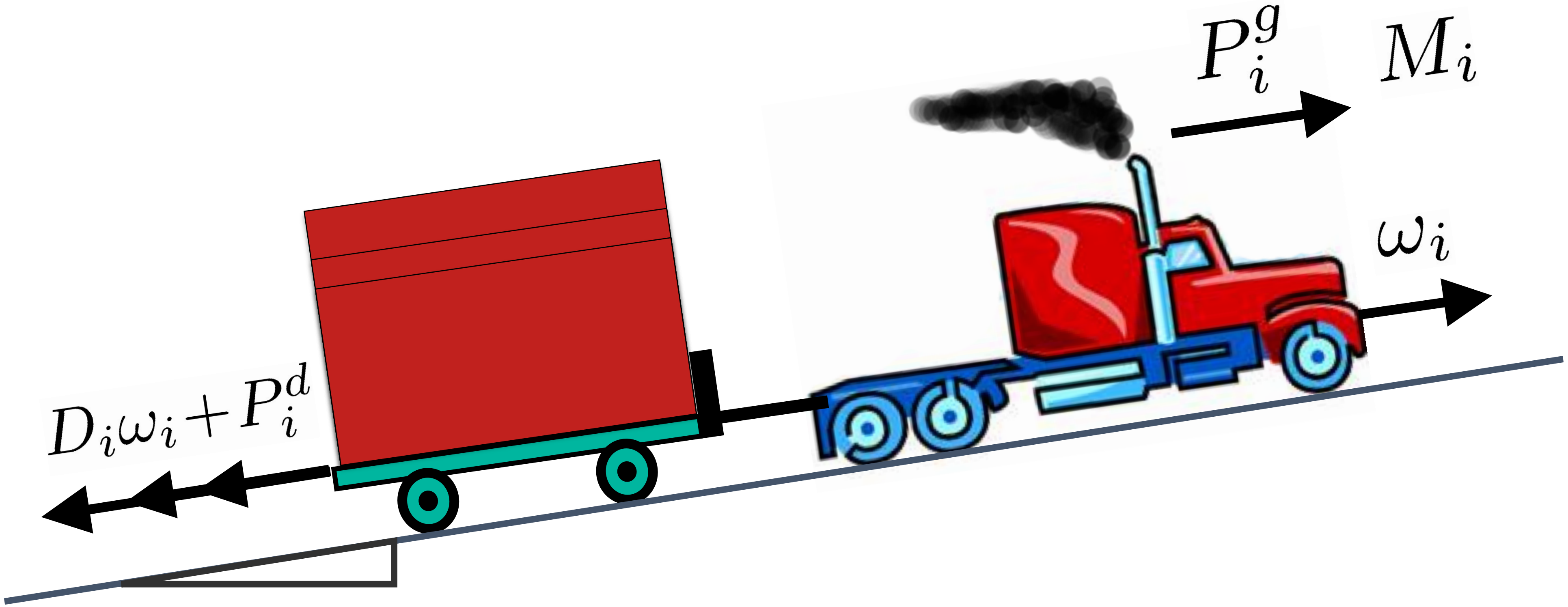




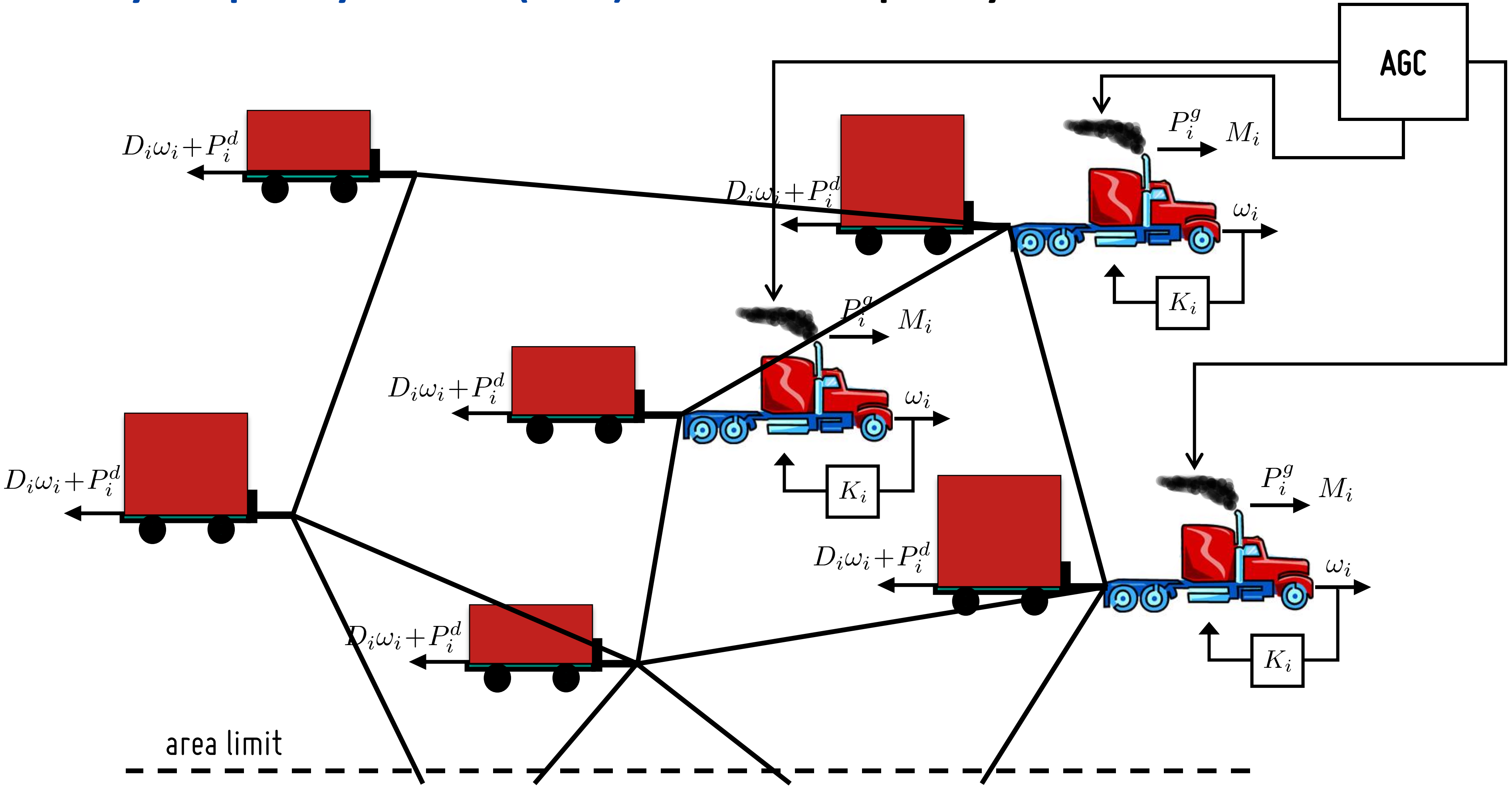
Mechanical analogue



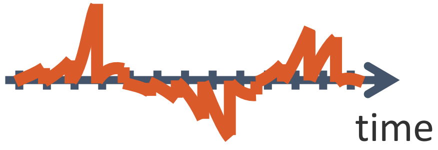
Objective: Maintain speed ω_i constant

Frequency control

- **Primary frequency control:** Rebalance power & resynchronize generators
- **Secondary frequency control (AGC):** Restore frequency & inter-area flows



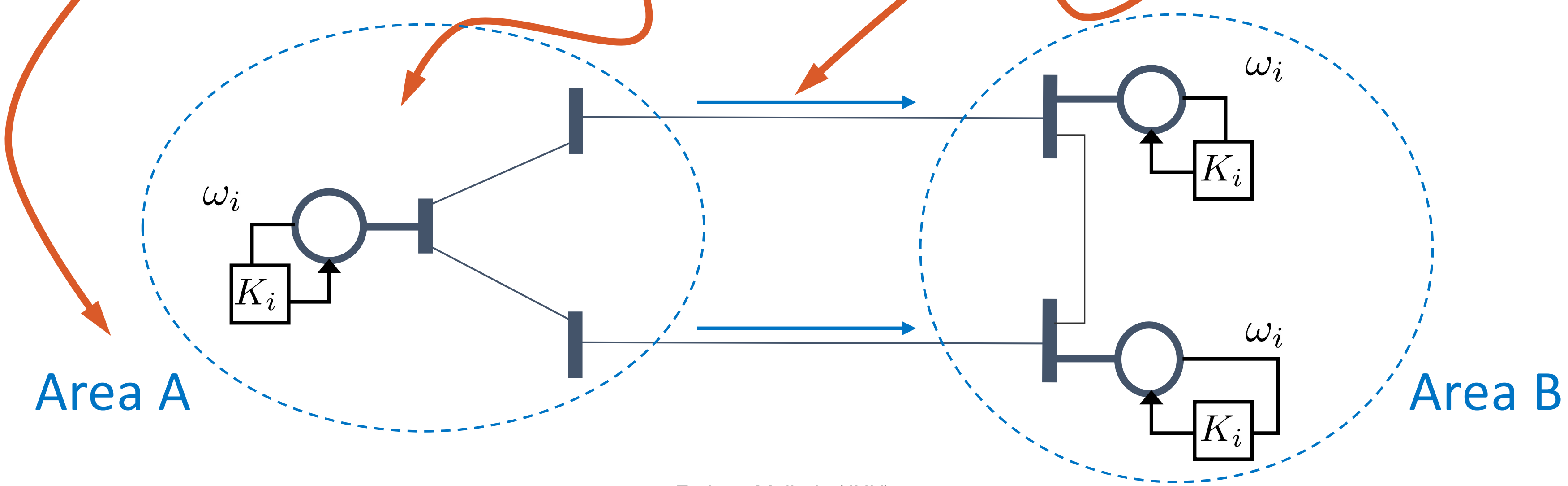
Frequency Control



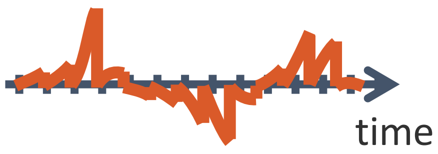
- Corrects ED errors while **maintaining stability**
- **Primary freq. control:** Rebalance power & resynchronize generators
- **Secondary freq. control (AGC):** Restore freq. and inter-area flows

$$ACE_A(t) = K_A\omega(t) + \Delta\mathrm{Tie}_A(t)$$

area control error = supply-demand imbalance + inter-area flow mismatch



Frequency Control



- Corrects ED errors while **maintaining stability**
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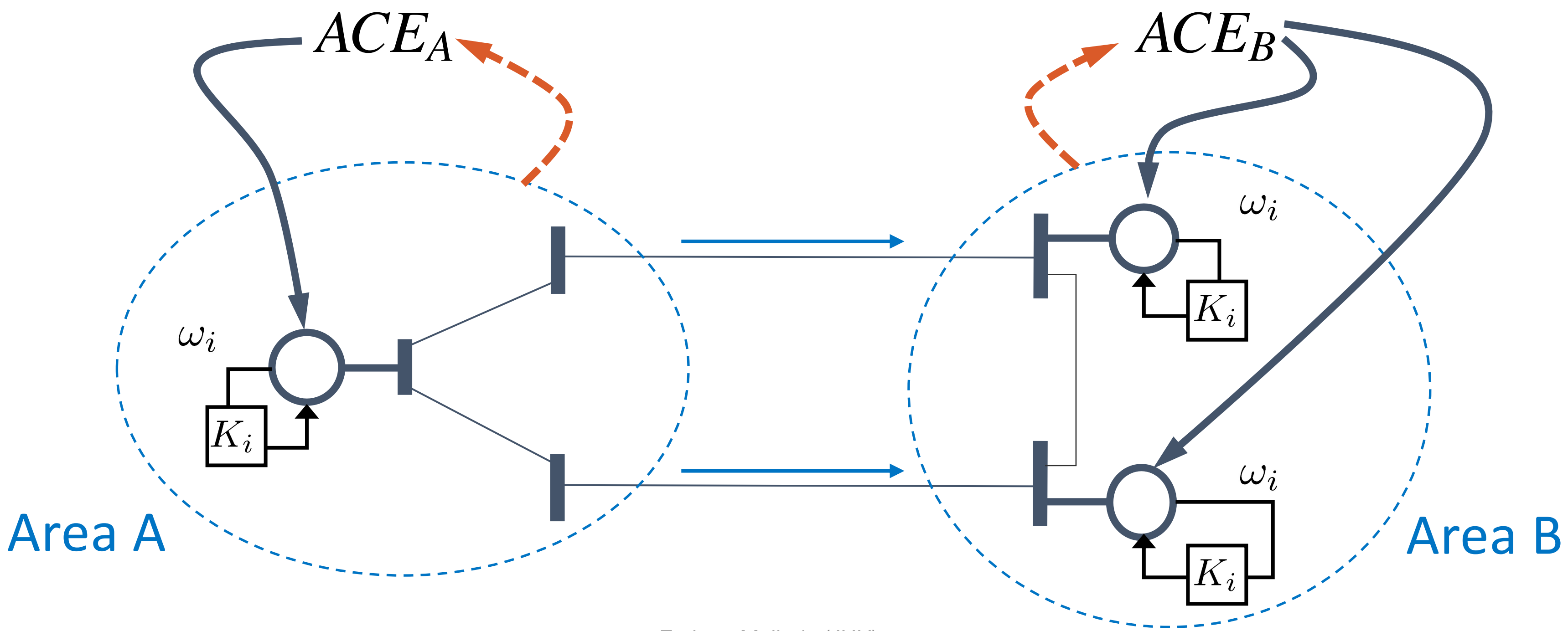
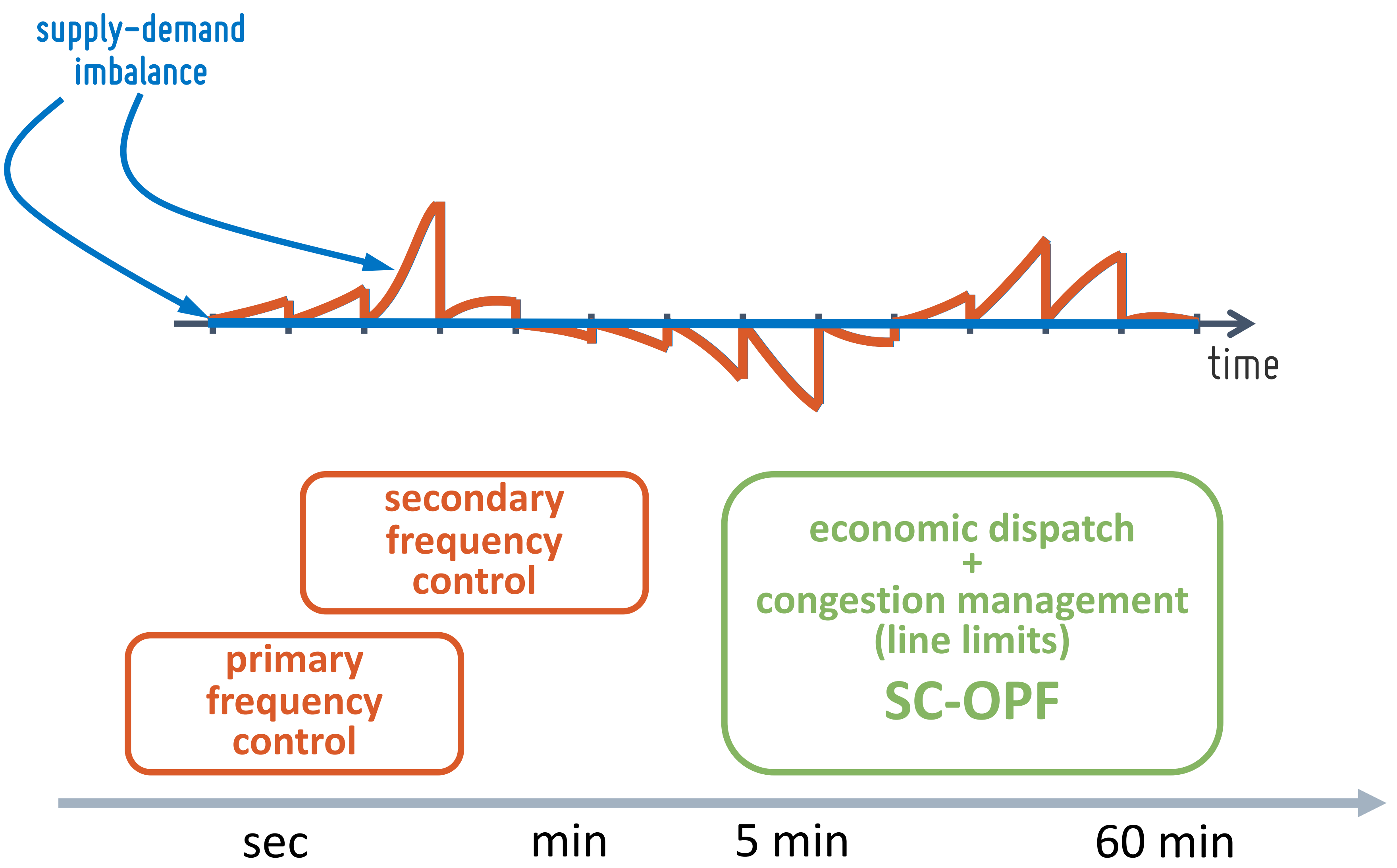


Multi-timescale Approach Supply-Demand Balance



SC-OPF: Chance constrained; N-1 secure

Existing Architecture

secondary frequency control

primary frequency control

economic dispatch
+
congestion management
SC-OPF

sec | min | 5 min | 60 min

Control->Stability

Market->Efficiency

works well…

… but not sustainable!

California 50% by 2030

Germany 45% by 2030

Challenge

fuel efficiency ↓

emission ↑

secondary frequency control

primary frequency control

economic dispatch
+
congestion management
SC-OPF

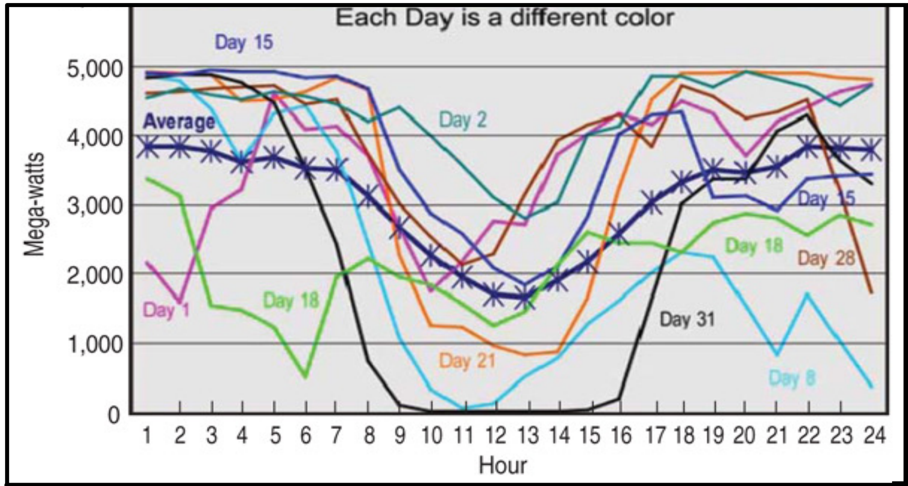
↑ conservative

↓ optimal

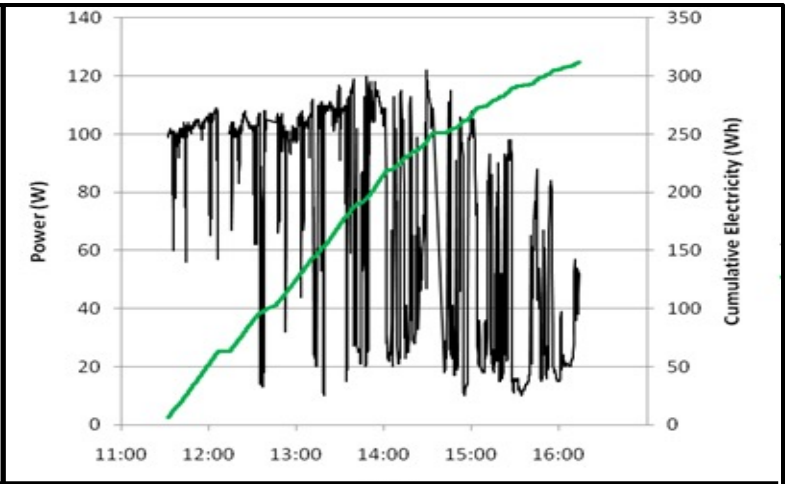
sec | min | 5 min | 60 min

Control->Stability | **Market->Efficiency**

High Volatility

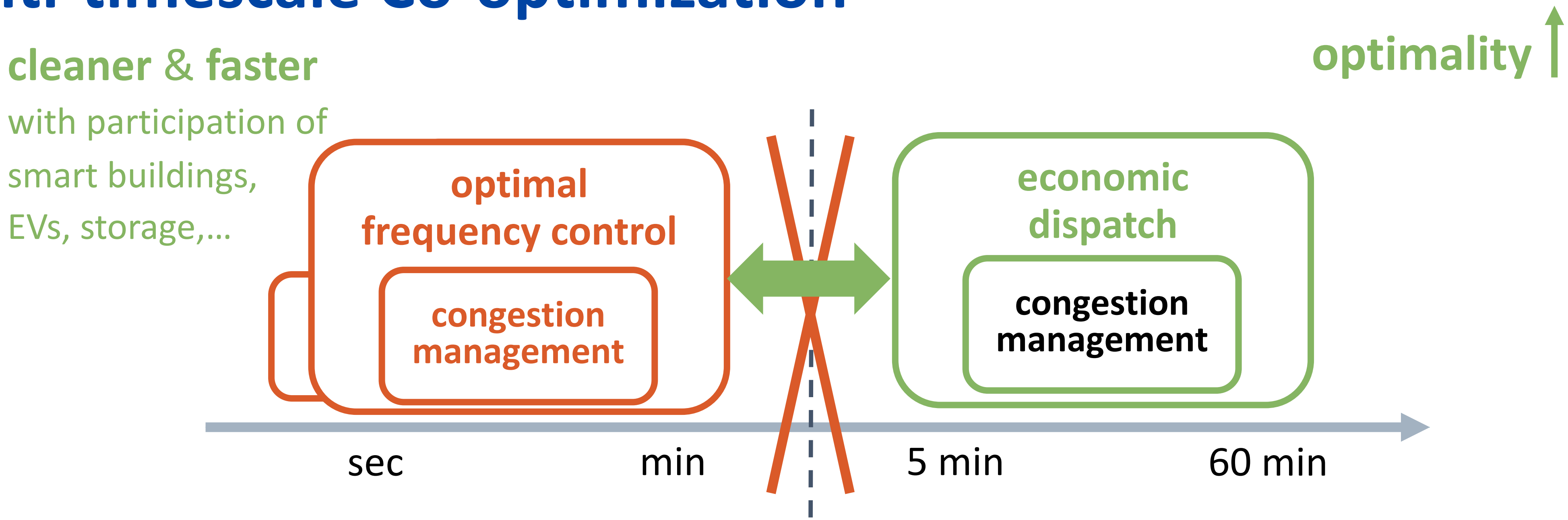


Daily **wind** generation [Tehachapi, CA]



5-hour **solar** generation [Columbia Univ.]

Multi-timescale Co-optimization



Optimal Freq. Control

- Generator + **load** control
- **Fully distributed**
- Stability + **efficiency**
- **Congestion management**

Joint Ec. Dispatch and Freq. Reg.

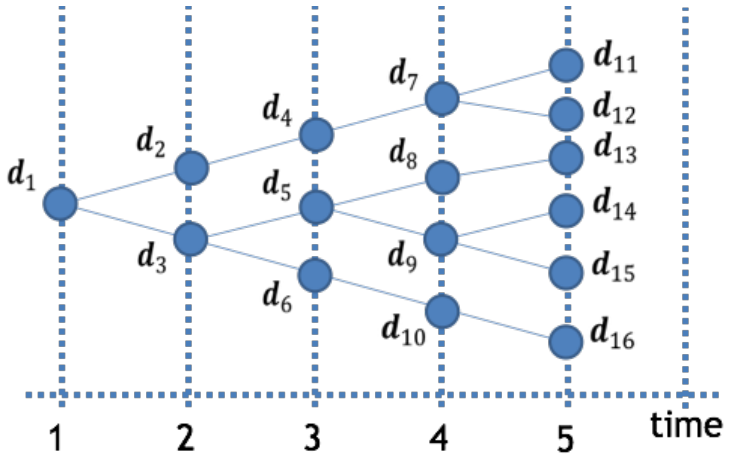
- **Co-optimized** multiple time-scales
- **Increased** efficiency
- **Market-based** Implementation

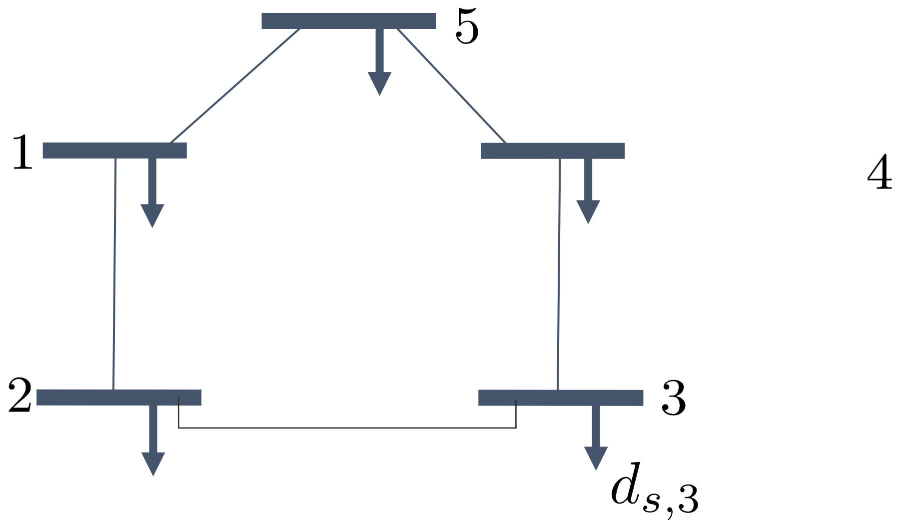
How to get there?

- **Step 1:** First principles model of joint grid objectives
- **Step 2:** Decompose across timescales to identify markets and/or products
- **Step 3:** Implement algorithms in existing market & control grid’s ecosystem

Demand Model

Scenario Tree: $|K| = 5 \quad |S| = 16$





Set of **time steps** K.

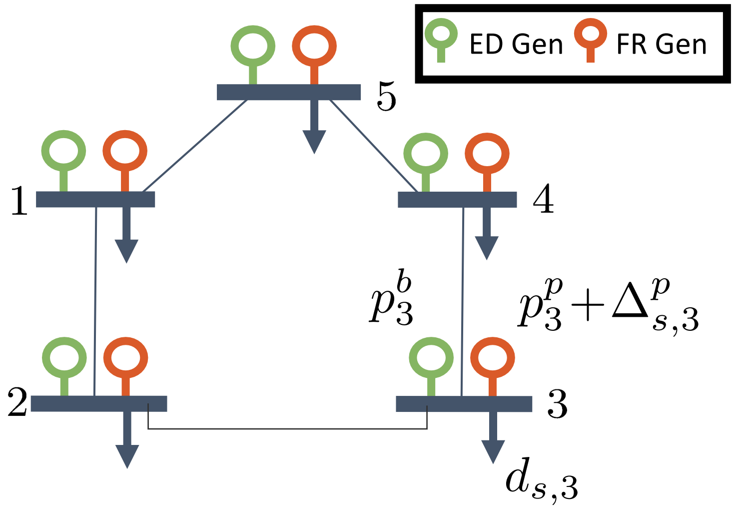
Set of **outcomes** S.

$\kappa(s)$ = Time step of outcome s.

q_s = Probability of outcome s conditioned on knowing time step is $\kappa(s)$.

$d_{s,i}$ = Demand at bus i in outcome s.

Generator Model

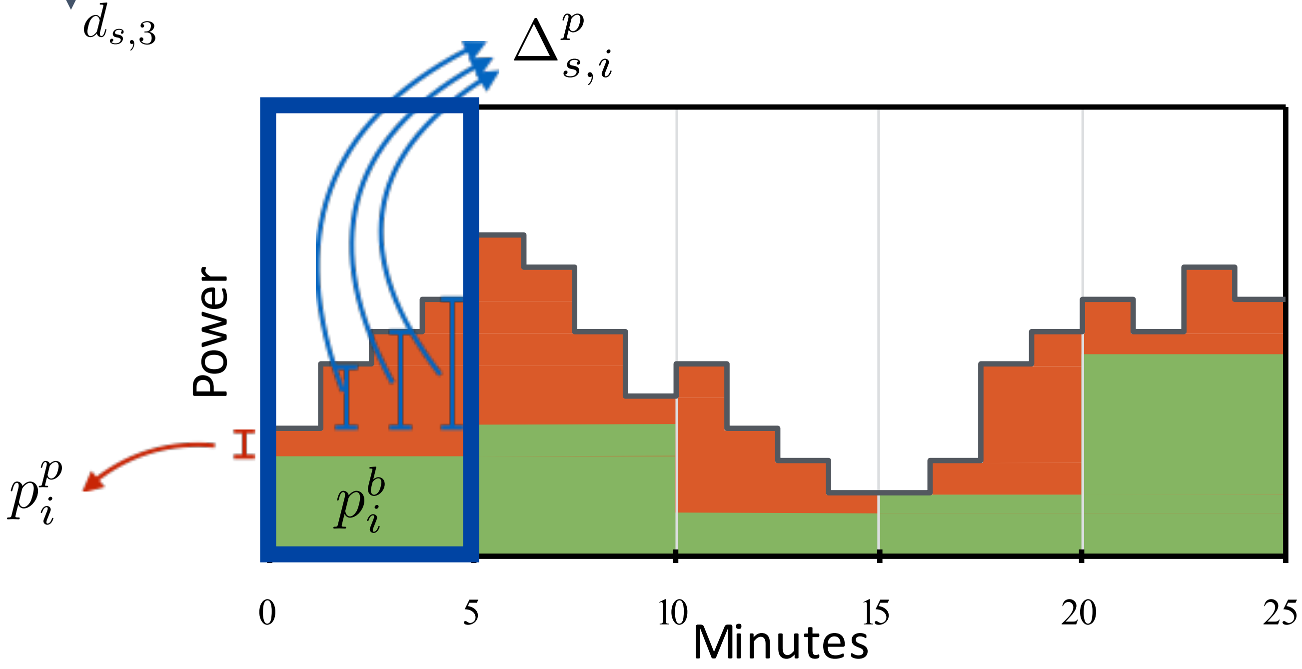


Two types of generators

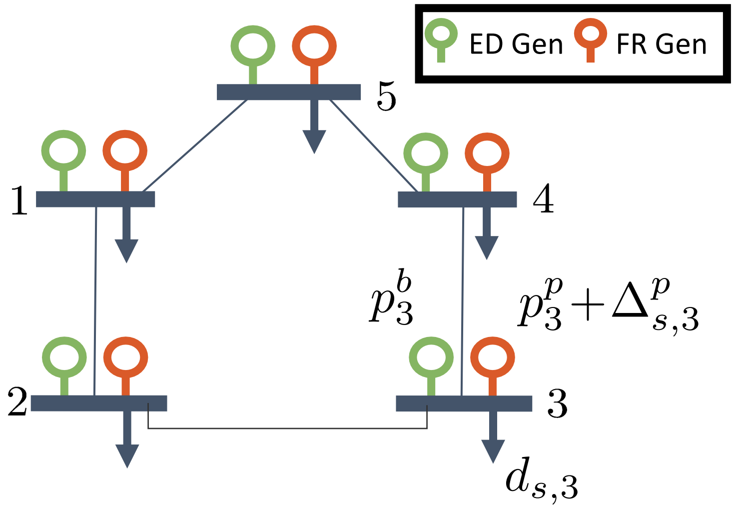
p_i^b = setpoint of **ED gen** at i .

p_i^p = setpoint of **FR gen** at i .

$\Delta_{s,i}^p$ = additional dispatch of peaker at i in outcome s.



System Constraints



Feasible dispatch given demand : $\mathbf{d}_s$

$$\Omega(\mathbf{d}_s) := \left\{ (\mathbf{p}^b, \mathbf{p}^p, \boldsymbol{\Delta}_s^p) : \begin{array}{l} \underline{\mathbf{p}}^b \leq \mathbf{p}^b \leq \bar{\mathbf{p}}^b \\ \underline{\mathbf{p}}^p \leq \mathbf{p}^p + \boldsymbol{\Delta}_s^p \leq \bar{\mathbf{p}}^p \\ \mathbf{1}^\top (\mathbf{p}^b + \mathbf{p}^p + \boldsymbol{\Delta}_s^p - \mathbf{d}_s) = 0 \\ \underline{\mathbf{P}} \leq \mathbf{H} \left(\mathbf{p}^b + \mathbf{p}^p + \boldsymbol{\Delta}_s^p - \mathbf{d}_s \right) \leq \overline{\mathbf{P}} \end{array} \right\}$$

baseload capacities

peakers capacities

supply=demand

thermal limits

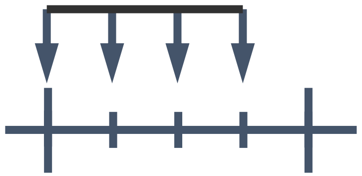
How to get there?

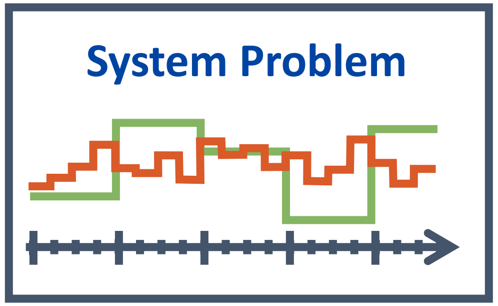
- **Step 1:** First principles model of joint grid objectives

- **Step 2:** Decompose across timescales to identify markets and/or products

- **Step 3:** Implement algorithms in existing market & control grid's ecosystem

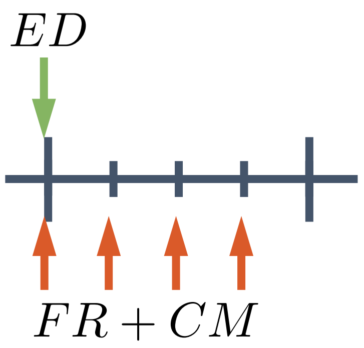
Step 2: Decompose Across Timescales

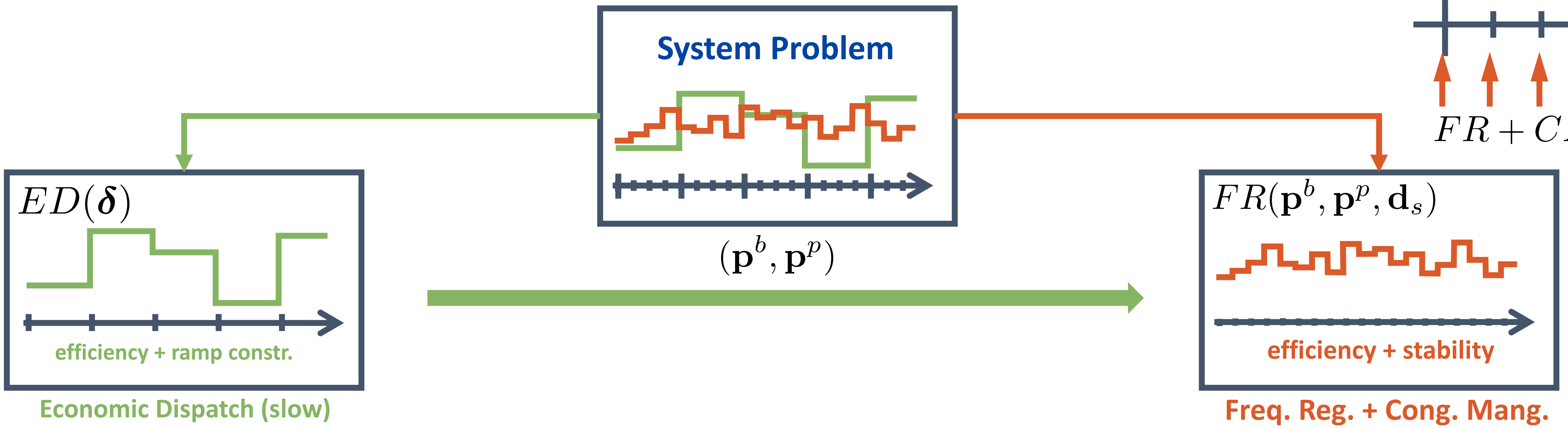




$$
\begin{aligned}
&SYSTEM:\\
&\min_{\mathbf{p}^b, \mathbf{p}^p, \mathbf{\Delta}_s^p} \sum_{i \in N} |K| c_i^b(p_i^b) + \sum_{s \in S} q_s \sum_{i \in N} c_i^p(p_i^p + \Delta_{s,i}^p)\\
&\text{s.t.} \qquad (\mathbf{p}^b, \mathbf{p}^p, \mathbf{\Delta}_s^p) \in \Omega(\mathbf{d}_s), \quad \forall s \in S.
\end{aligned}
$$

Step 2: Decompose Across Timescales





$\boldsymbol{\delta}$

$ED(\boldsymbol{\delta})$:

$$\min_{\mathbf{p}^b, \mathbf{p}^p} \sum_{i \in N} \left(|K| c_i^b(p_i^b) + |K| c_i^p(p_i^p) - \delta_i p_i^b \right)$$

$$\text{s.t.} \quad (\mathbf{p}^b, \mathbf{p}^p, \mathbf{0}) \in \Omega(\mathbf{d}_1)$$

optimal $\boldsymbol{p}^b, \boldsymbol{p}^p$

$FR(\mathbf{p}^b, \mathbf{p}^p, \mathbf{d}_s)$:

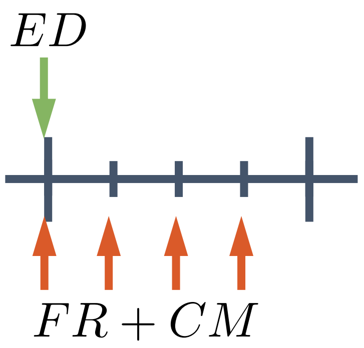
$$\min_{\boldsymbol{\Delta}_s^p} \sum_{i \in N} c_i^p(p_i^p + \Delta_{s,i}^p)$$

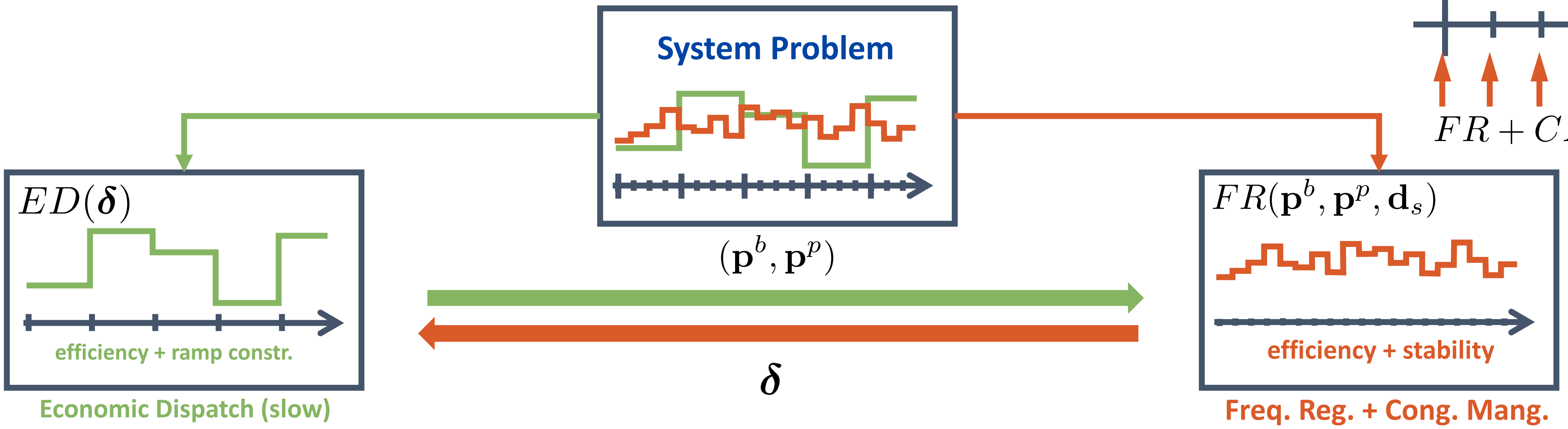
$$\text{s.t.} \quad (\mathbf{p}^b, \mathbf{p}^p, \boldsymbol{\Delta}_s^p) \in \Omega(\mathbf{d}_s)$$

optimal $\boldsymbol{\Delta}_s^p$

Note: requires real-time congestion management!

Step 2: Decompose Across Timescales





When is this optimal?

expected price correction

$$\boxed{\boldsymbol{\delta} = \sum_{s \in S} q_s [\boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s) - \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1)]}$$

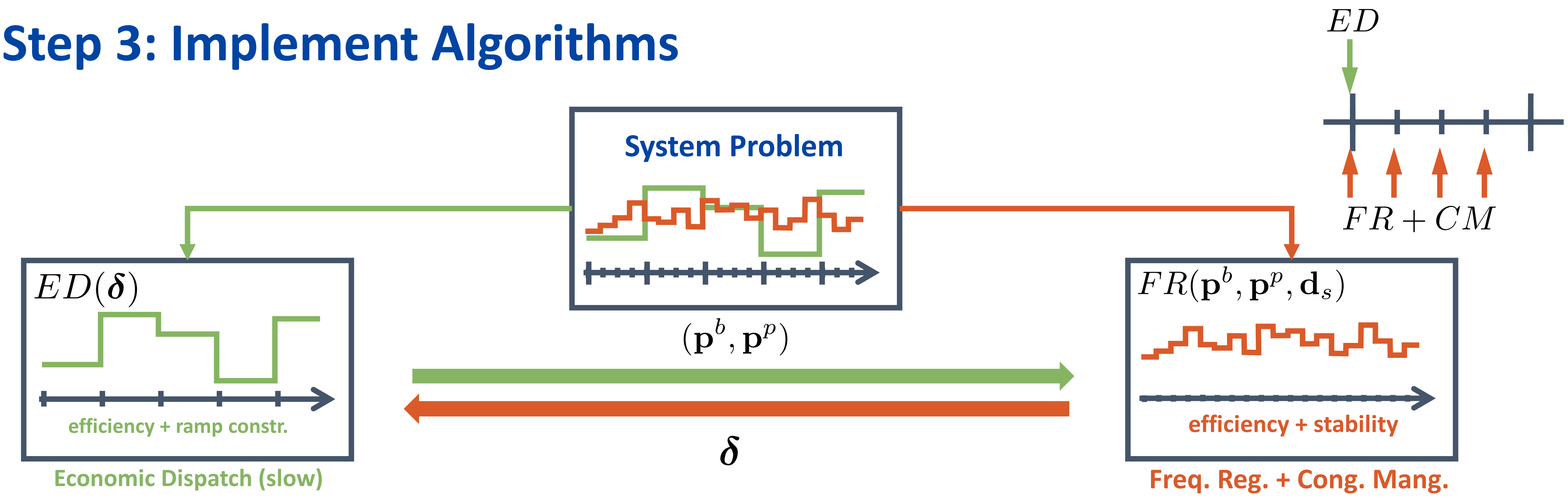
How to get there?

- **Step 1:** First principles model of joint grid objectives

- **Step 2:** Decompose across timescales to identify markets and/or products

- **Step 3:** Implement algorithms in existing market & control grid's ecosystem

Step 3: Implement Algorithms



Step 3: Implement Algorithms - Markets

$\boxed{k = 1}$

baseload gen

bids $\hat{\theta}^b$

$ED(\delta)$

bids $\hat{\theta}^p$

peaker

$FR_{k=1}$

$$\text{power} = f(\hat{\theta}, \text{price})$$

d_1

1 2 3 4

Step 3: Implement Algorithms - Markets

$\boxed{k = 1}$

baseload gen

$\boxed{ED(\delta)}$

slow prices

$$\boldsymbol{\pi}^b = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1) + \delta$$

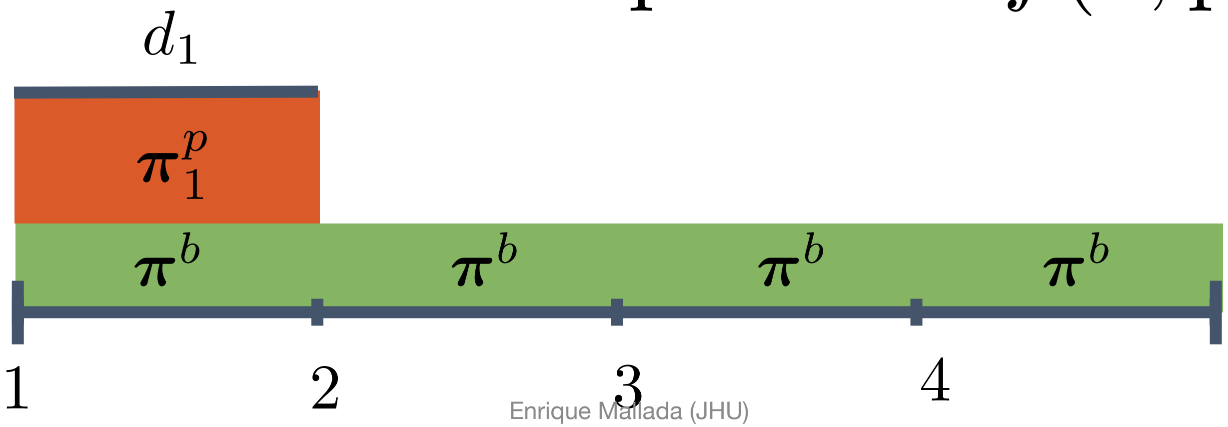
$\boxed{FR_{k=1}}$

peaker

fast price

$$\boldsymbol{\pi}^p_s = \boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s)$$

$$\text{power} = f(\hat{\theta}, \text{price})$$



Step 3: Implement Algorithms - Markets

$$\boxed{k = 2}$$

baseload gen

$$\boxed{ED(\delta)}$$

slow prices

$$\pi^b = \pi(\lambda_1, \underline{\mu}_1, \overline{\mu}_1) + \delta$$

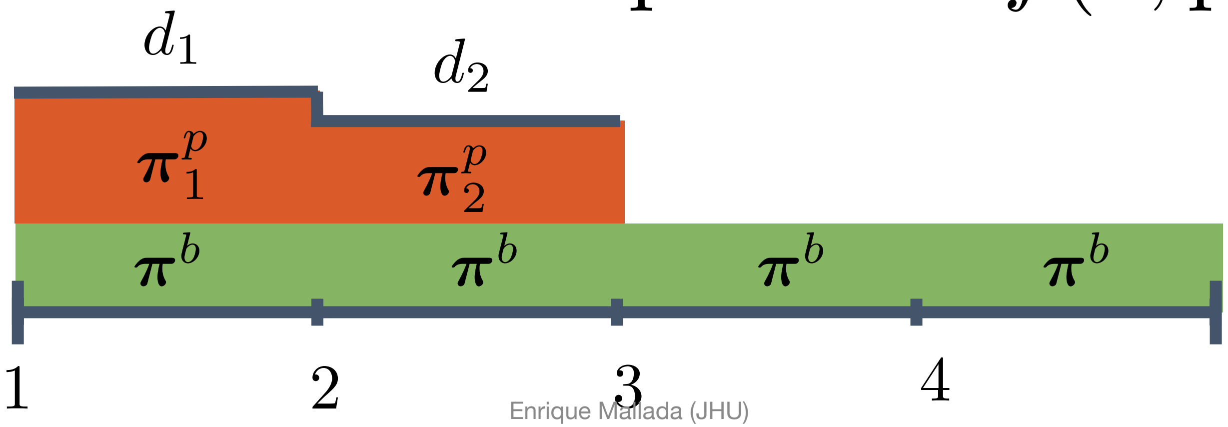
$$\boxed{FR_{k=2}}$$

peaker

fast price

$$\pi_s^p = \pi(\lambda_s, \underline{\mu}_s, \overline{\mu}_s)$$

$$\text{power} = f(\hat{\theta}, \text{price})$$



Step 3: Implement Algorithms - Markets

$$\boxed{k = 3}$$

baseload gen

$$\boxed{ED(\delta)}$$

slow prices

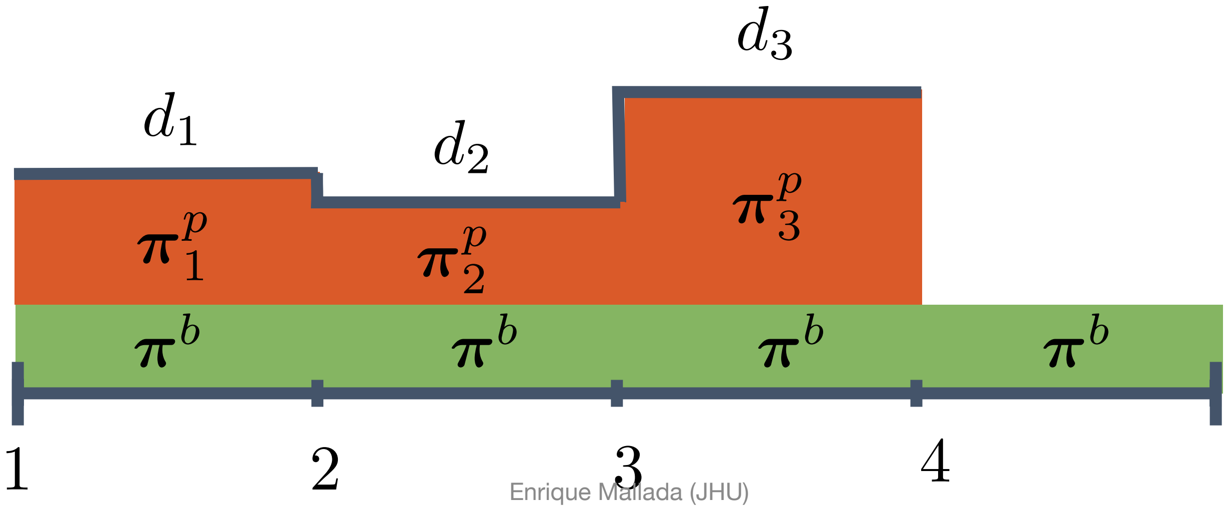
$$\boldsymbol{\pi}^b = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1) + \delta$$

$$\boxed{FR_{k=3}}$$

peaker

fast price

$$\boldsymbol{\pi}_s^p = \boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s)$$



Step 3: Implement Algorithms - Markets

$$\boxed{k = 4}$$

baseload gen

$$\boxed{ED(\delta)}$$

slow prices

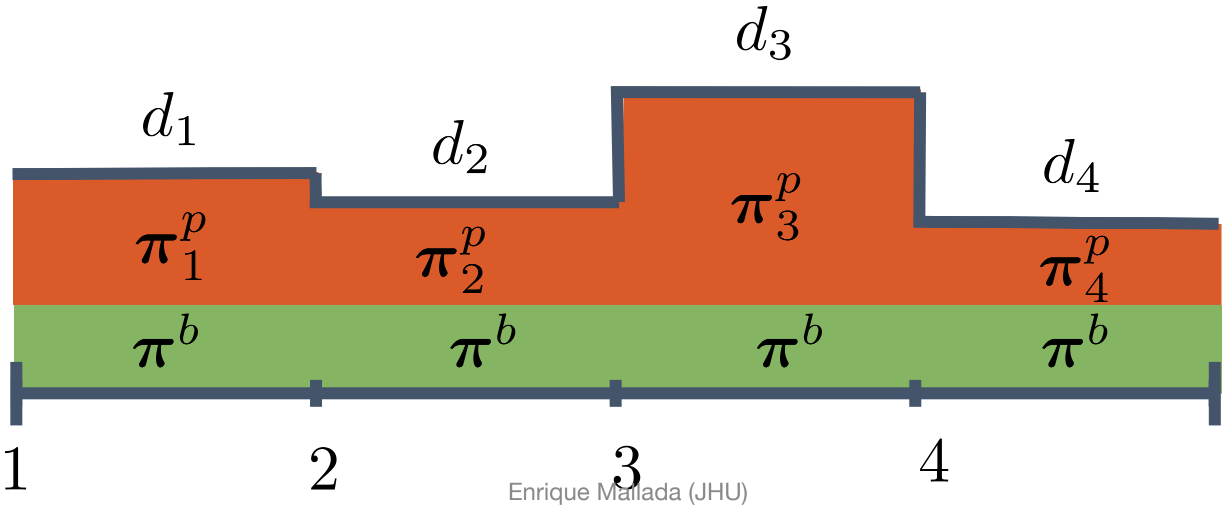
$$\boldsymbol{\pi}^b = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1) + \delta$$

$$\boxed{FR_{k=4}}$$

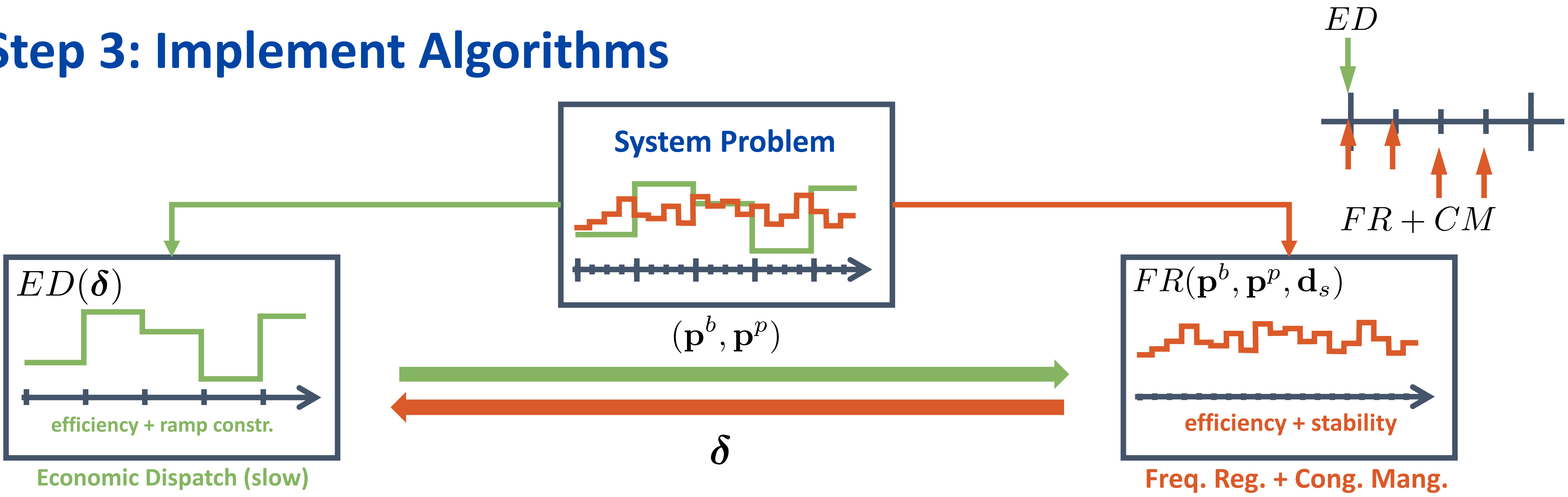
peaker

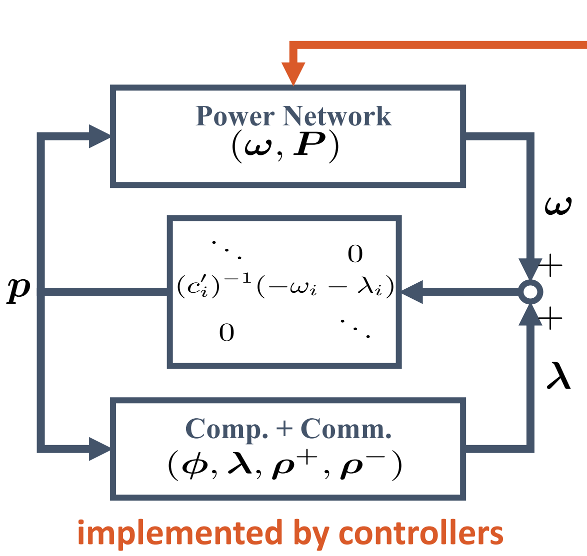
fast price

$$\boldsymbol{\pi}^p_s = \boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s)$$



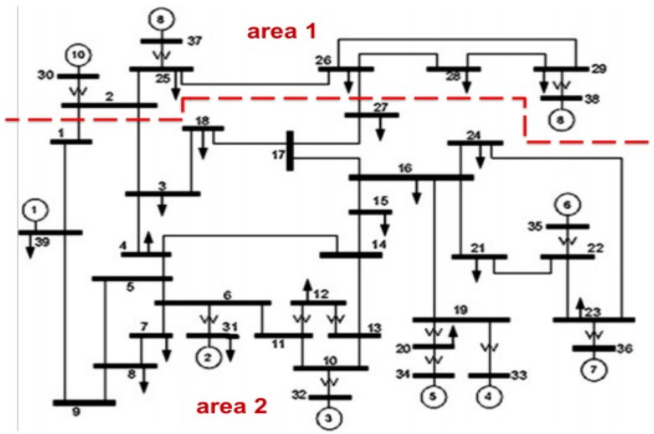
Step 3: Implement Algorithms



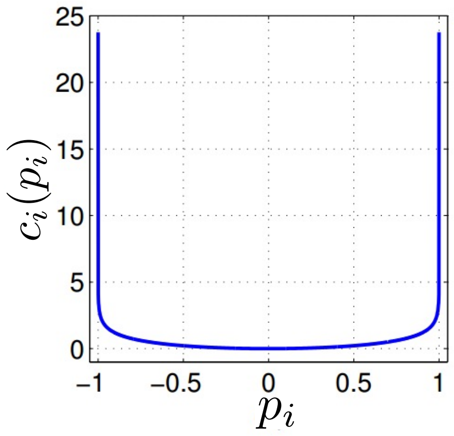


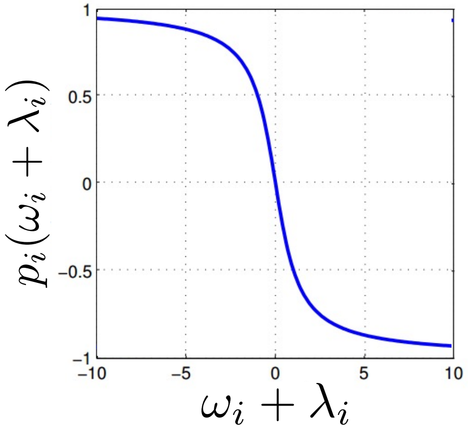
[TAC '17] E. M., C. Zhao, and S. H. Low, "Optimal load-side control for frequency regulation in smart grids," **IEEE Transactions on Automatic Control**, Jun. 2017.
[PSCC '16] C. Zhao, E M., S. H. Low, J. Bialek, "A unified framework for frequency control and congestion management," **Power Systems Computation Conference (PSCC)**, 2016.

Real-time Congestion Management

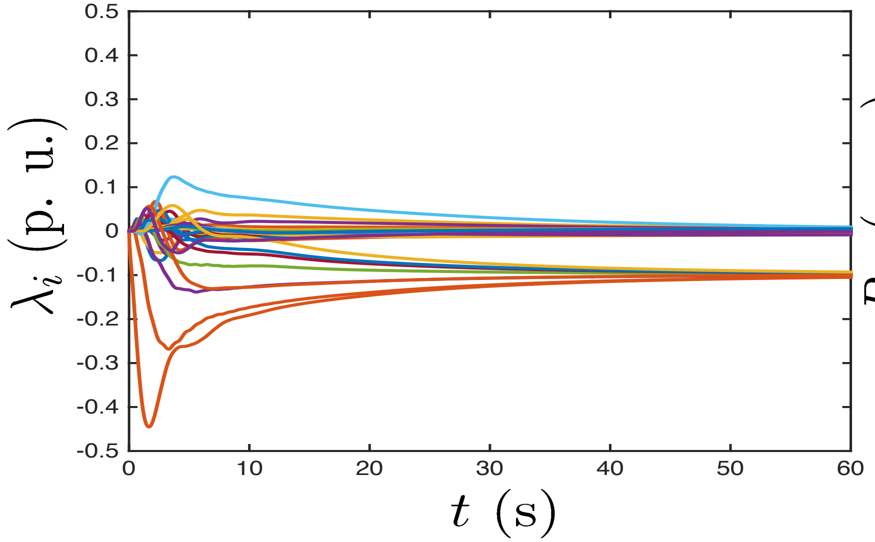


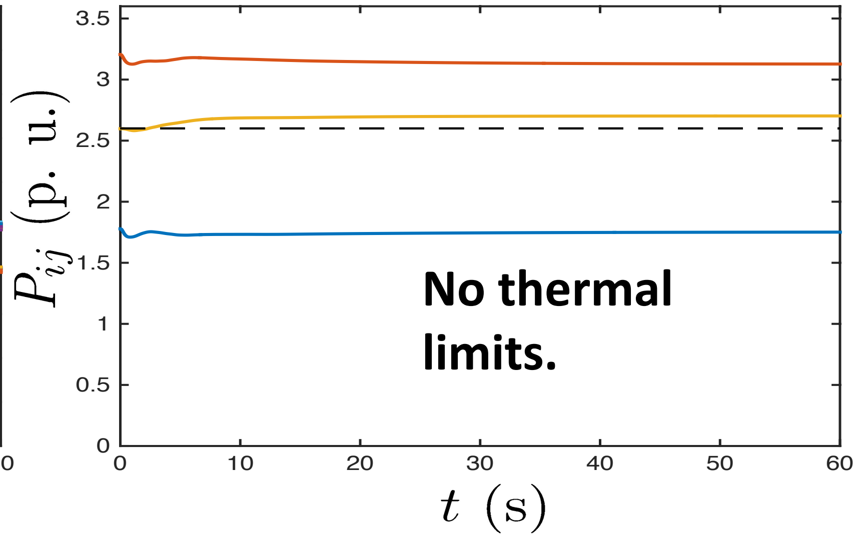
Exogenous input: $\Delta P_i^{net} = -0.5$ p.u.



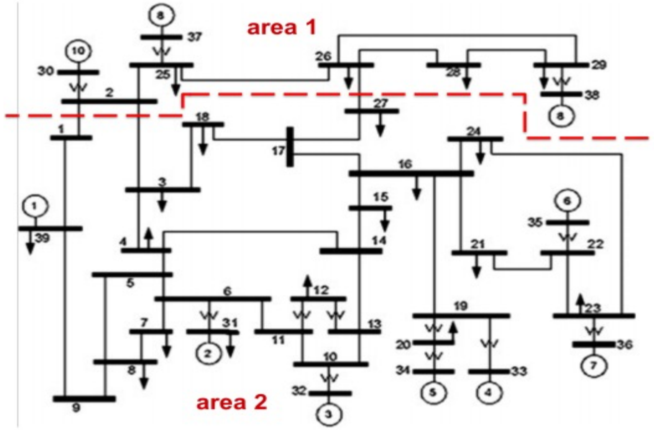


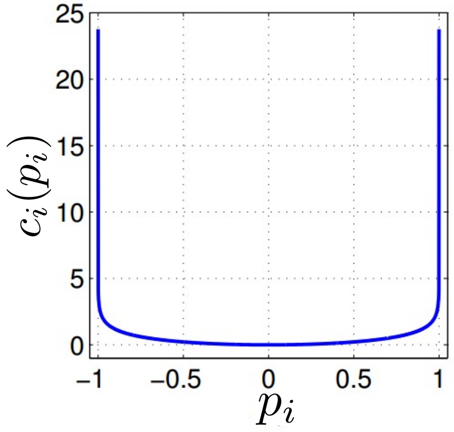
Without respecting thermal limits

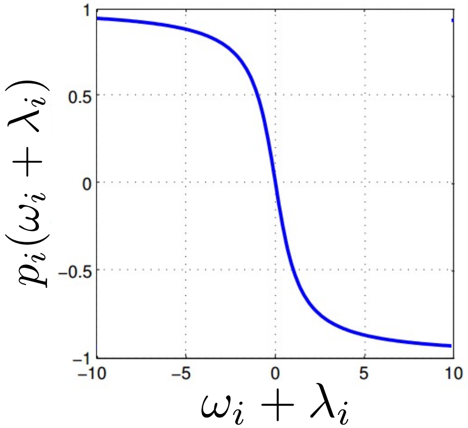




Real-time Congestion Management

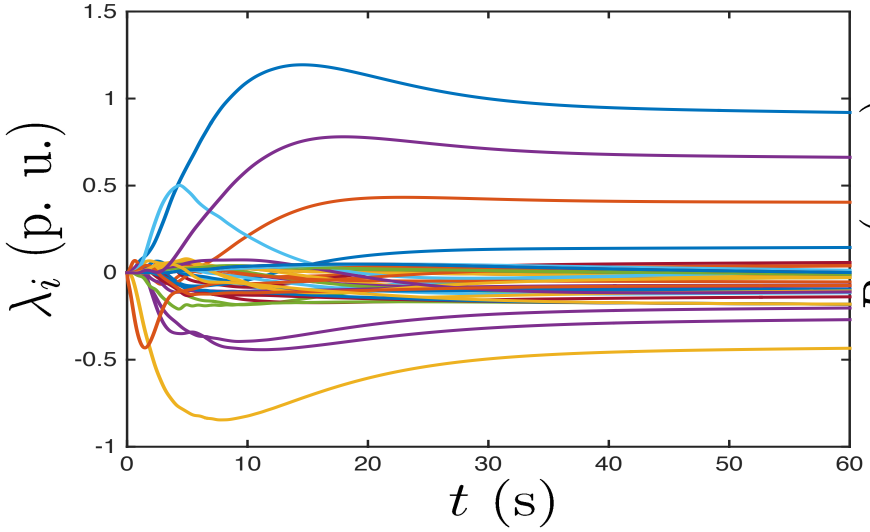


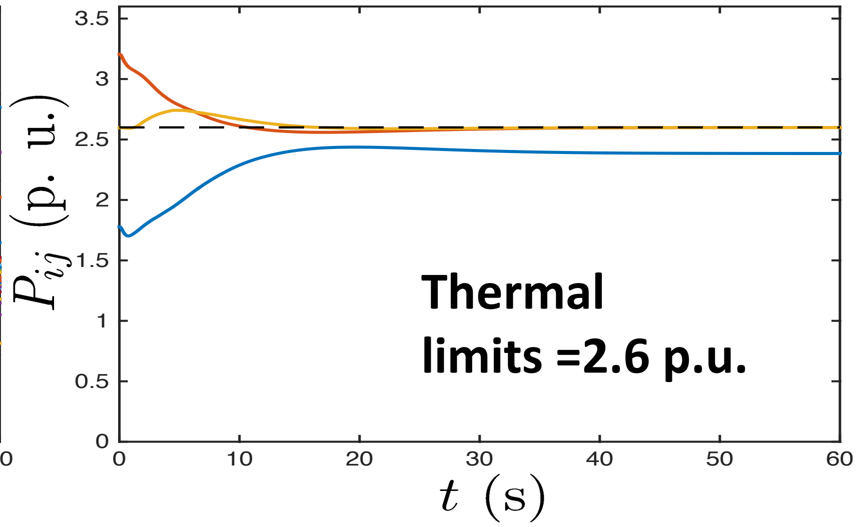




Exogenous input: $\Delta P_i^{net} = -0.5$ p.u.

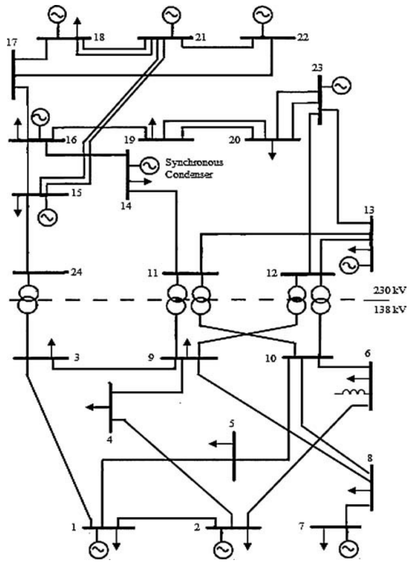
With real-time congestion management





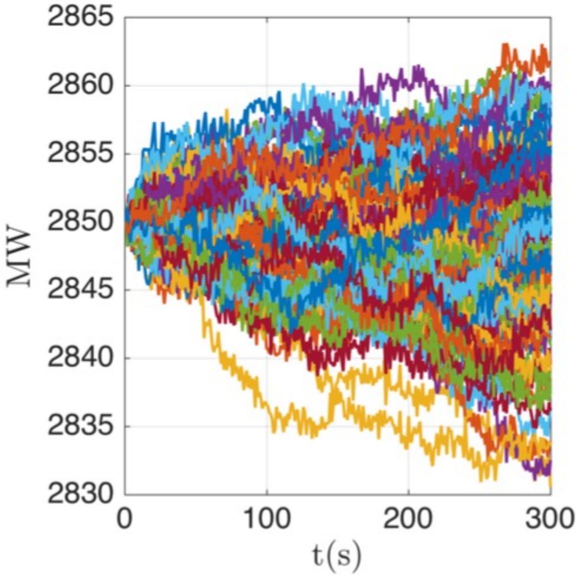
Numerical Evaluation of Savings

IEEE 24 RTS

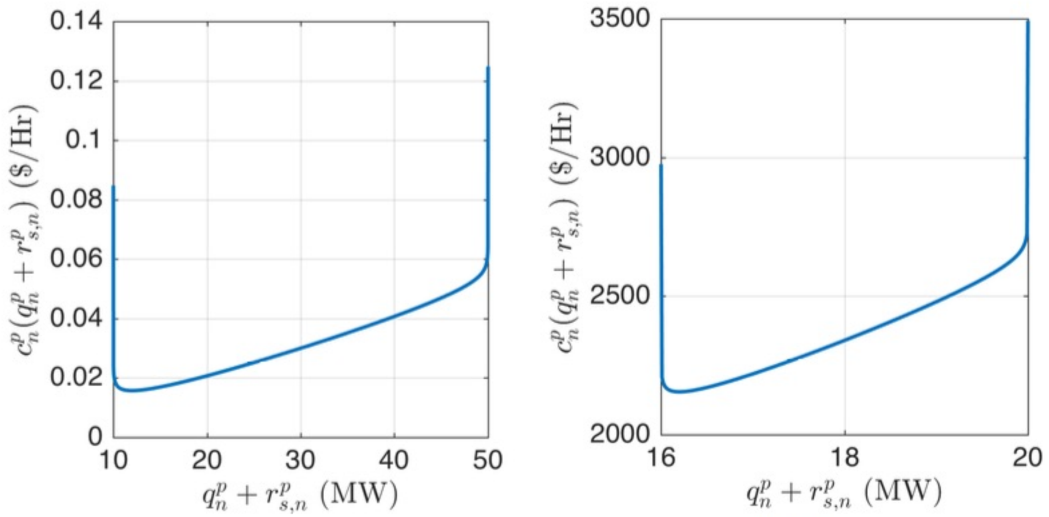


Unit Group	Unit Type	Number	Production Range (MW)	Marginal Cost Range (\$/MWh)	Assignment
U12	Oil/Steam	5	[2.4, 12]	[58.14, 64.446]	Dispatch
U20	Oil/CT	4	[16, 20]	See Fig. 2	Regulation
U50	Hydro	6	[10, 50]	See Fig. 2	Regulation
U76	Coal/Steam	4	[15.2, 76]	[16.511, 18.231]	Dispatch
U100	Oil/Steam	3	[25, 100]	[46.295, 54.196]	Dispatch
U155	Coal/Steam	4	[54.3, 155]	[13.294, 14.974]	Dispatch
U197	Oil/Steam	3	[69, 197]	[49.57, 51.405]	Dispatch
U350	Coal/Steam	1	[140, 350]	[13.22, 15.276]	Dispatch
U400	Nuclear	2	[100, 400]	[4.466, 4.594]	Dispatch

Demand



Cost Regulation



(a) Hydro cost

(c) CT cost

Numerical Evaluation of Savings

Unit Group	Unit Type	Number	Production Range (MW)	Marginal Cost Range ($/MWh)	Assignment
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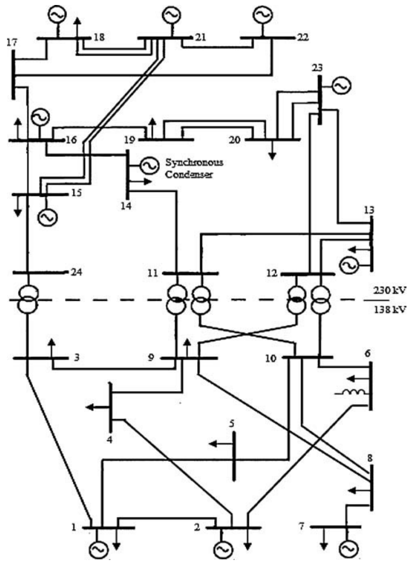
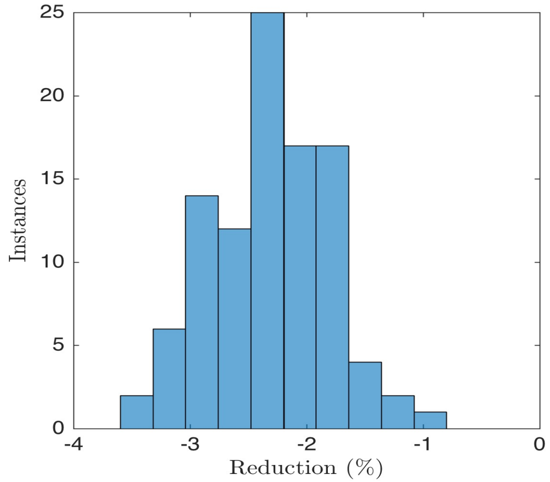
U155	Coal/Steam	4	[54.3, 155]	[13.294, 14.974]	Dispatch
U197	Oil/Steam	3	[69, 197]	[49.57, 51.405]	Dispatch
U350	Coal/Steam	1	[140, 350]	[13.22, 15.276]	Dispatch
U400	Nuclear	2	[100, 400]	[4.466, 4.594]	Dispatch

IEEE 24 RTS

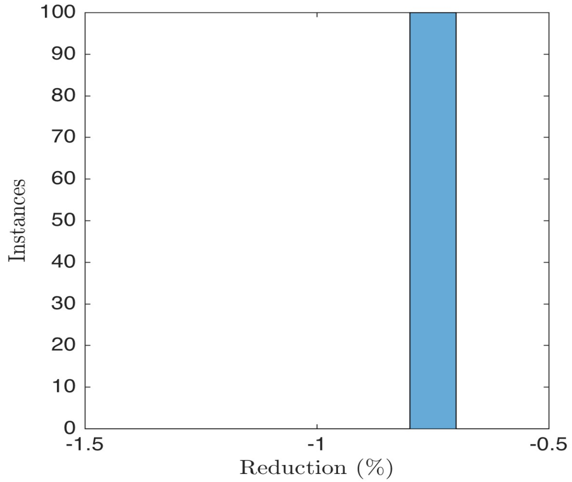


Cost Savings (AGC+ ED vs Our Solution)

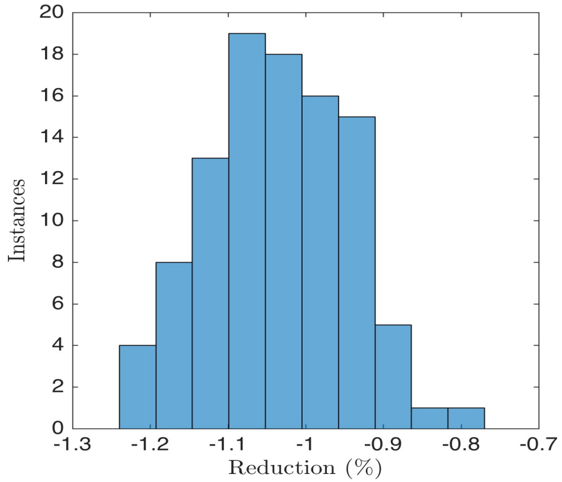
Regulation



Dispatch



Total



Towards Multi-timescale Market Design

- Coupled Incentives in Two-stage Markets

- Co-Optimizing Economic Dispatch and Freq. Regulation

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 behavior matters! It can even beat generators.
    - Virtual bidders benefit from, and limits only, demand market power

- Co-optimization of Economic Dispatch and Frequency Regulation
  - Developed a principled methodology to design co-optimized markets and frequency controllers
  - Real-time congestion management allows for a more flexible use of resources
  - Co-optimized ED and FR can further lead to operational savings

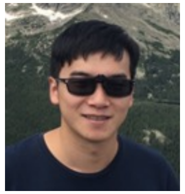
Thanks!

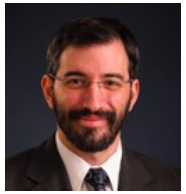
Papers

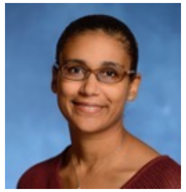
- P. You, M. Fernandez, D. Gayme, E. M., “The Role of Strategic Participants in Two-Stage Settlement Markets,” ***Preprint,*** 2021
- D. Cai, E. M., A. Wierman, “Distributed optimization decomposition for joint economic dispatch and frequency regulation,” **IEEE Transactions on Power Systems**, Mar. 2017.

Other Related Work

- C. Zhao, E. M., S. H. Low, and J. Bialek, "Distributed plug-and-play optimal generator and load control for power system frequency regulation," **International Journal of Electrical Power and Energy Systems**, Oct. 2018
- E. M., C. Zhao, and S. H. Low, “Optimal load-side control for frequency regulation in smart grids,” **IEEE Transactions on Automatic Control**, Jun. 2017.
- P. You, Y. Jiang, E. Yeung, D. Gayme, M, “On the Stability and Economic Efficiency of Electricity Market Dynamics ,” **IEEE TAC, submitted**


Pengcheng You
JOHNS HOPKINS UNIVERSITY


Marcelo Fernandez
JOHNS HOPKINS UNIVERSITY


Dennice Gayme
JOHNS HOPKINS UNIVERSITY

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


Desmond Cai
Institute of High Performance Computing A*STAR


Adam Wierman
Caltech