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Multi-scale Simulation of Energy Systems-Electricity Market Interactions

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INFORMS Annual Meeting, November 10, 2020

AIChE Annual Meeting, November 19, 2020

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Operation of the (US) electric grid

Grid operations incorporate decision-making processes on time scales covering **12 orders of magnitude**

- Individual energy system outcomes (e.g., operational hours, generation levels, and revenue) determined through market interactions
- Multiscale energy **markets drive power system economics**
- IDAES is building and extending capabilities across these time scales

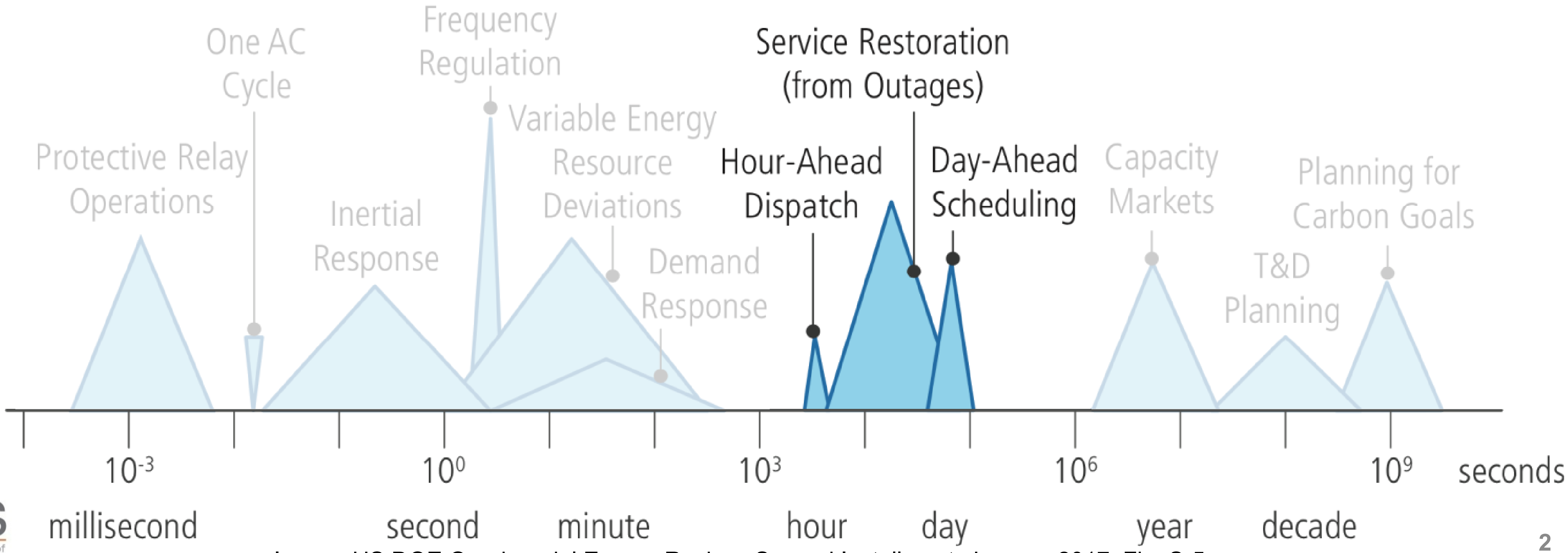

Image: US DOE Quadrennial Energy Review, Second Installment, January 2017, Fig. S-5.

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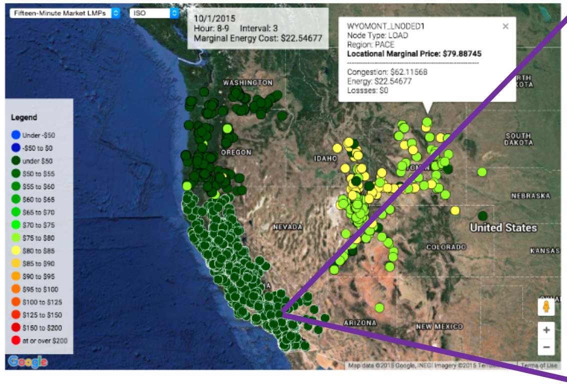
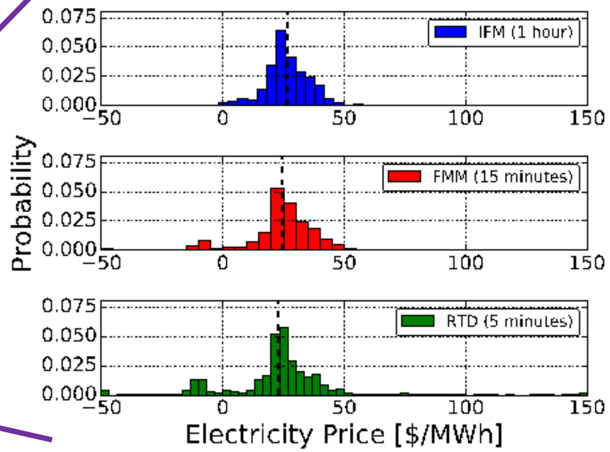
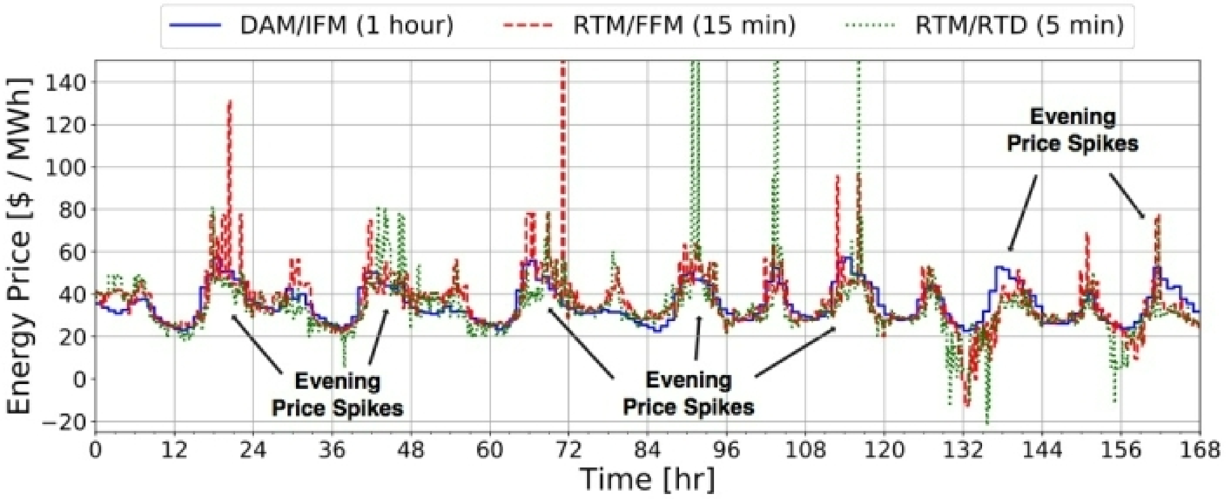
Hierarchical Markets Example: California (CAISO)

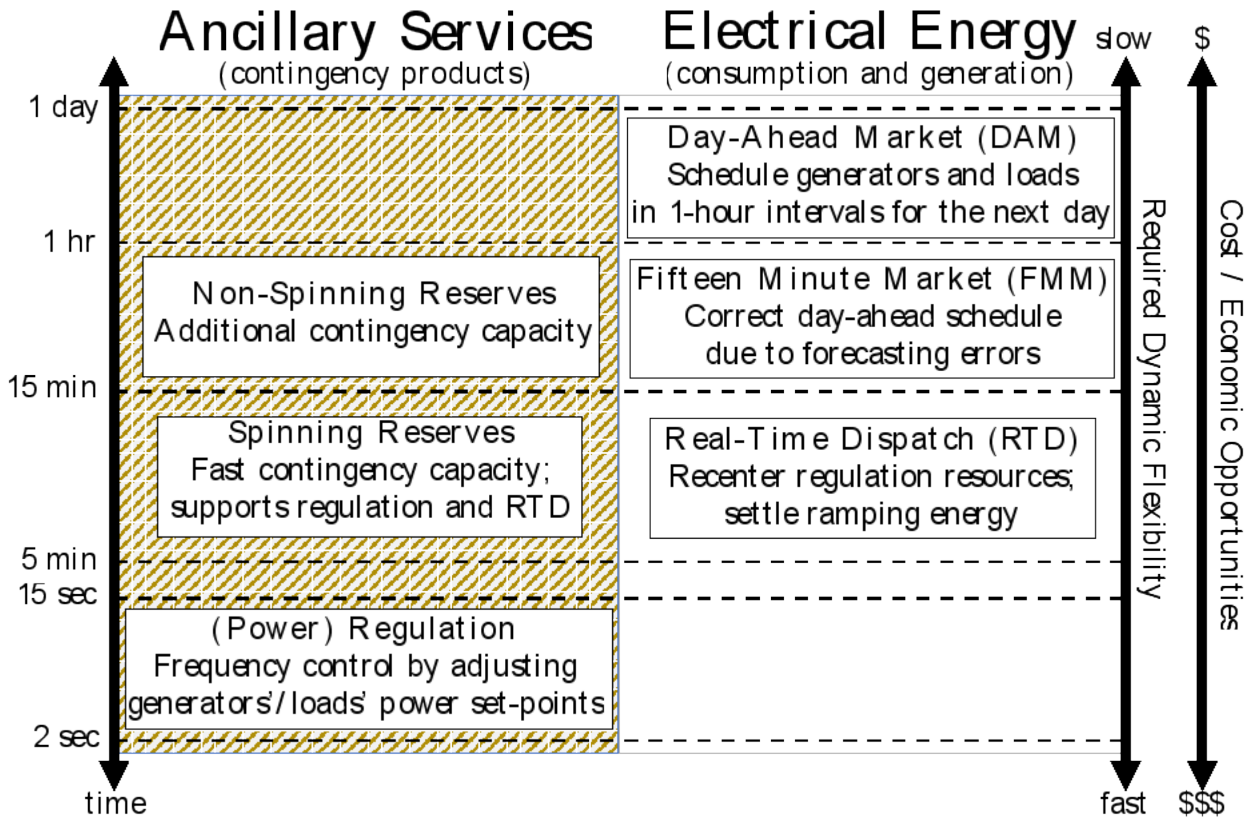
Data from http://oasis.caiso.com



Annual price distribution for 1-3pm







Dowling, Kumar, & Zavala (2017), *Applied Energy*
Dowling & Zavala (2018), *Comp. & Chem. Eng.*

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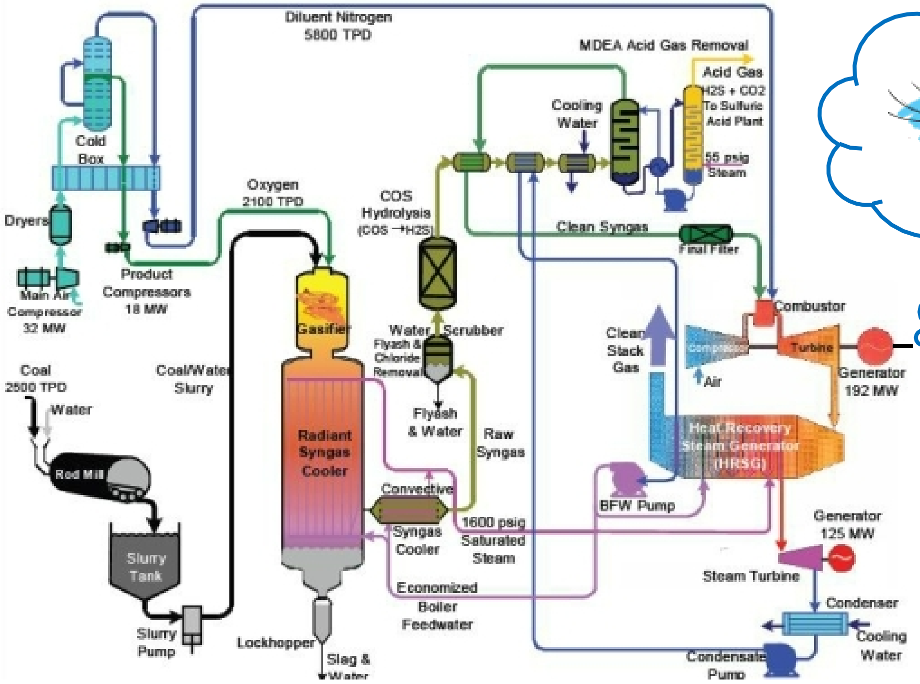
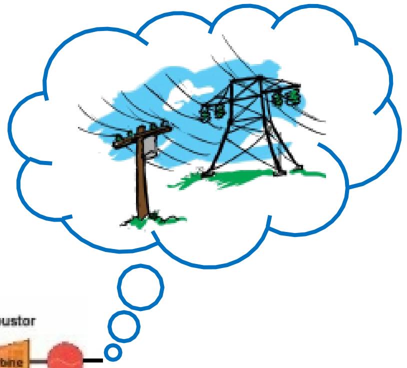
Energy system analysis capabilities are applied in isolation

Process-centric Modeling

Detailed steady state or dynamic process models, with the grid modeled as an infinite capacity bus





https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/igcc-config

Scheduling with Time-Varying Prices (and Uncertainty)

Flour Mills: Ashok & Banerjee (2001), *IEEE Tran. Power Sys.*
Air Separation: Ierapetritou, Wu, Vin, Sweeney, & Chigirinskiy (2002), *IECR*
Multiproduct Plant: Castro, Harjunkoski, & Grossmann (2011), *CACE*
Air Separation: Mitra, Grossmann, Pinto, & Arora (2012), *CACE*
Combined Heat Power Plant: Mitra, Sun, & Grossmann (2013), *Energy*
Air Separation: Zhang, Cremer, Grossmann, Sundaramoorthy, & Pinto (2016), *CACE*

Providing Ancillary Services

Aluminum Smelter: Zhang & Hug (2015), *IEEE PES ISGT*
Air Separation: Zhang, Morari, Grossmann, Sundaramoorthy, & Pinto (2016), *CACE*
Concentrated Solar Plant: Dowling, Tian, and Zavala. RSER 2017.
Redox Flow Battery: Fares, Meyers, and Webber (2014), *Applied Energy*
Aluminum Smelter: Zhang & Hug (2015), *IEEE PES Gen. Meet.*
HVAC: Lin, Barooah, Meyn, & Middelkoop (2015), *IEEE Trans. Smart Grid*
Distillation: Dowling & Zavala (2018), *CACE*

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Energy system analysis capabilities are applied in isolation

Unit Commitment Modeling
Combined Cycle Units: Hua, Huang, Baldick & Chen (2020), *IEEE Trans. Power Syst.*
MIP Formulations: Knueven, Ostrowski & Watson (2020). *INFORMS Journal on Computing*

DC/AC Optimal Power Flow (OPF)
FERC OPF Papers: O'Neill, Castillo, et al. (2012-2013), *FERC*
Relaxation & Approximation: Molzahn & Hiskens (2019), *Now Publishers.*

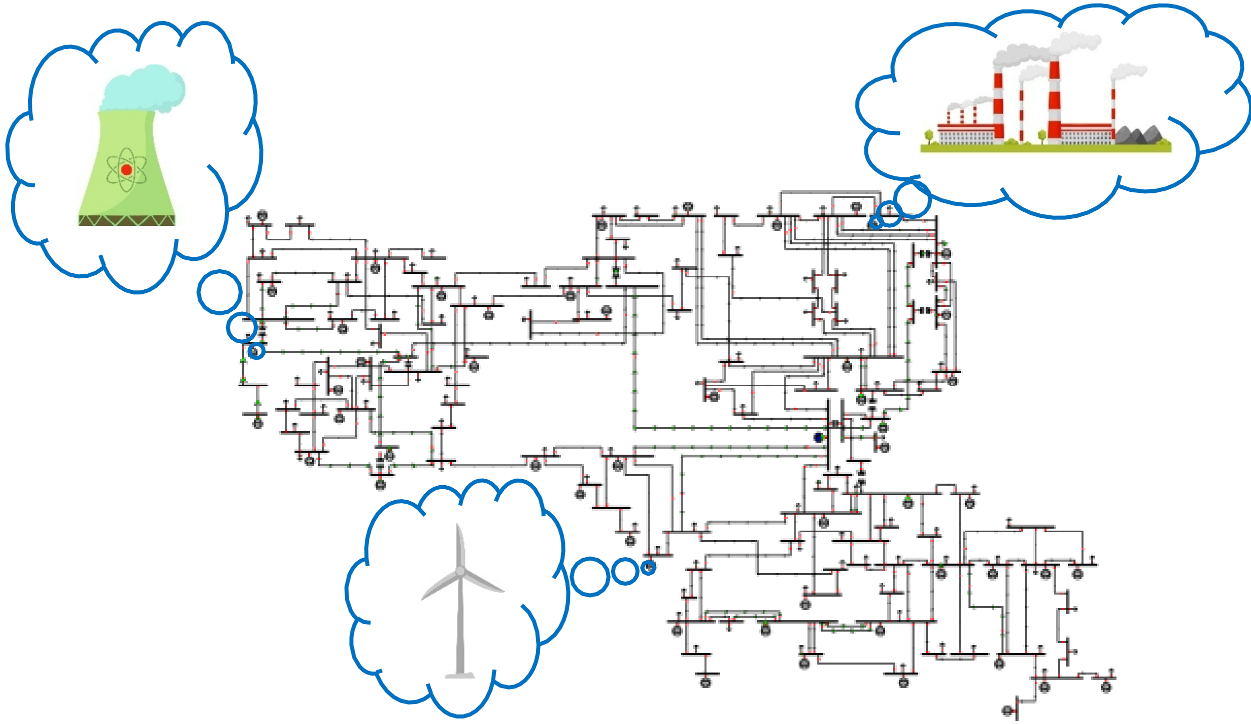
N-1 / T-1 Security Constraints
LODF Calculation: Guo, Fu & Li (2009), *IEEE Trans. Power Syst*.
Constraint Filtering: Xavier, Qiu, Wang & Thimmapuam (2019), *IEEE Trans. Power Syst.*

Enhanced Ancillary Service Products
Flexible Ramp: Wang & Hobbs (2014), *EPRS*
Short-term Reserve: Wang & Chen (2020), *IEEE Trans. Power Syst.*

Stochastic Unit Commitment
Progressive Hedging: Cheung et. al (2015). *Energy Systems*
High Variability Renewables: Rachunok, Staid, Watson, Woodruff & Yang (2018). *PMAPS*

Grid-centric Modeling

Detailed power flow models,
with individual generators modeled as either
dispatchable point sources or stochastic "negative loads"



https://icseg.iti.illinois.edu/files/2013/10/IEEE118.png

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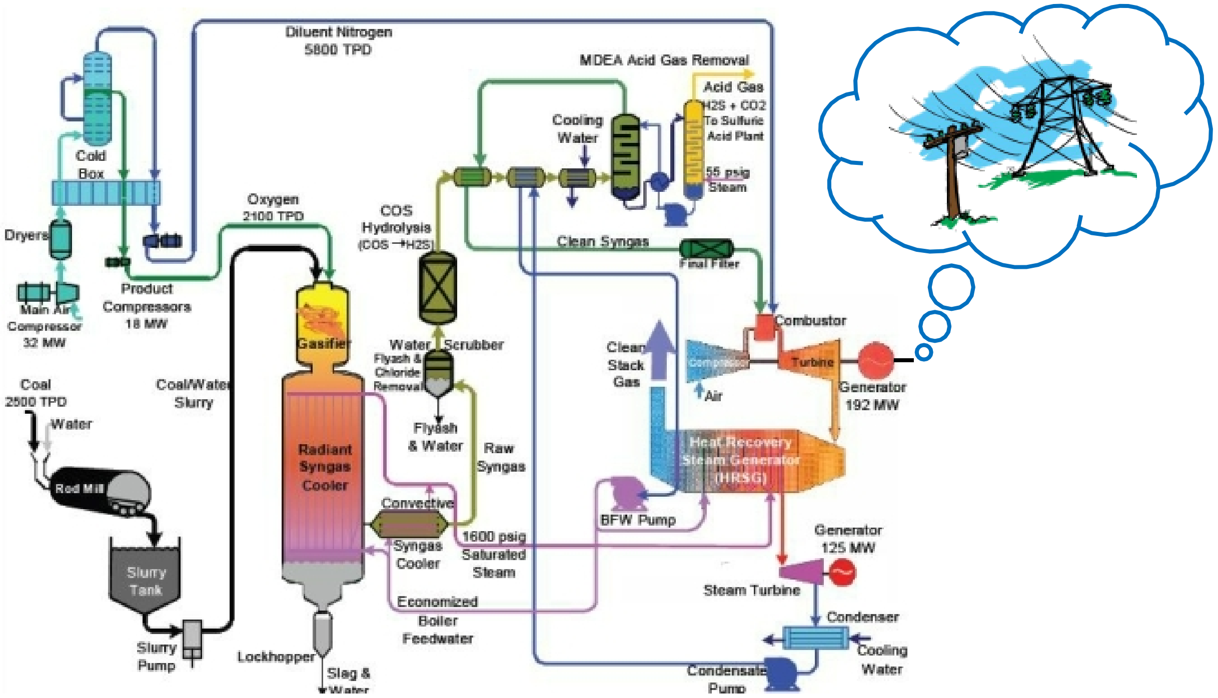
Detailed steady state or dynamic process models, with the grid modeled as an infinite capacity bus



https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/igcc-config

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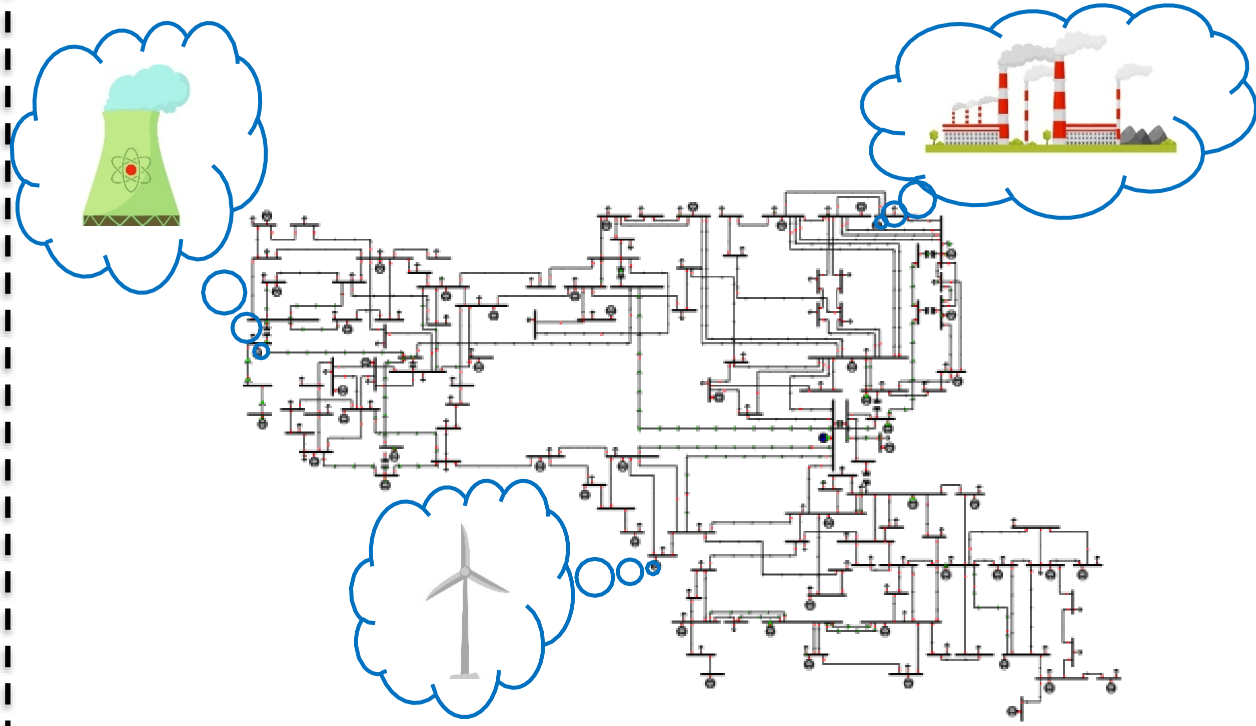

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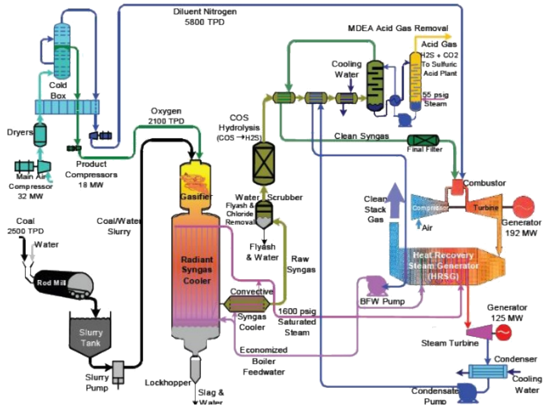
Bridging timescales in IDAES enables unique analyses

High-Fidelity Process Modeling



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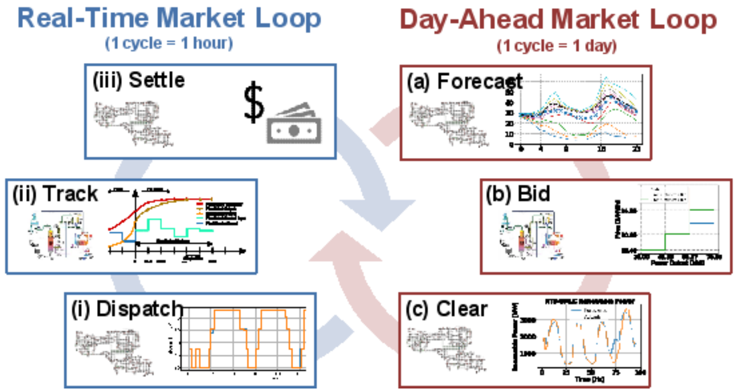
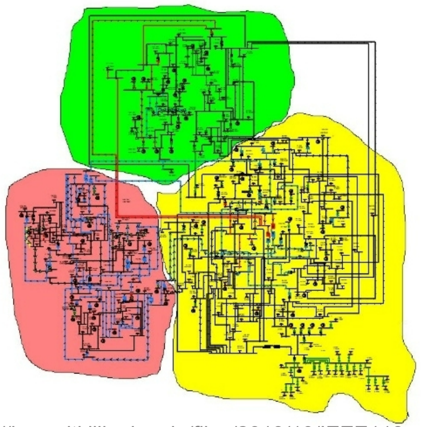
Integrated Resource-Grid Model



Grid Modeling



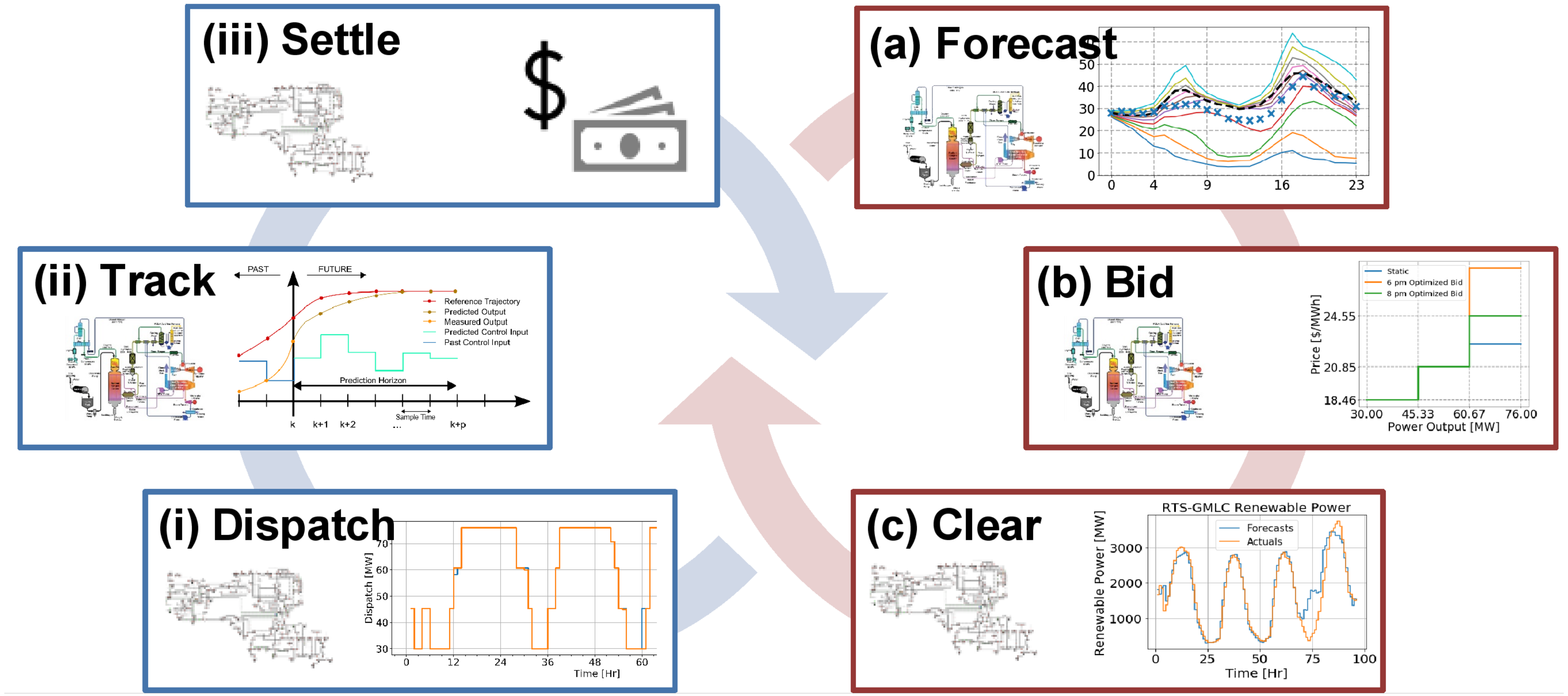
https://icseg.iti.illinois.edu/files/2013/10/IEEE118.png

1. Elucidate complex relationships between resource dynamics and market dispatch (with uncertainty, beyond price-taker assumption)
2. Predict the economic opportunities and market impacts of emerging technologies (e.g., CoalFIRST, tightly-coupled hybrid energy systems)
3. Guide conceptual design & retrofit to meet current and future power grid needs

Modeling multiscale resource and grid decision-making

Real-Time Market Loop
(1 cycle = 1 hour)

Day-Ahead Market Loop
(1 cycle = 1 day)



IDAES integrates detailed process models (b, ii) into the daily (a, c) and hourly (i, iii) grid operations workflows

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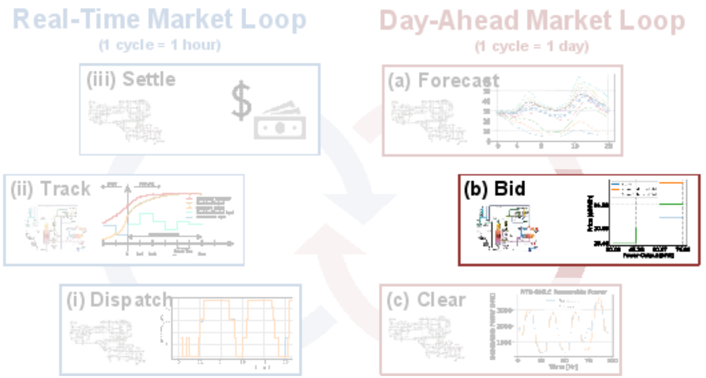
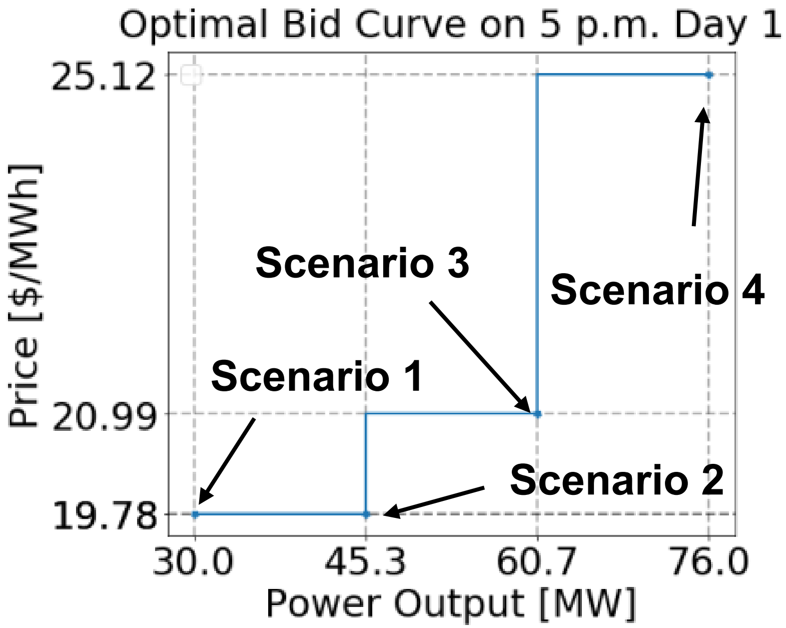
(b) Optimize Bid





Revenue — Costs

$$\max_{z,\ x,\ u,\ y} \quad \mathbb{E}_{\pi_{s,t}} \sum_{t \in \mathcal{T}} \underbrace{\pi_{s,t} u_{s,t}}_{\text{Revenue}} - \underbrace{c(z_{s,t}, u_{s,t}, x_{s,t}, y_{s,t})}_{\text{Costs}}$$

$$\approx \frac{1}{|\mathcal{S}|} \sum_{t \in \mathcal{T}, s \in \mathcal{S}} \pi_{s,t} u_{s,t} - c(z_{s,t}, u_{s,t}, x_{s,t}, y_{s,t})$$

s.t. $Au_{s,t} + By_{s,t} \leq 0$ Market rules, startup/shutdown limits

$$(u_{s,t} - u_{\bar{s},t})(\pi_{s,t} - \pi_{\bar{s},t}) \geq 0, \quad \forall s \in \mathcal{S},\ \bar{s} \in \mathcal{S},\ s \neq \bar{s}$$

$$z_{t+1} = f(z_t, x_t, u_{s,t})$$
$$g(z_{s,t}, x_{s,t}, u_{s,t}) = 0$$

Dynamic or time-indexed steady-state model

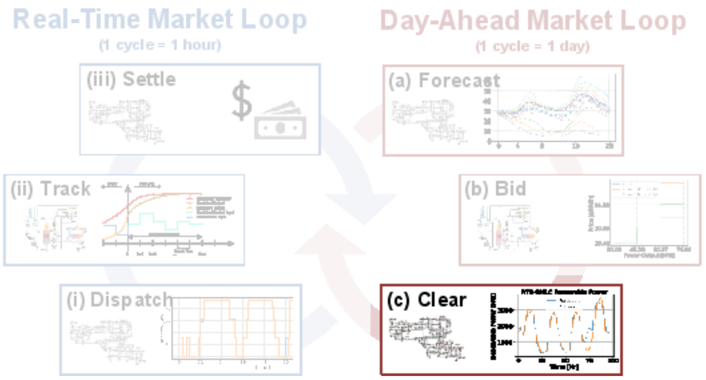
$$\underline{\Delta z} \leq z_{s,t+1} - z_{s,t} \leq \bar{\Delta z}$$
$$\underline{\Delta x} \leq x_{s,t+1} - x_{s,t} \leq \bar{\Delta x}$$
$$\underline{\Delta u} \leq u_{s,t+1} - u_{s,t} \leq \bar{\Delta u}$$

Ramping

$$\underline{z} \leq z_{s,t} \leq \bar{z}$$
$$\underline{x} \leq x_{s,t} \leq \bar{x}$$
$$\underline{u} \leq u_{s,t} \leq \bar{u}$$

Bounds

- s price forecast scenario index
- t time index
- z state variables
- x algebraic variables
- u control variables
- y discrete variables
- π electricity price parameter



(c) Clear Day-Ahead Market

$$\min \sum_{g \in \mathcal{G}} c^g \tag{1}$$

subject to

$$\sum_{g \in \mathcal{G}} (A^g p^g + B^g u^g) = D \tag{2}$$

$$(u^g, p^g, c^g) \in \Pi^g, \ \forall g \in \mathcal{G}. \tag{3}$$

1. Objective function (1) minimizes generation/system operation cost
2. Constraints (2) are the system operating constraints (load satisfaction, transmission thermal limits, reserve requirements, etc.)
3. Constraints (3) are the technical limits/constraints and cost of operation c^g for schedule u^g, p^g, for each generator. Variables u^g are the “commitment” decisions for the generator (generally understood to be discrete) and variables p^g are the “dispatch” decisions for the generator.
4. Prices are computed as the dual values of the system constraints (2) (requires relaxing and/or fixing some discrete decisions).

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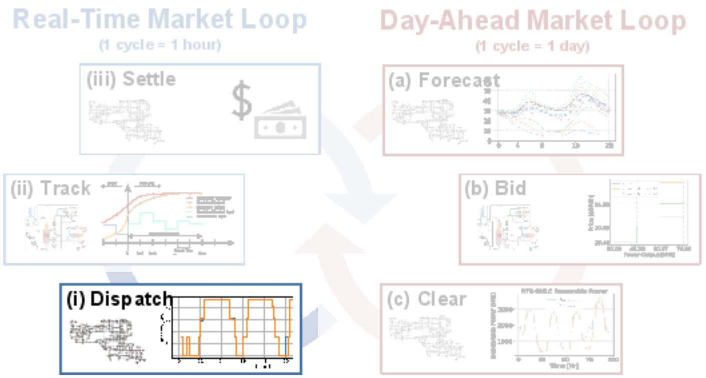

(i) Clear Real-Time Market & Dispatch

$$\min \sum_{g \in \mathcal{G}} c^g \qquad (1)$$

subject to

$$\sum_{g \in \mathcal{G}} (A^g p^g + B^g u^g) = D \qquad (2)$$

$$(u^g, p^g, c^g) \in \Pi^g, \quad \forall g \in \mathcal{G} \qquad (3)$$

$$u^g = \hat{u}^g, \qquad \forall g \in \mathcal{G}. \qquad (4)$$

1. Same basic formulation as Day-Ahead market
2. Time discretization and horizon may be different
3. Data is updated with better forecasts
4. Discrete/commitment decisions are fixed; constraint (4)
5. Real-Time prices are the dual values of constraint (2)

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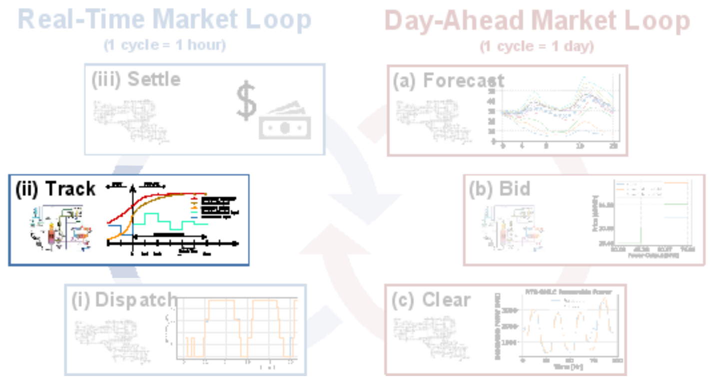
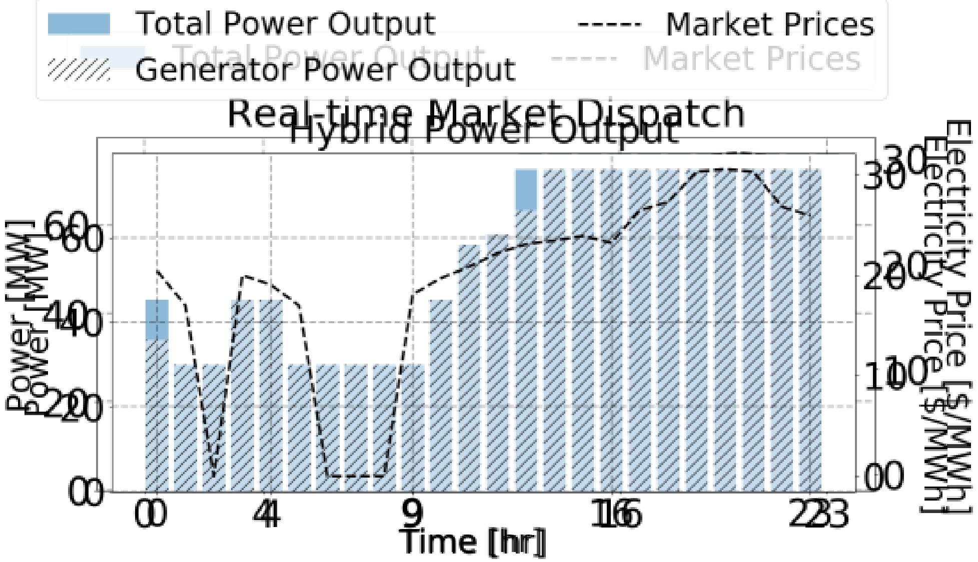
(ii) Track Market Dispatch





Cost — Health — Tracking

$$\min_{z,\ x,\ u,\ y} \quad \sum_{t=0}^{T_f} \underbrace{w_c c(z_t, u_t, x_t, y_t)}_{\text{Cost}} + \underbrace{w_h |u_t - u_{t-1}|}_{\text{Health}} + \underbrace{w_t |u_t - \hat{u}_t|}_{\text{Tracking}}$$

$$\text{s.t.} \quad A u_t + B y_t \leq 0$$

Dynamic or time-indexed steady-state model:

$$z_{t+1} = f(z_t, x_t, u_t)$$
$$g(z_t, x_t, u_t) = 0$$

Ramping:

$$\underline{\Delta z} \leq z_{t+1} - z_t \leq \bar{\Delta z}$$
$$\underline{\Delta x} \leq x_{t+1} - x_t \leq \bar{\Delta x}$$
$$\underline{\Delta u} \leq u_{t+1} - u_t \leq \bar{\Delta u}$$

Bounds:

$$\underline{z} \leq z_t \leq \bar{z}$$
$$\underline{x} \leq x_t \leq \bar{x}$$
$$\underline{u} \leq u_t \leq \bar{u}$$

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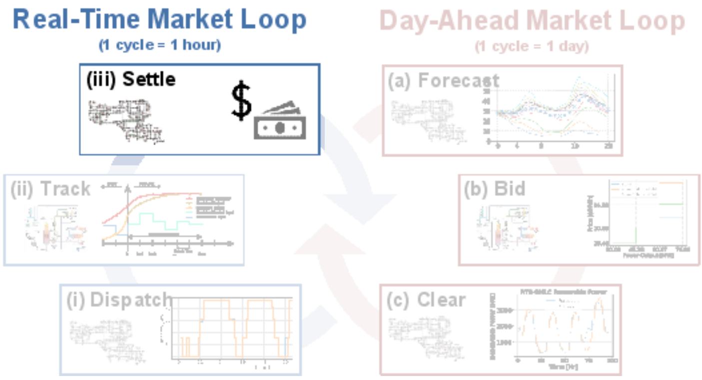


(iii) Settle

$$m_g^e = \sum_t (\Delta t)\pi_t^{DA} p_{g,t}^{DA} + \sum_t (\Delta t)\pi_t^{RT}(p_{g,t}^{RT} - p_{g,t}^{DA})$$

$$m_g^r = \sum_t (\Delta t)\rho_t^{DA} r_{g,t}^{DA} + \sum_t (\Delta t)\rho_t^{RT}(r_{g,t}^{RT} - r_{g,t}^{DA})$$

$$m_g = m_g^e + m_g^r$$

Day-ahead energy price / dispatch: π_t^{DA}, $p_{g,t}^{DA}$

Real-time energy price / dispatch: π_t^{RT}, $p_{g,t}^{RT}$

Day-ahead reserve price / dispatch: ρ_t^{DA}, $r_{g,t}^{DA}$

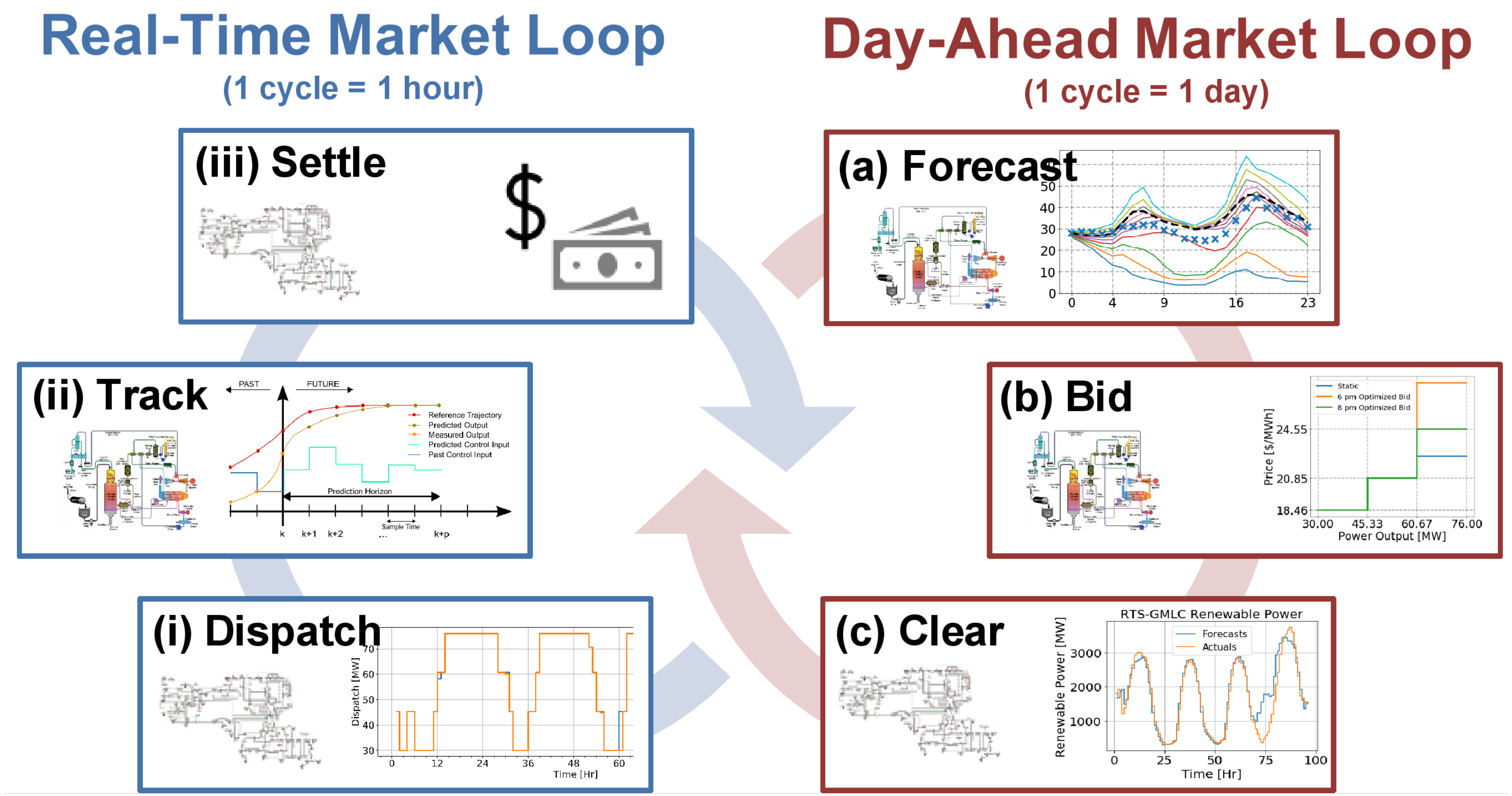
Real-time reserve price / dispatch: ρ_t^{RT}, $r_{g,t}^{RT}$

Market revenue: m_g

Market cost (bid): c_g

Total Profit: $\max\{m_g - c_g, 0\}$

Modeling multiscale resource and grid decision-making



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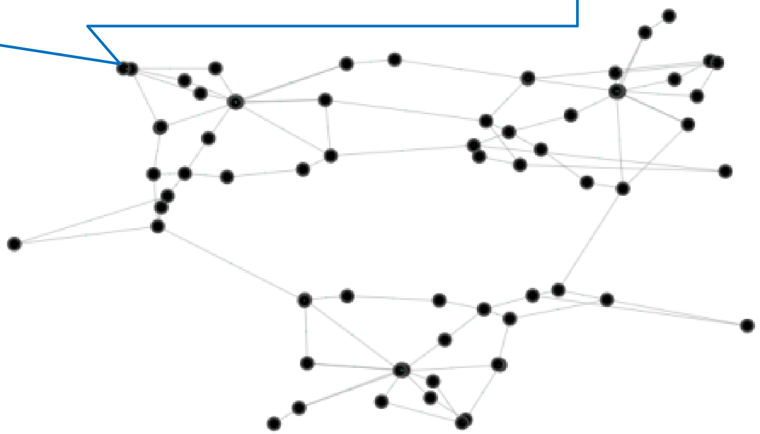
Case study: optimize a single generator's bidding strategy

- Take a single generator in the RTS-GMLC test case and allow it to optimize its bid curves throughout the day.
  - Evaluate over a 4-day simulation period

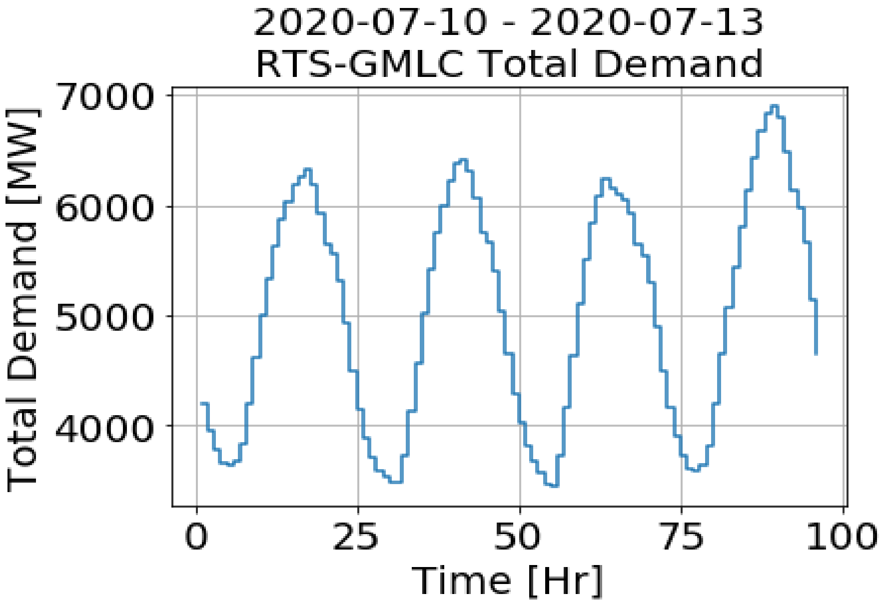
"Bus 102 Steam 3" Generator

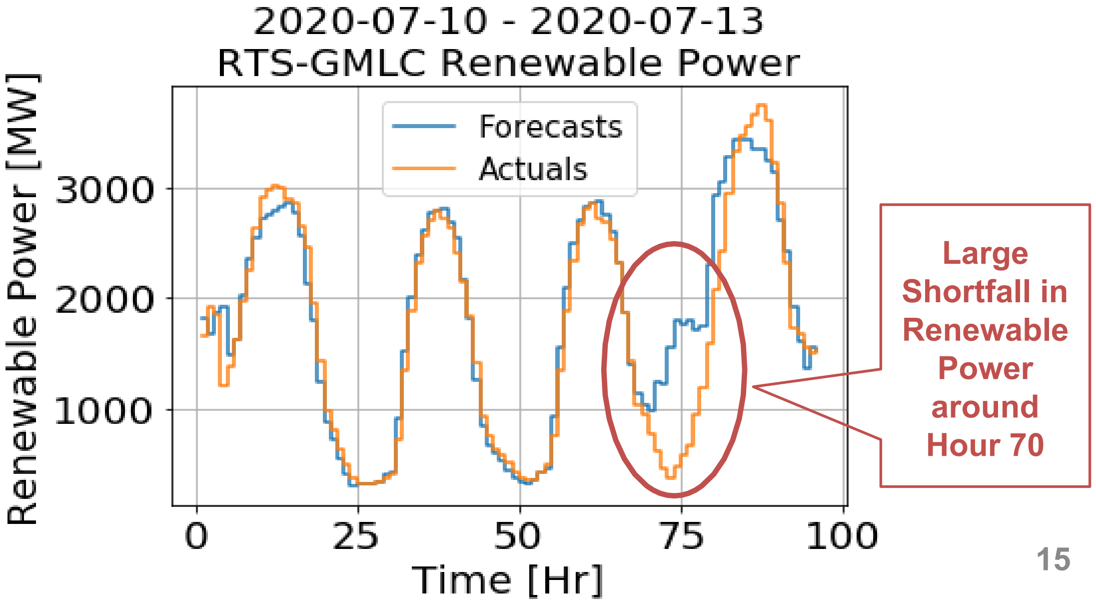
76 MW
32.6% efficient (full capacity)



RTS-GMLC Test System
158 generators (42% dispatchable)
14,550 MW capacity (54% dispatchable)

Data: RTS-GMLC, https://github.com/GridMod/RTS-GMLC





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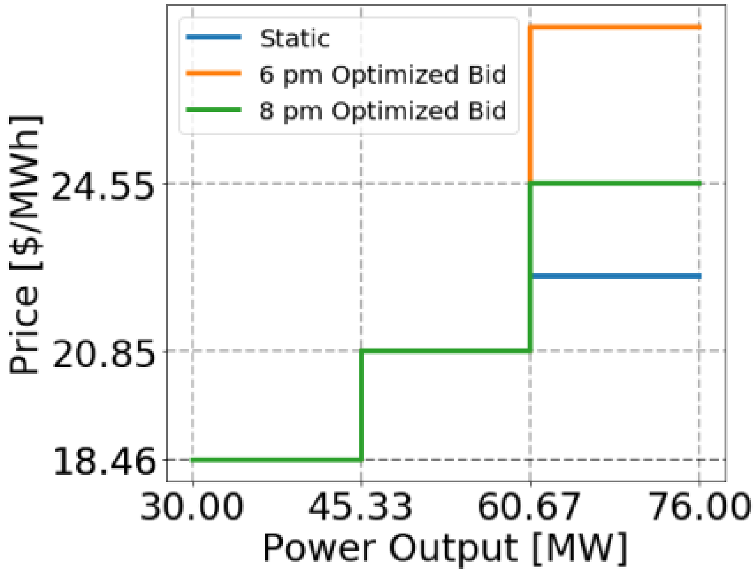
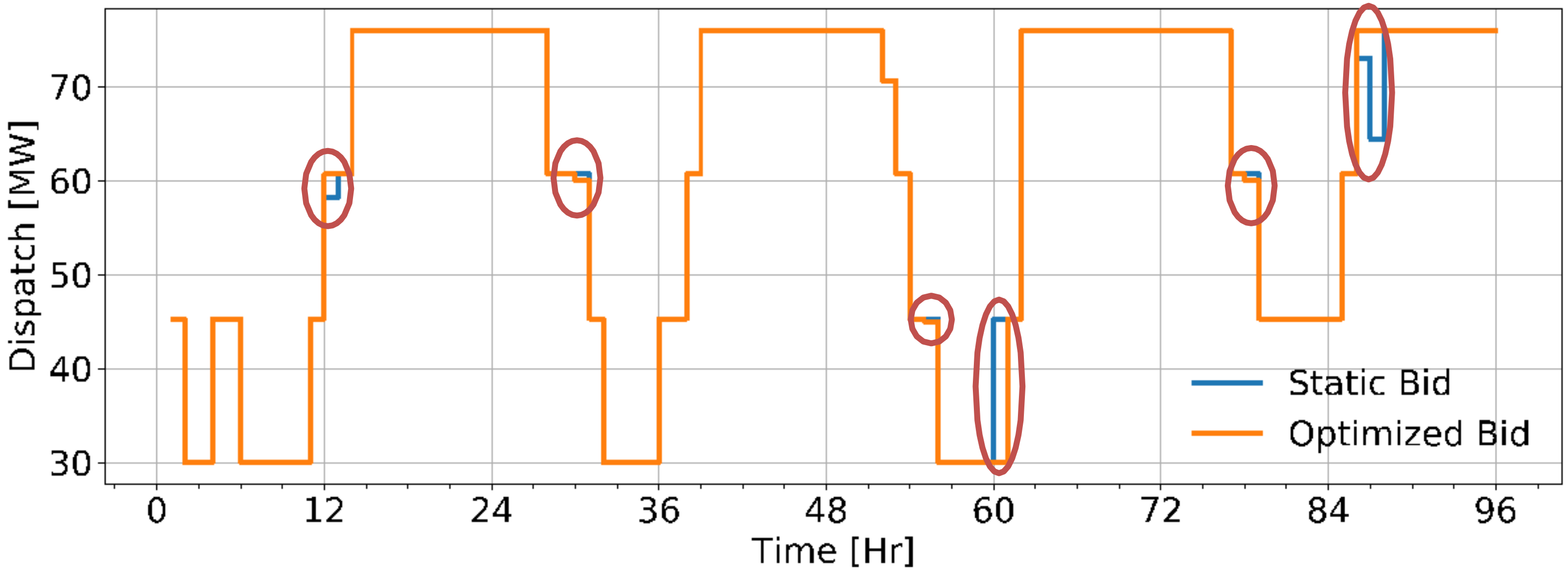
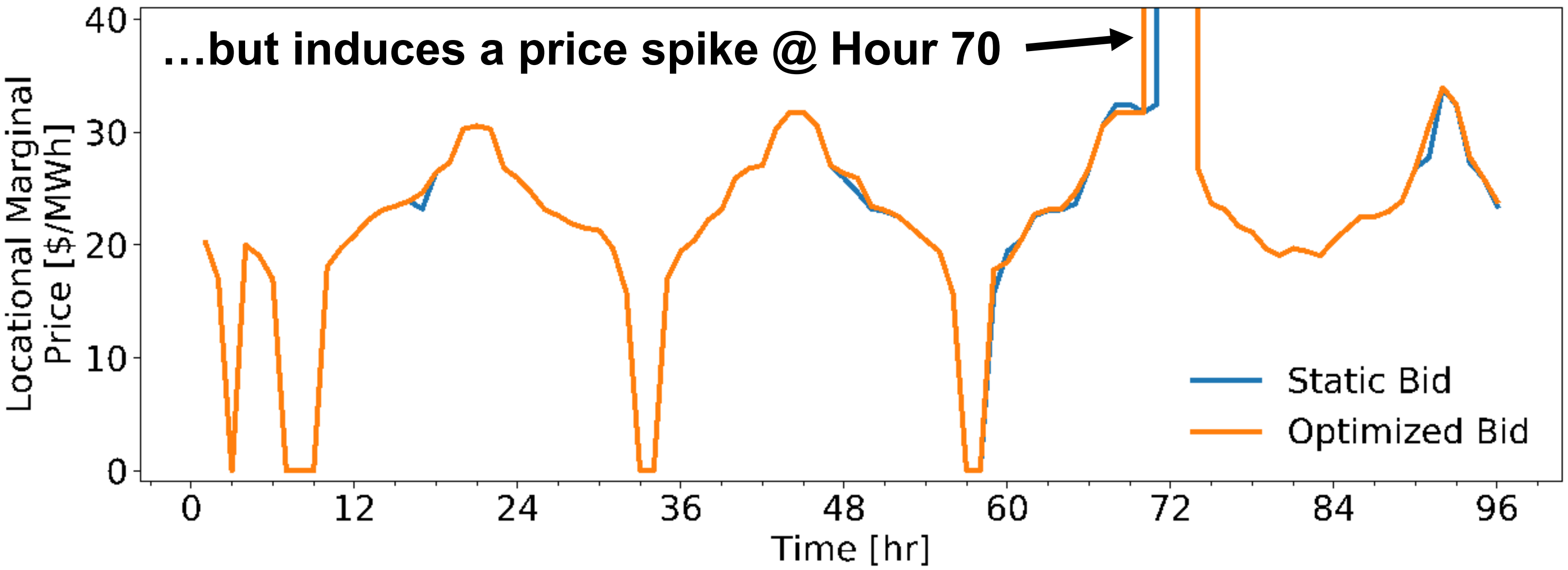
"Bus 102 Steam 3" dispatch without reserves

Optimizing the bid curves for "Bus 102 Steam 3" generator causes only minor changes in its market dispatch schedule…







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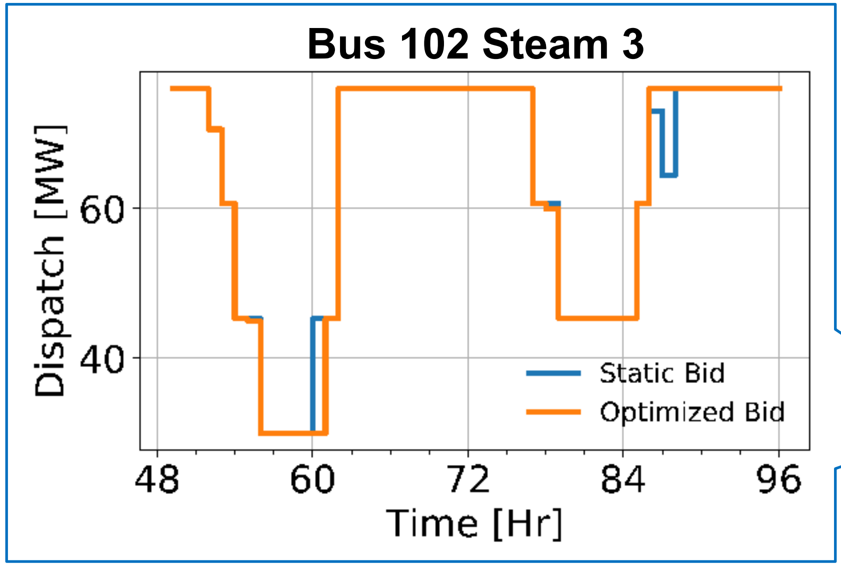
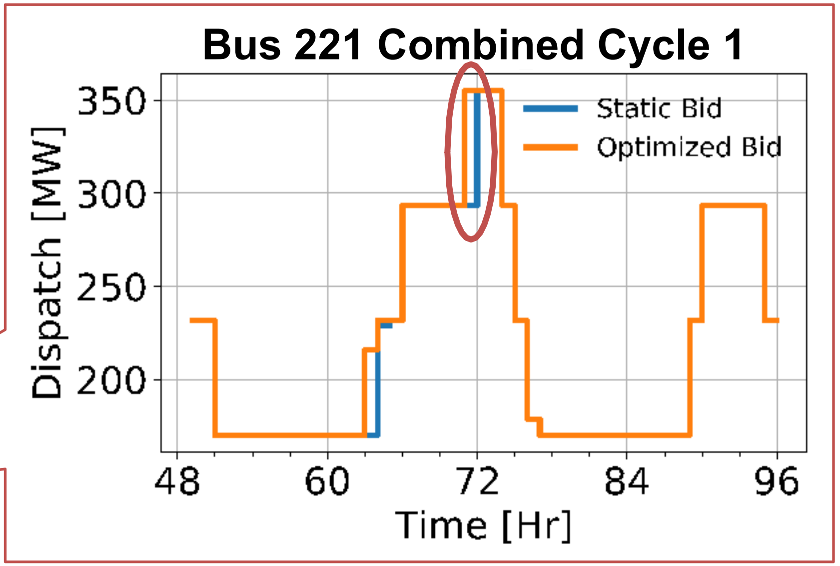
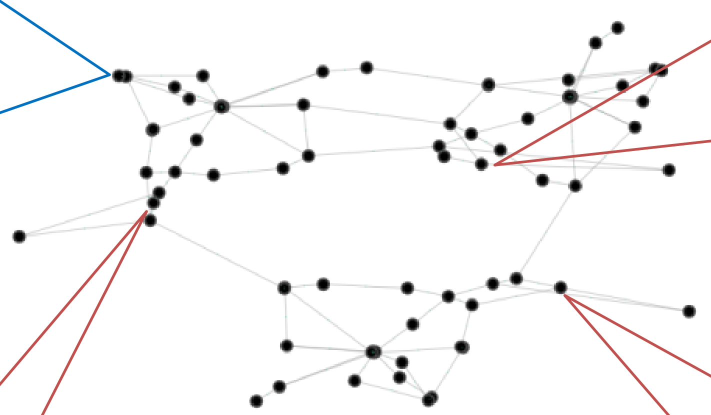
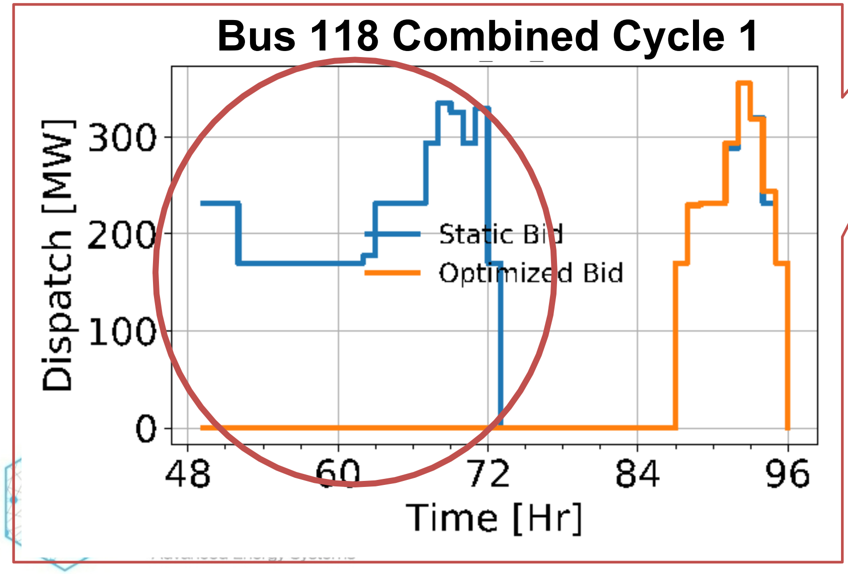
What causes the price spike @ Hour 70 with optimized bids?



There is a shortfall at Hour 70 (not enough generation) causing the price spike.

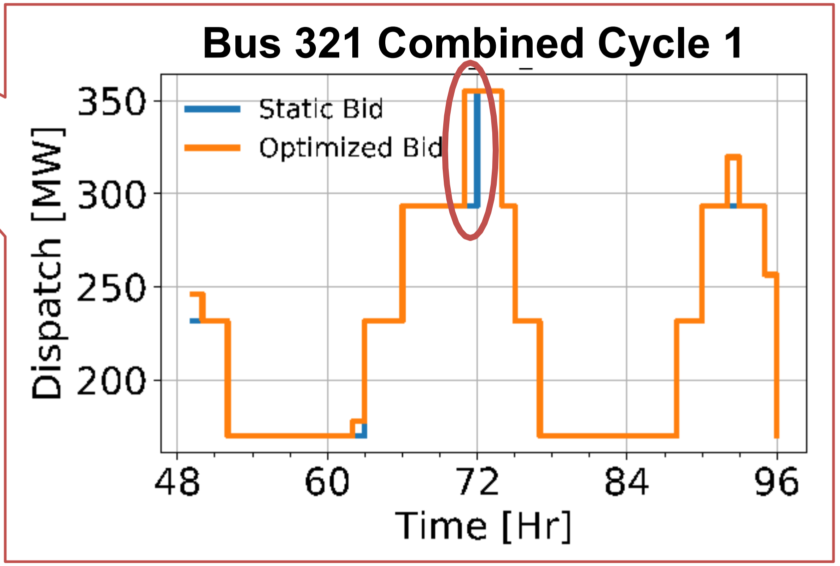






Effects ripple through grid:

- Combined Cycle 1 plant at Bus 118 is OFF in Day 3.
- Combined Cycle plants at busses 221 and 321 are dispatched at 100%.



Take Away Message

A small change in the bid for a target thermal generator (Bus 102 Steam 3) only slightly changes its dispatch schedule, but **induces significant impacts on the entire network**, including unit commitment and market price changes.

Design and analysis of emerging flexible energy systems with dynamic operation must capture interactions with the balance of the grid in order to accurately capture economic impacts and rewards.

IDAES *enables* unique integrated multiscale analysis and the elucidation of the complex interactions among individual generators through the electric grid markets.

Qualification:

These conclusions are based on a specific simulation using RTS-GMLC, a DOE/GMI developed synthetic test case. RTS-GMLC is NOT intended to be a simulation of a real grid in the U.S. and is known to have specific features that are not necessarily shared by actual grid systems.

Open-source grid modeling packages: https://github.com/grid-parity-exchange/Prescient
https://github.com/GridMod/RTS-GMLC

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- **University of Notre Dame**: Alexander Dowling, Xian Gao