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Institute for the Design of Advanced Energy Systems

Grid and Market Integration via Multi-Scale Approaches

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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 generator 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

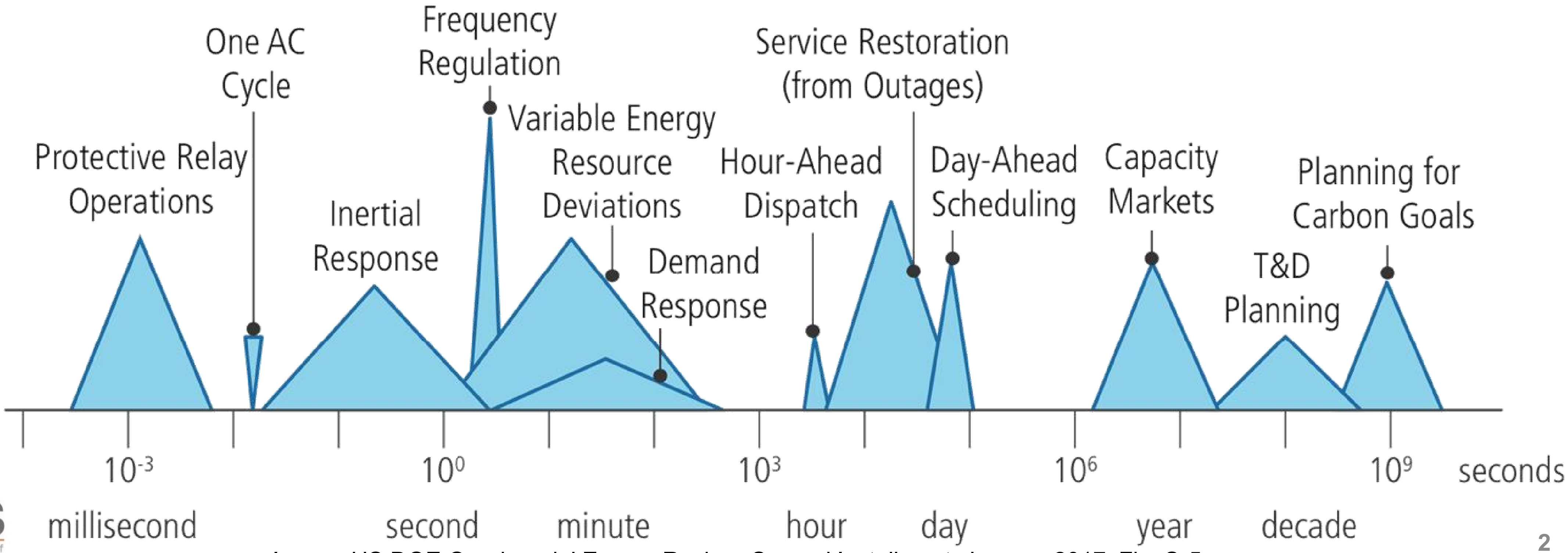
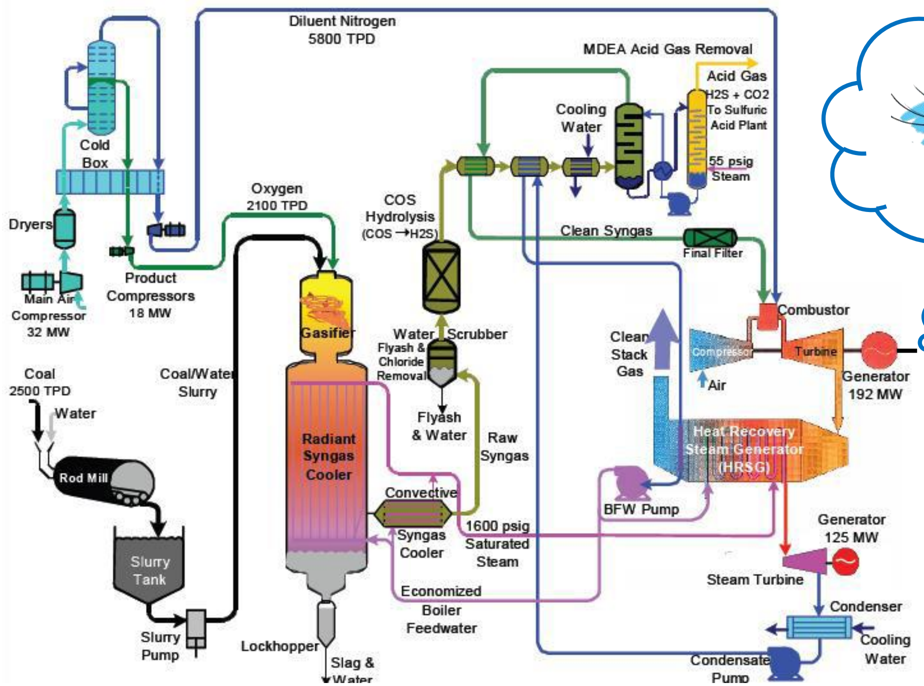


Image: US DOE Quadrennial Energy Review, Second Installment, January 2017, Fig. S-5.

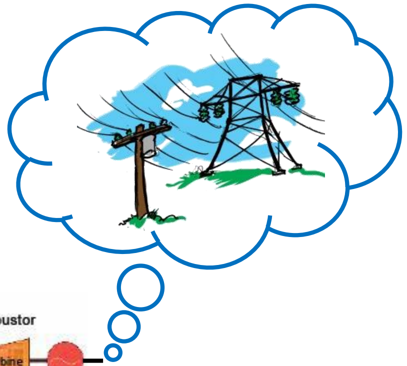
Energy system analysis capabilities are applied in isolation

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 Modelling
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.*

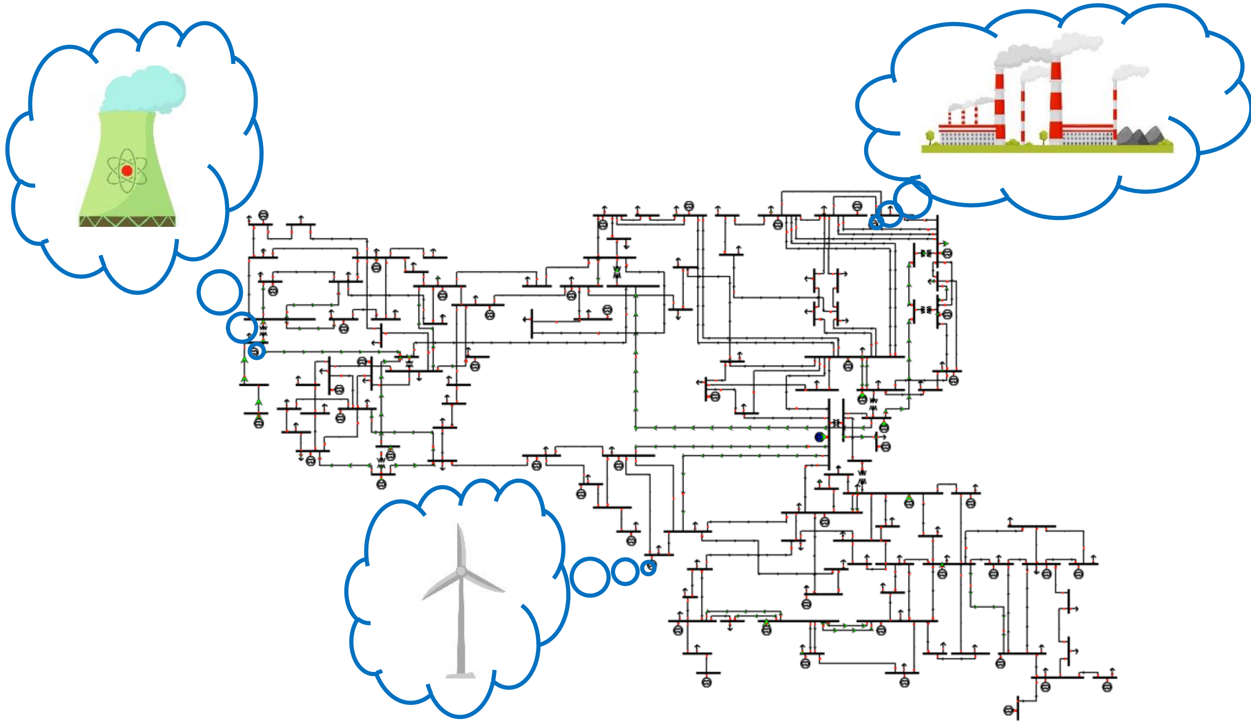
Enhanced Ancillary Service Products
Flexible Ramp: Wang & Hobbs (2014), *EPRS*
Short-term Reserve: Wang & Chen (2020), *IEEE Trans. Power Syst.*

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

Expansion Planning
Low-Carbon Scenarios: Boffino et al (2019), *Energy Economics*.
With Energy Storage: Shahmohammadi et al (2018), *Energy Convers. Manag.*
Electricity-Gas Systems: Guelpa et al (2019), *Energy*.

Grid-centric Modeling

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



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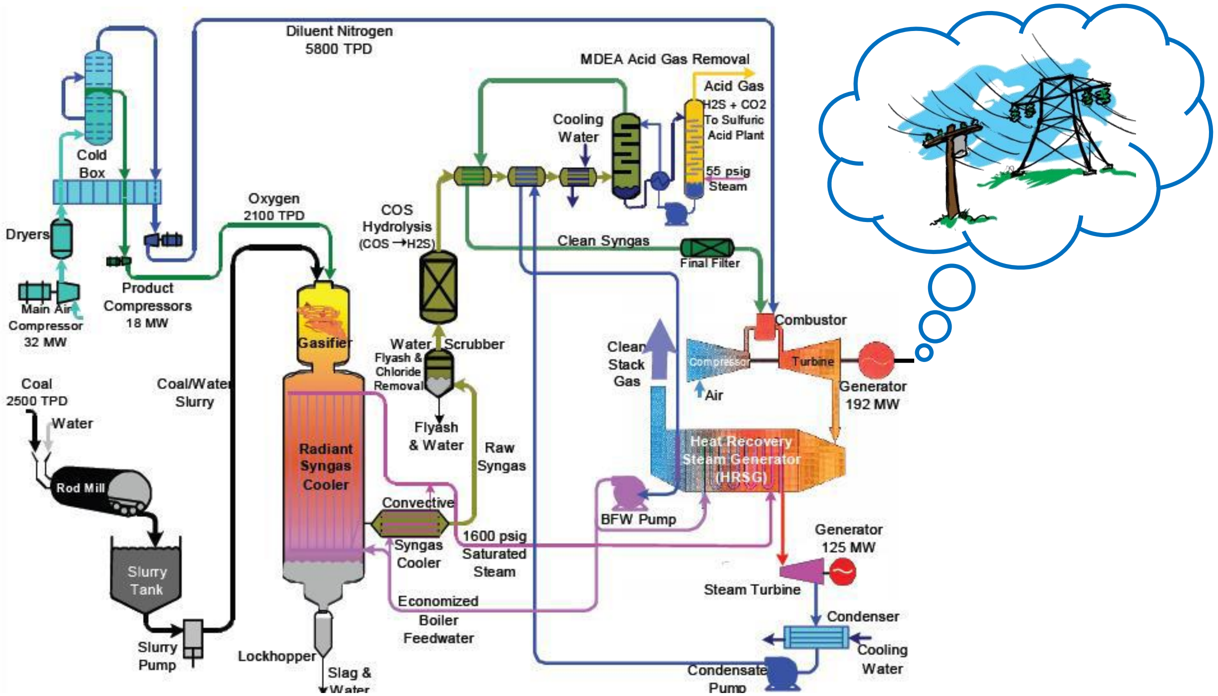

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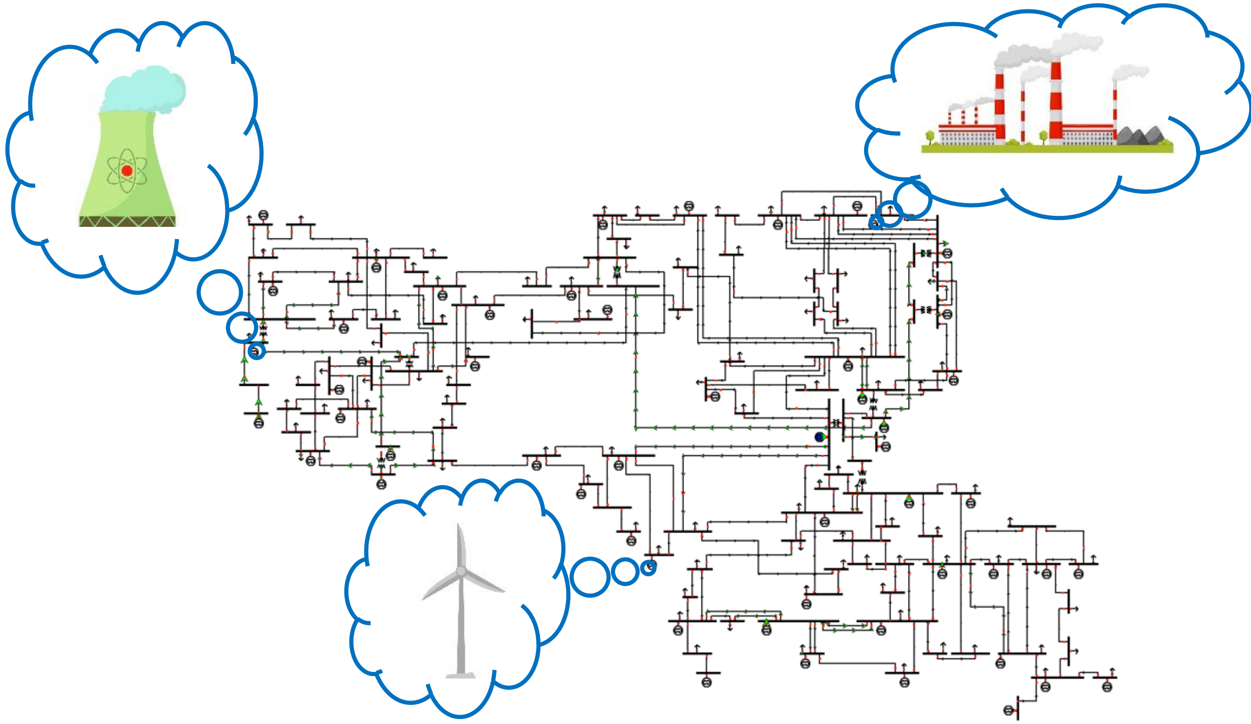

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IDAES is creating a new integrated modeling paradigm

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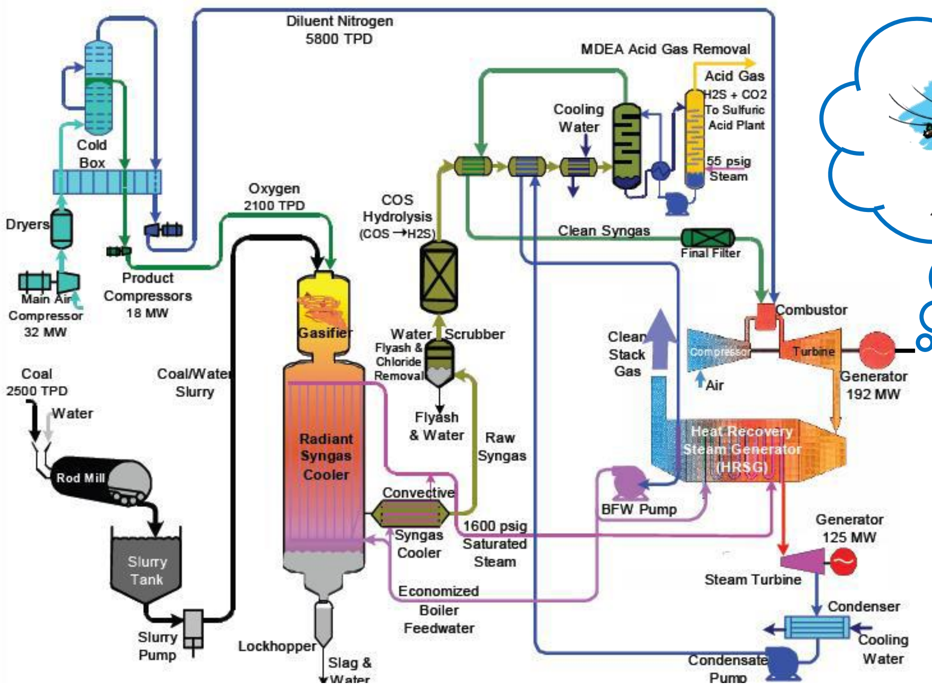

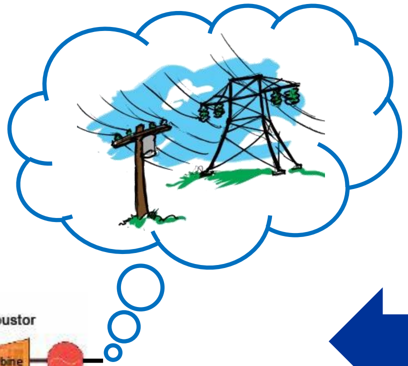

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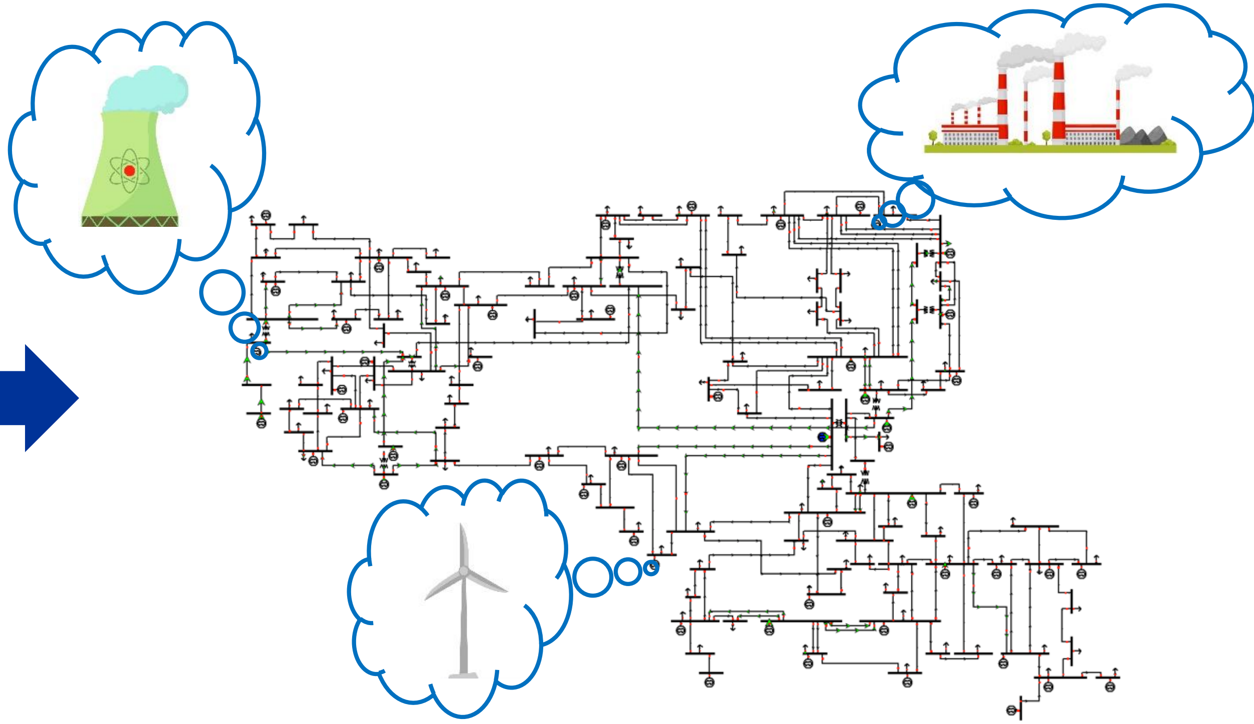

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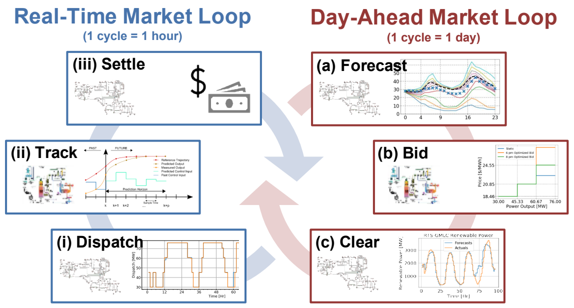
2020 IDAES Integrated Grid Modeling Accomplishments

- New algorithmic development
  - Custom Benders decomposition
    - Reduced memory requirements by ~60% and improved solution time by ~50%

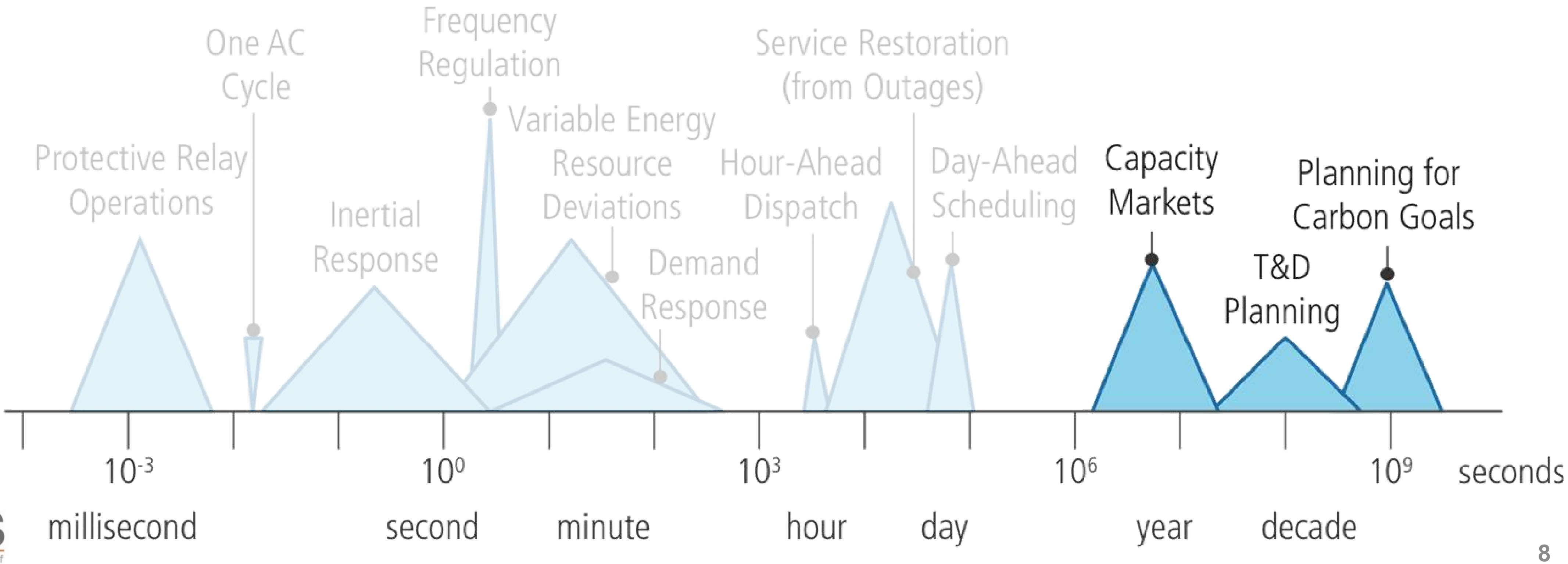
- Expansion planning case studies
  - Developed new case study based on Southwest Power Pool
    - ~30x larger that ERCOT case study (~3x generators, regions, and transmission lines)
  - Integrated generation and transmission expansion planning model
    - Highlighted the interplay between technology selection and transmission limits (ERCOT)
  - Modeling endogenous uncertainty of cost of new technologies
    - Demonstrated the value of new technology investment to resolve cost uncertainties
  - Evaluating the use of "representative days"
    - Indication that "representative days" can undervalue generation flexibility

- Integrated process and grid operations
  - Prototyped “double loop” integration simulation strategy
    - Anecdotal evidence suggests price-taker assumptions may not be valid



Part 1: Expansion planning

- Ultimate success for new generation technologies is marketplace adoption
- Over **multi-decade planning horizons**,
  - What technologies / designs are selected for installation (and where)?
  - What facilities are renewed, retired, or phased out?



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Challenges in expansion planning: fidelity and scalability

- Expansion planning models are very large
  - 30+ year horizons, 1000's of possible investment decisions per year
  - Models rely on various levels of aggregation to manage the problem size
    - Generator, location aggregation
    - Temporal aggregation (e.g., Levelized Cost of Electricity [LCOE])

- Dynamics play an increasing role in future grid operations
  - Managing non-dispatchable resources
  - Revenue from temporal demand, price fluctuations
    - Congestion pricing, ancillary services, demand response, storage opportunities
  - *Must* include spatial / temporal analysis to capture interplay among net load fluctuations, generator dynamics, and network congestion
    - LCOE cannot capture actual costs / revenues

- Uncertainty is ubiquitous throughout the problem
  - Uncertain future demands, fuel prices, regulatory policies
  - Investment-dependent (endogenous) uncertainties
    - e.g., new technology costs, learning curves

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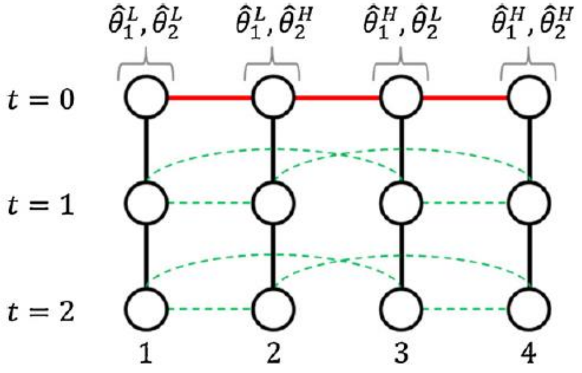
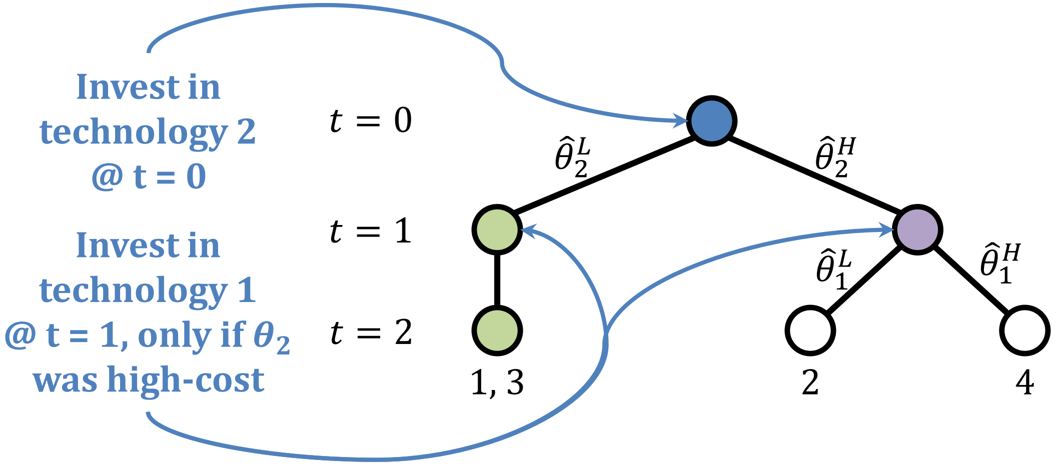
Understanding the impact of new technology risk

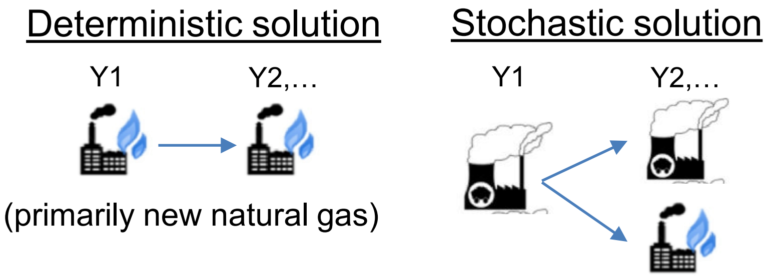
- Costs for new technologies are highly uncertain
  - …and are only truly known after the first unit(s) are installed: *endogenous uncertainty*
  - "shape" of the scenario tree depends on *when* investments are made

Scenario tree for two technologies {1, 2} that each could have a high (H) or low (L) cost that is only realized after installation

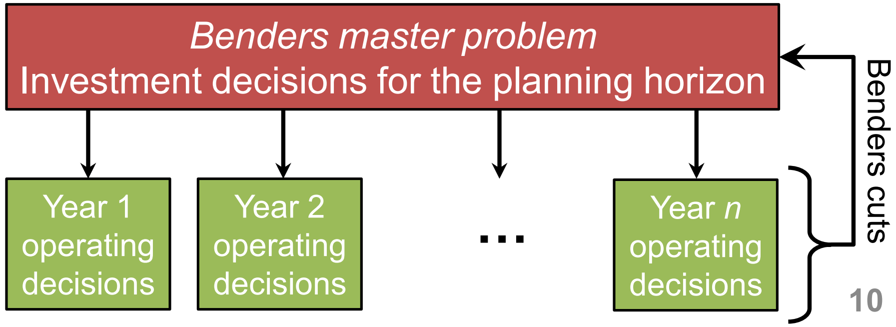




- Initial exploration with ERCOT case study
  - Impact of uncertainty in the cost of a hypothetical coal technology
  - Value of stochastic solution: ~$3.5 trillion over 5 years (vs deterministic model)



(if initial coal plant is low cost, then future plants are additional coal; otherwise they are natural gas)



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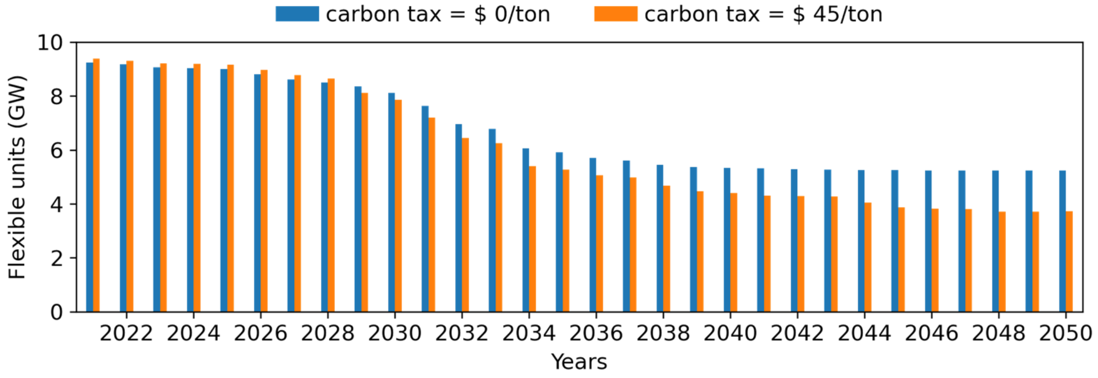
Quantifying the impact of flexibility

- Expansion planning with SPP case study
  - Results indicated significant reduction of installed flexible generation
    - Gas turbine, internal combustion turbine units
    - Lower efficiency, higher relative emissions
  - *Counter-intuitive result*



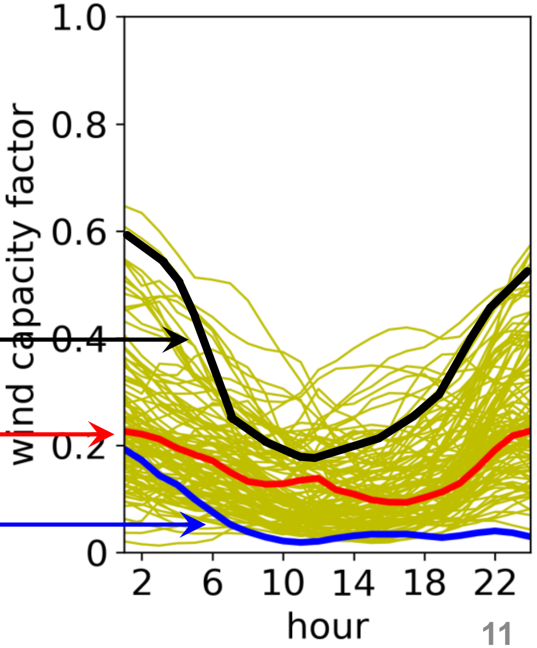
- Root cause: "representative" days did not capture
  - High ramp rates (volatility)
  - Low non-dispatchable generation (intermittency)

- Ongoing work
  - Augment representative days to include lower frequency scenarios
    - Capture intermittency and volatility
  - Inclusion of "n-1" reliability constraints

Scenario with high ramp rates (volatility)

Representative day

Scenario with low generation levels (intermittency)



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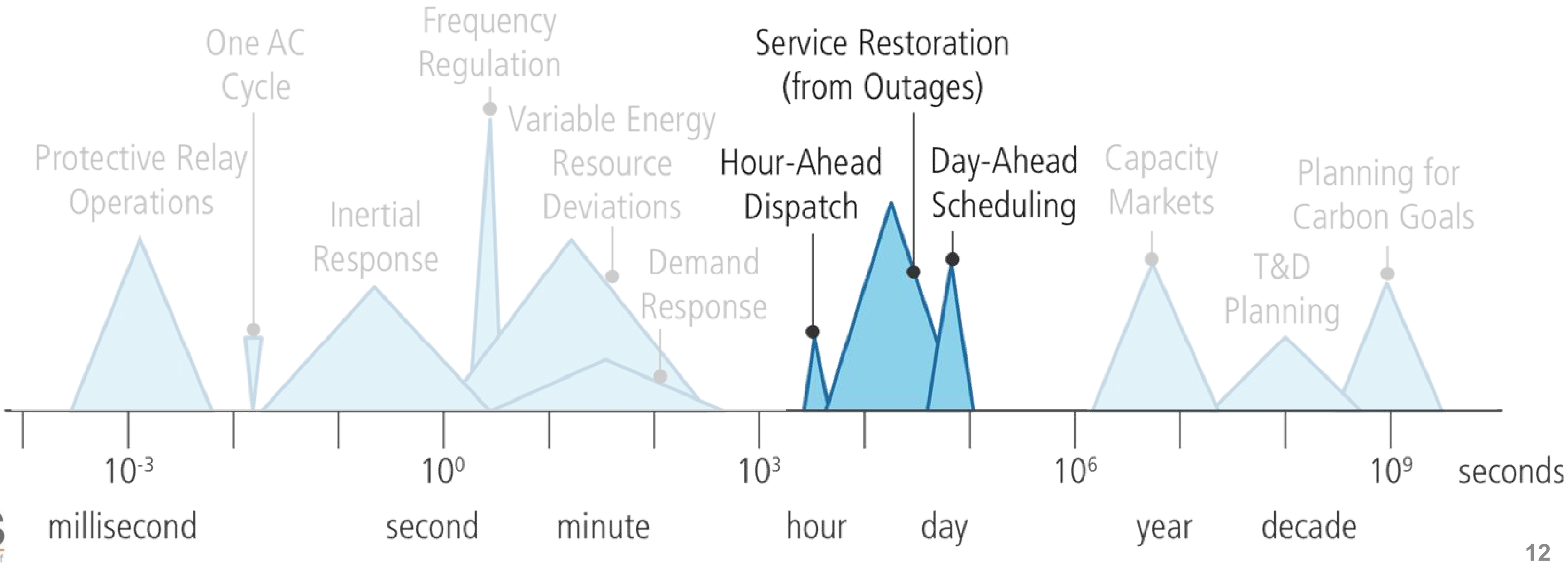
Part 2: Grid operations simulation

- How can existing plants change operations to increase participation / revenues?
- Generator profitability is not simply "*min(cost)*"
  - Unit properties (minimum power, ramp rate limits, on/off limits) significantly impact participation in the Grid markets
  - *Production cost models* simulate the Grid market structures



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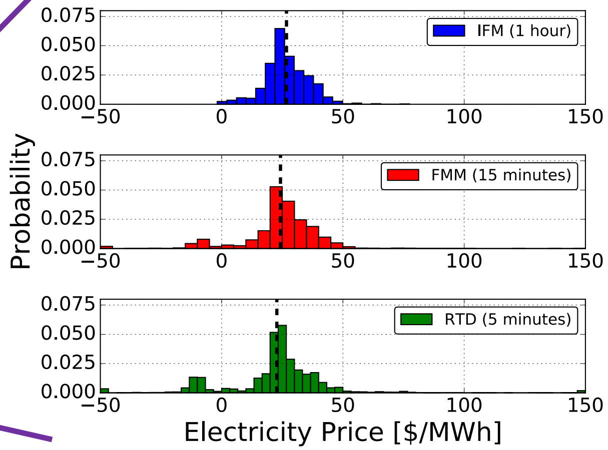
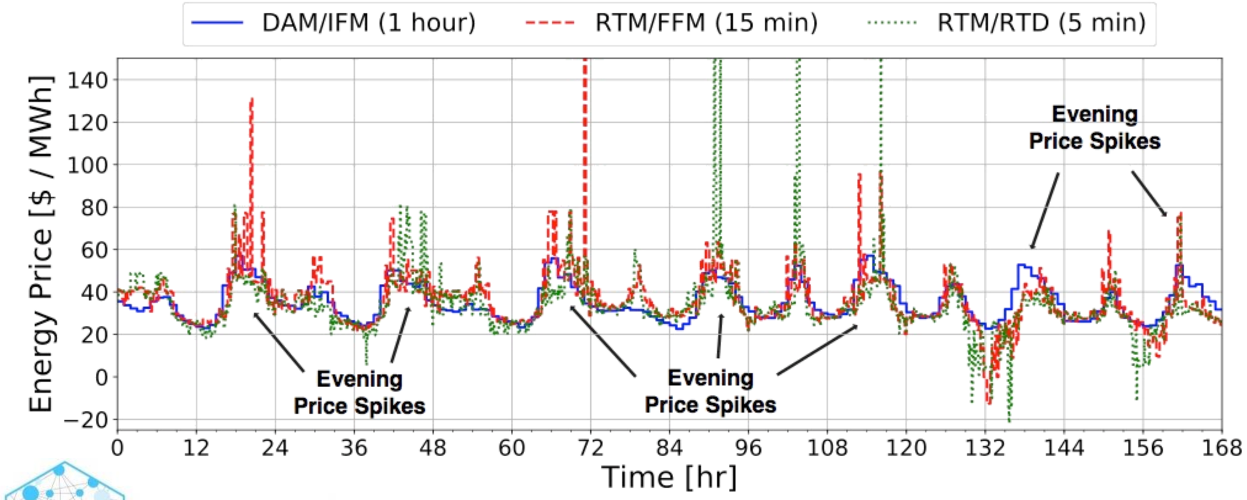
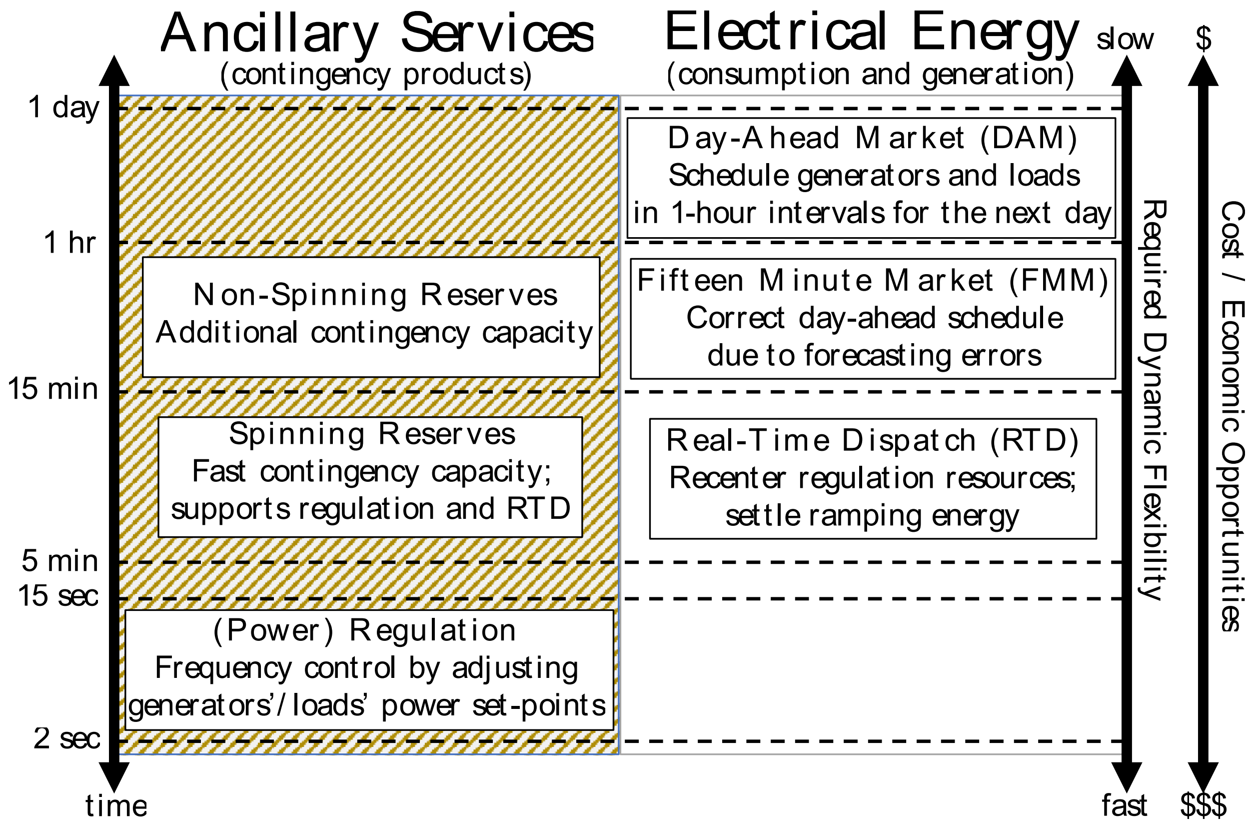
Hierarchical markets example: California (CAISO)

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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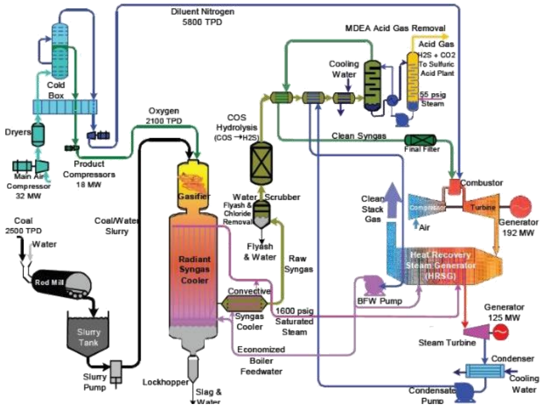
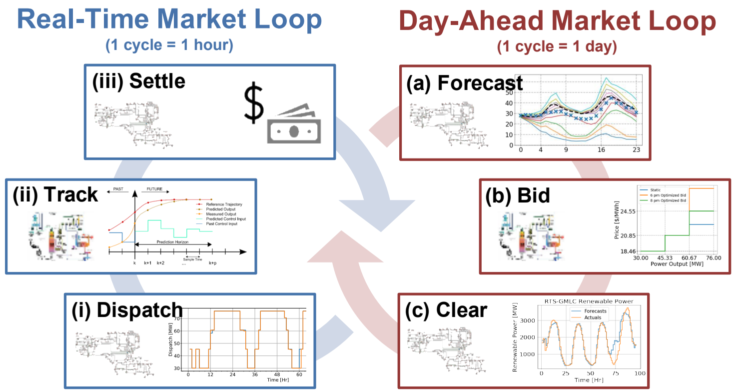
Bridging timescales in IDAES enables unique analyses

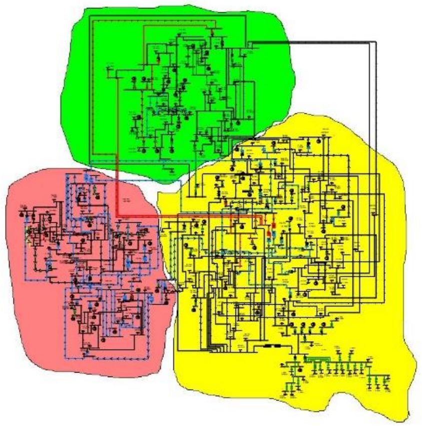
High-Fidelity Process Modeling



Integrated Resource-Grid Model



Grid Modeling



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

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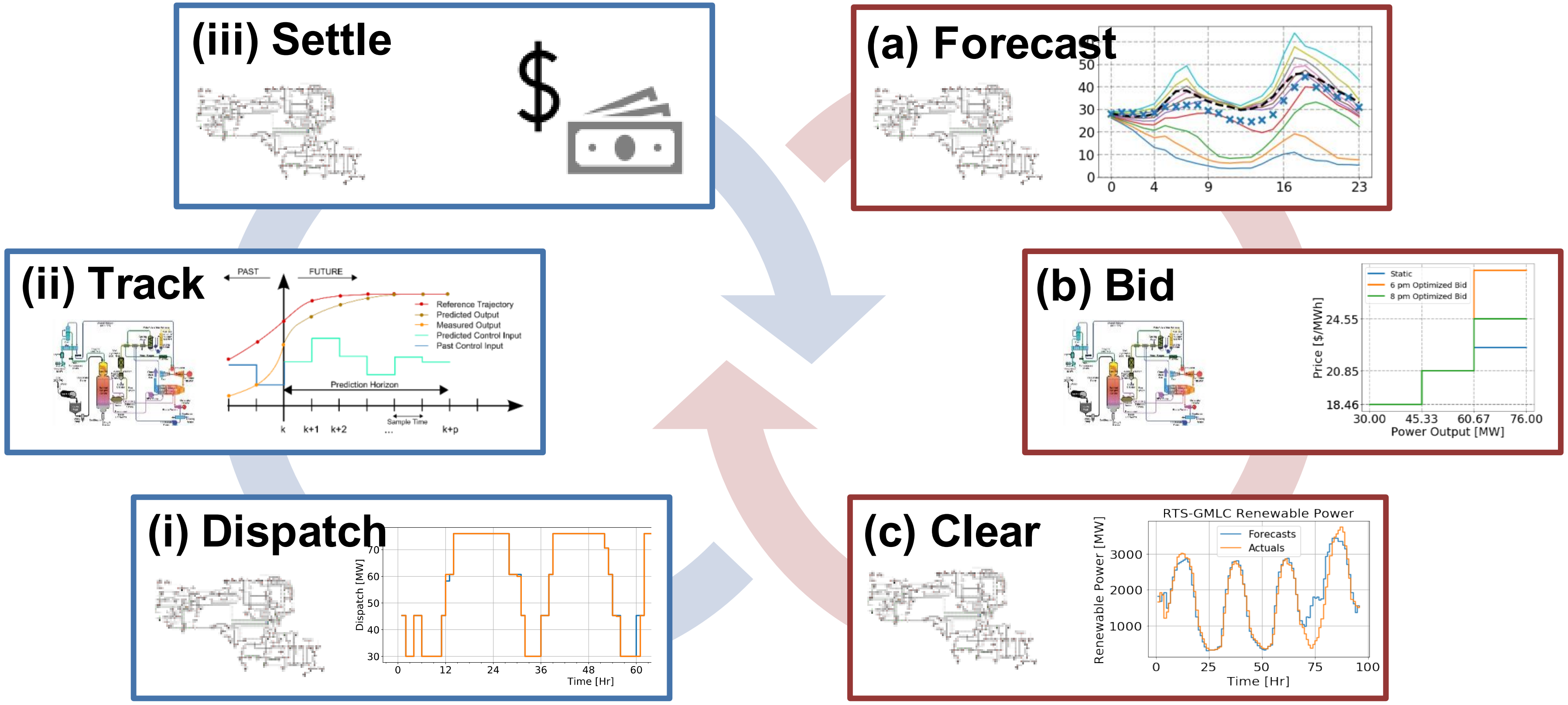
Modeling multiscale resource and grid decision-making

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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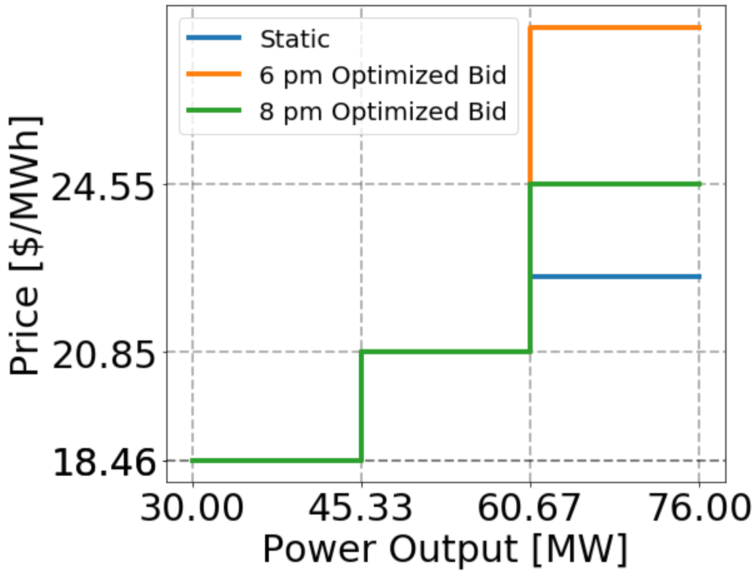
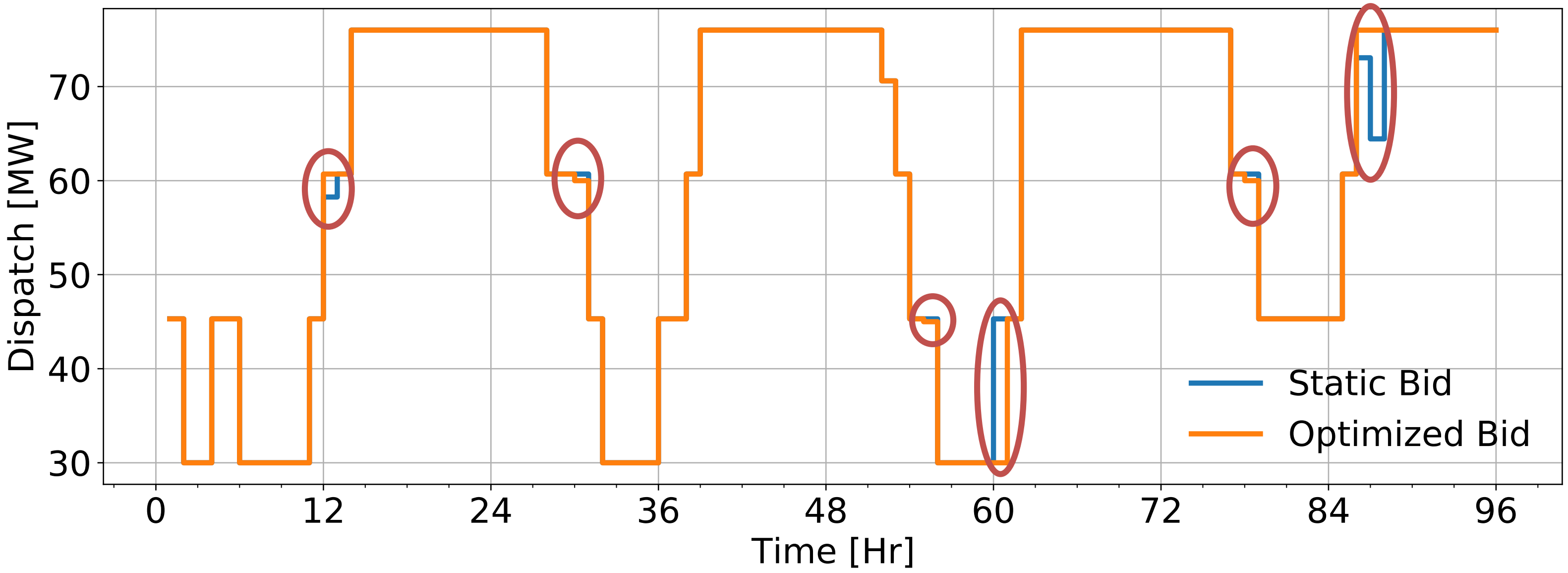
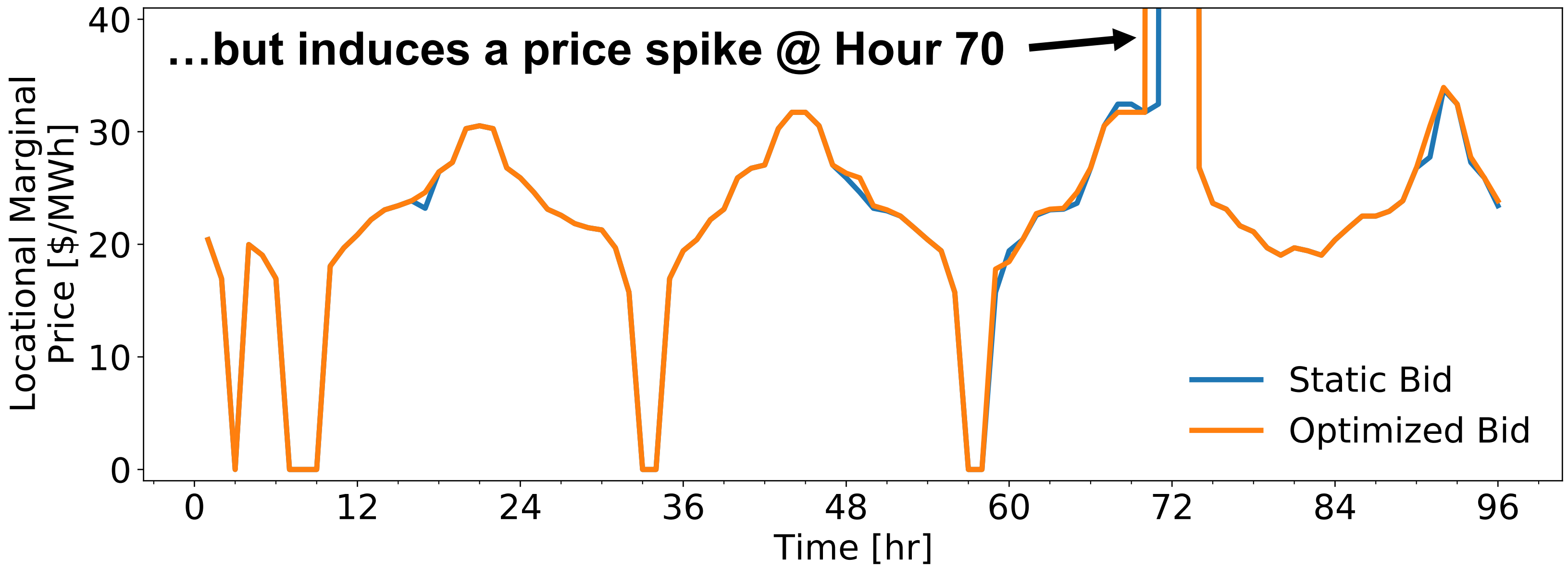
Want more details? Watch our ACC talk on the IDAES YouTube channel: https://www.youtube.com/watch?v=h1gzZXcsY-g

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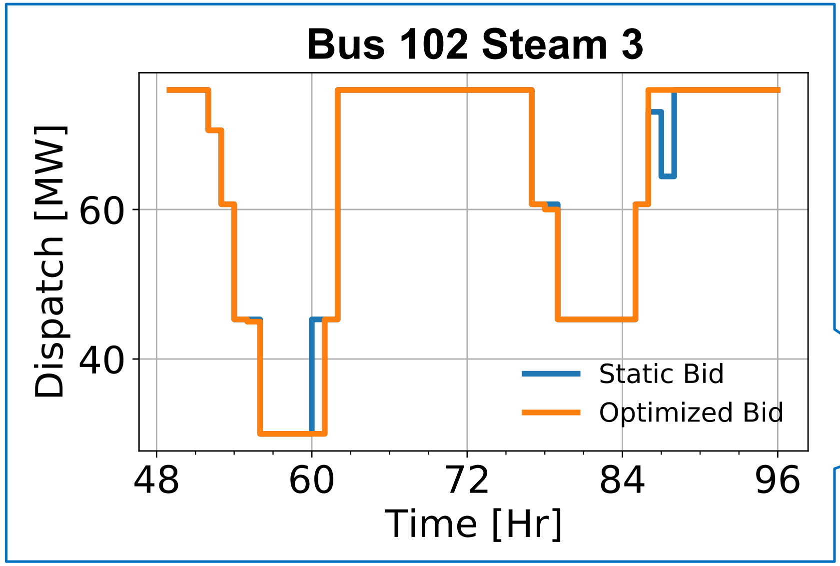
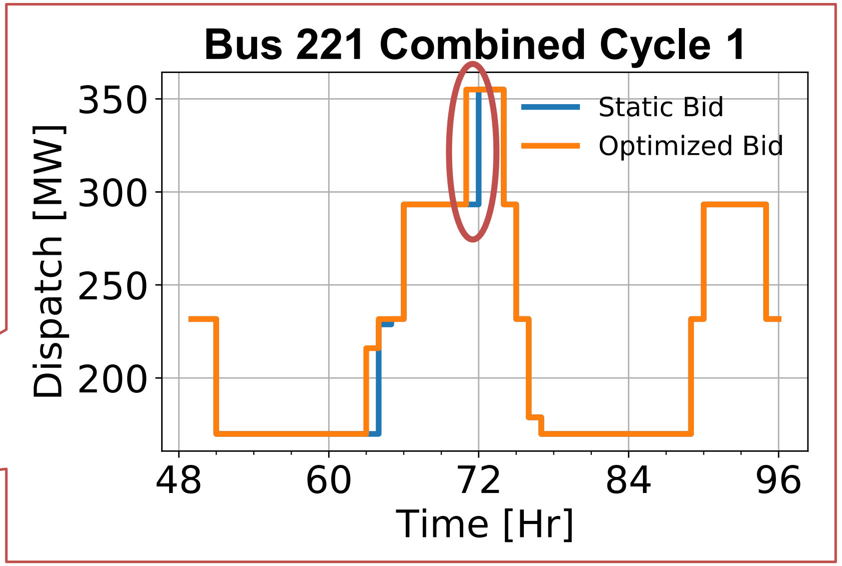
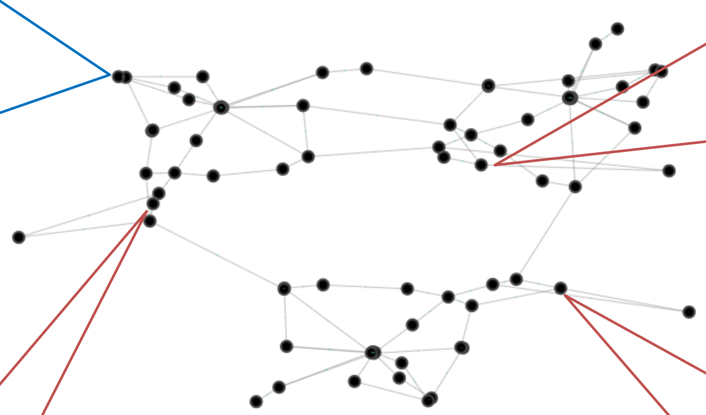
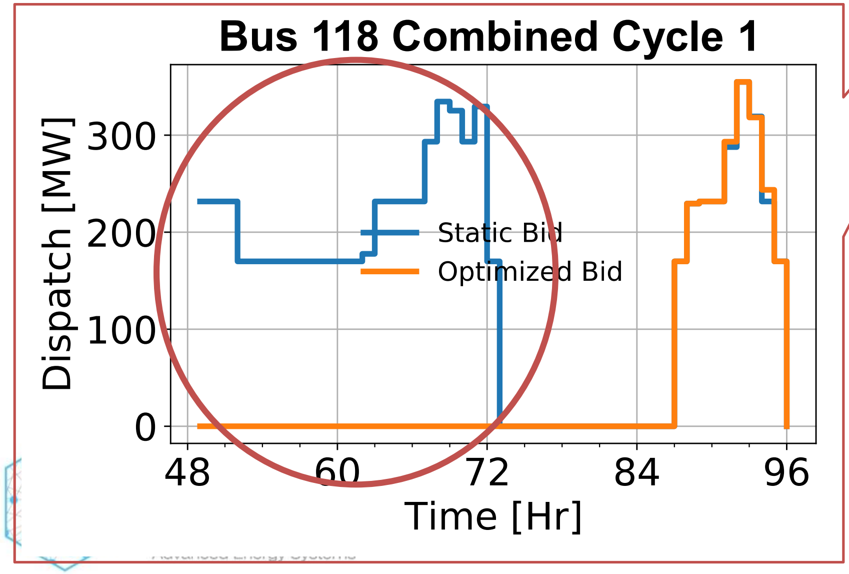
What causes the price spike @ Hour 70 with optimized bids?



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

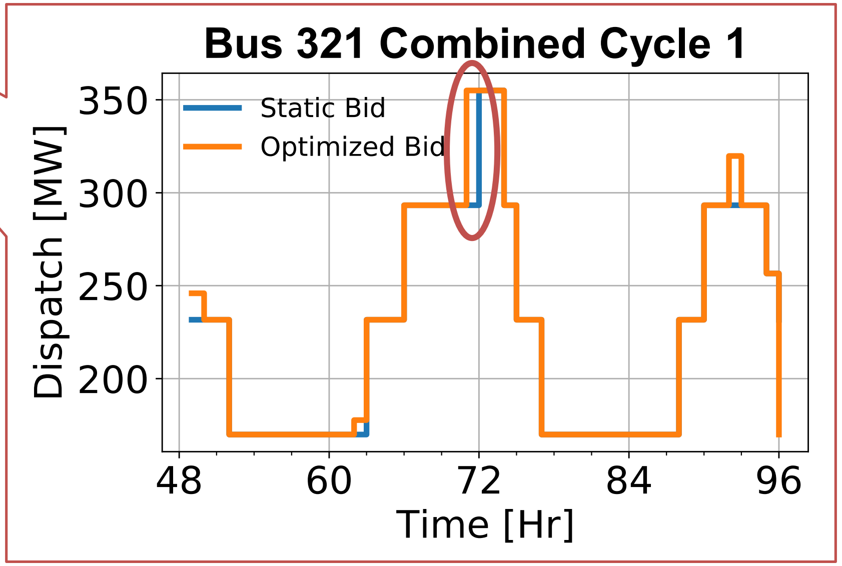






Effects ripple through grid:

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



Part 2: 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.

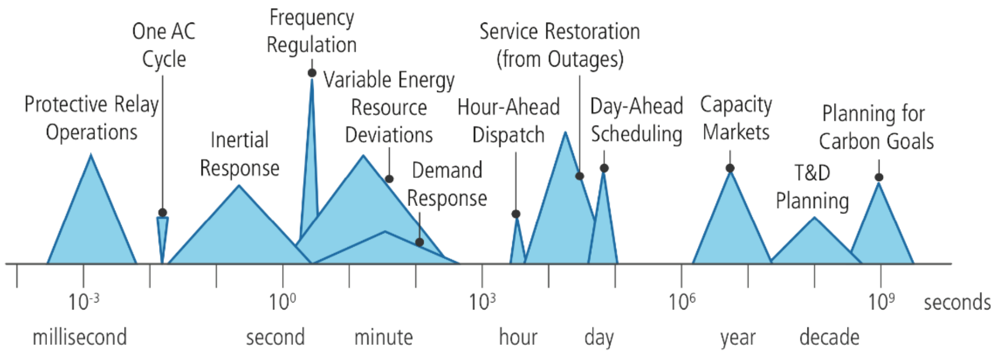
Qualification:

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

Conclusion

IDAES is developing a **unique cohesive suite** of multiscale modeling and power grid analysis capabilities **across control, operational, and planning time scales**



Current development activities

Expansion Planning

- Adding additional model detail (transmission systems, construction lead times)
- Relaxing algorithmic assumptions (e.g., stagewise independence)

Grid / Market Simulation

- Adding sub-hourly energy and ancillary service markets to Prescient

EMPC for Market Participation

- Interface with Prescient and IDAES Power Plant Models

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idaes.org

github.com/IDAES/idaes-pse

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