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Institute for the Design of Advanced Energy Systems

Multi-Period Optimization for Process Design and Market Integration

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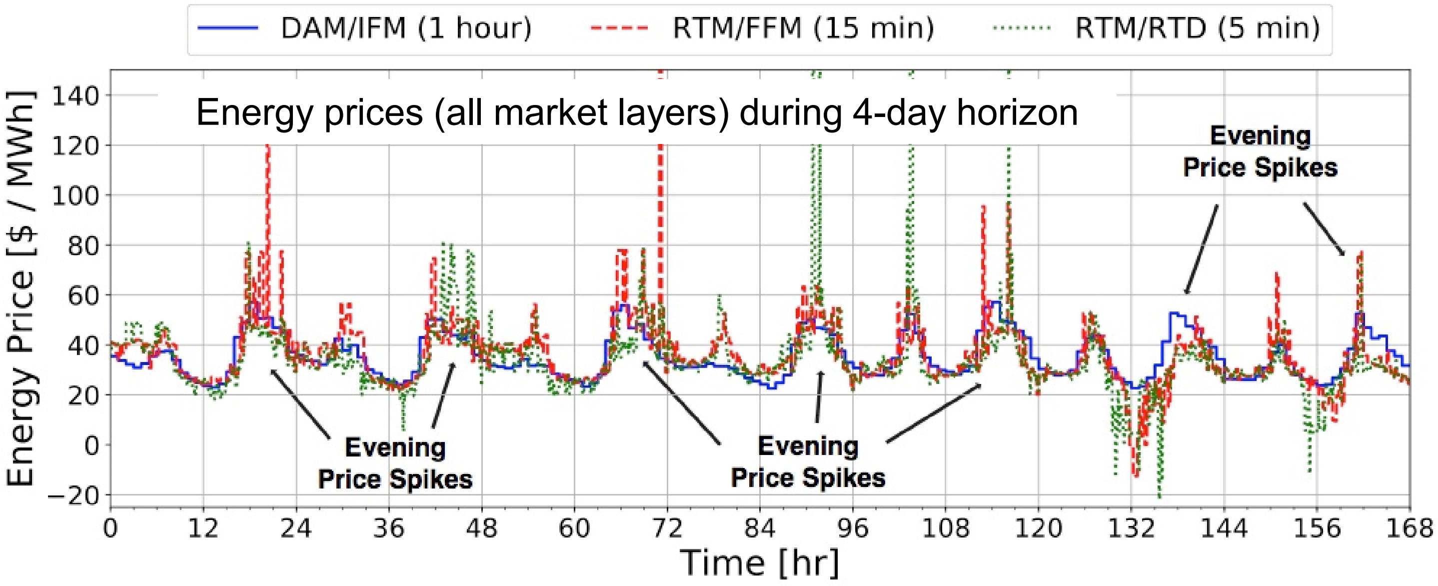
Motivation: Evolving Grid Increasingly Requires Flexibility

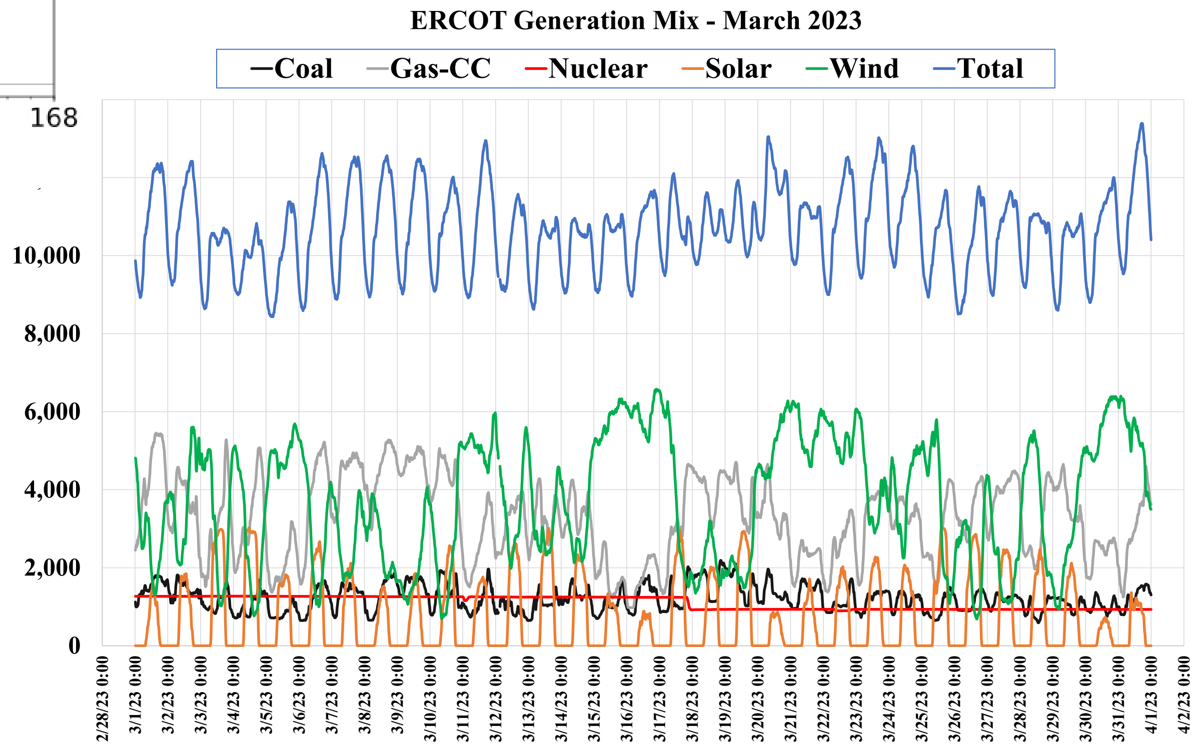
California ISO (CAISO)



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

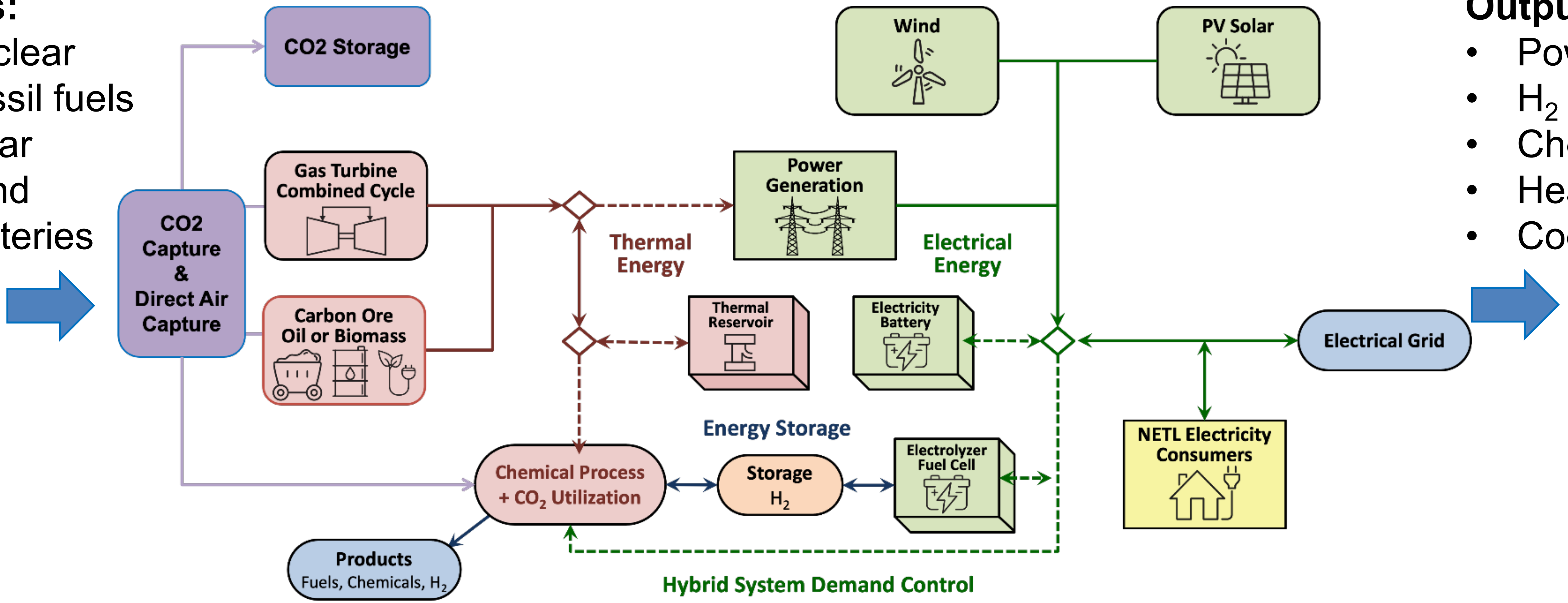
Electric Reliability Council of Texas (ERCOT)

Source: https://www.ercot.com/gridinfo/generation



Integrated Energy Systems (IES) Provide Dynamic Flexibility

Inputs:
- Nuclear
- Fossil fuels
- Solar
- Wind
- Batteries



Outputs:
- Power
- H_2
- Chemicals
- Heating
- Cooling

Challenge: How to **co-optimize** IES design and operation considering **dynamic market interactions**?

Figure: Arent, Bragg-Sitton, Miller, Tarka, Engel-Cox, Boardman, Balash, Ruth, Cox, and Garfield. (2020). *Joule*.

Key Contributions

- **Capabilities for process design and techno-economic analysis of “flexible” systems**

Applications: Simultaneous design and operations optimization

- **Natural gas combined cycle + capture system**
  - Determined the optimal capture rate and the effective capture rate for a given market

- **Direct-fired supercritical CO_2 power cycle**
  - Quantified the effectiveness of energy storage and participation in multiple markets

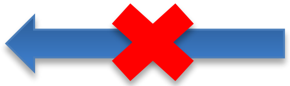
- **Co-production of power and hydrogen**
  - Quantified the impact of grid interactions on breakeven price of H_2

Key Contributions: Capabilities for Process Design and Techno Economic Analysis (TEA) of Flexible Systems

Add a new generator, or retrofit an existing generator

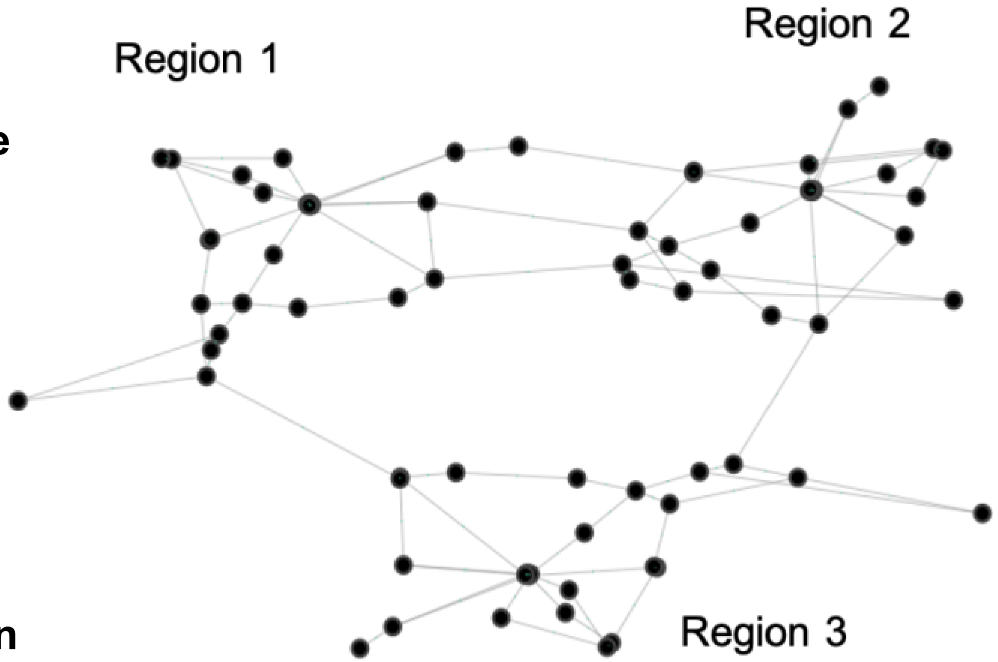
"Forward Interaction"

Generator's impact on the grid behavior



"Reverse Interaction"

Impact of grid behavior on design and operation



Traditional TEA Approach – Levelized Cost Analysis

- Ignores both forward and reverse interactions

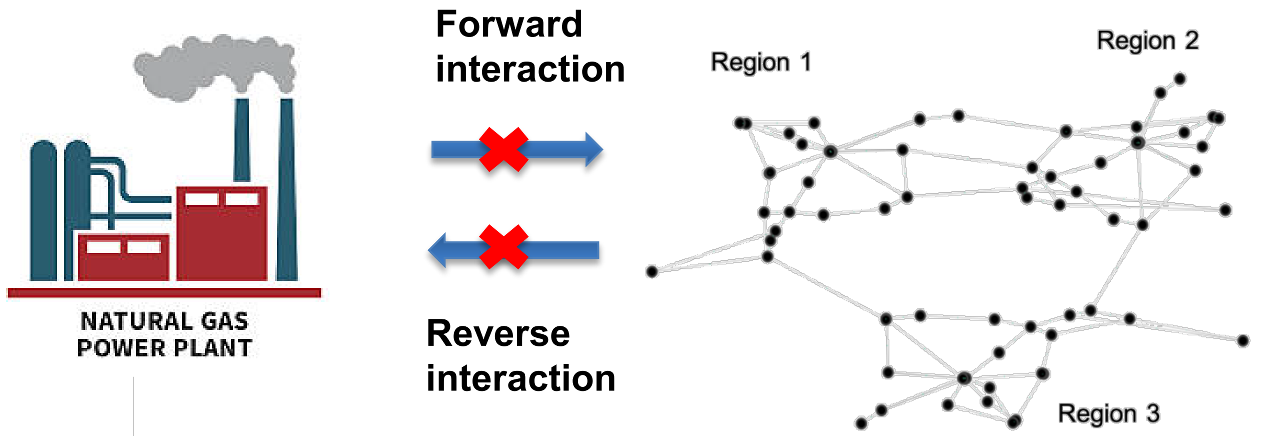
Price-Taker Approach

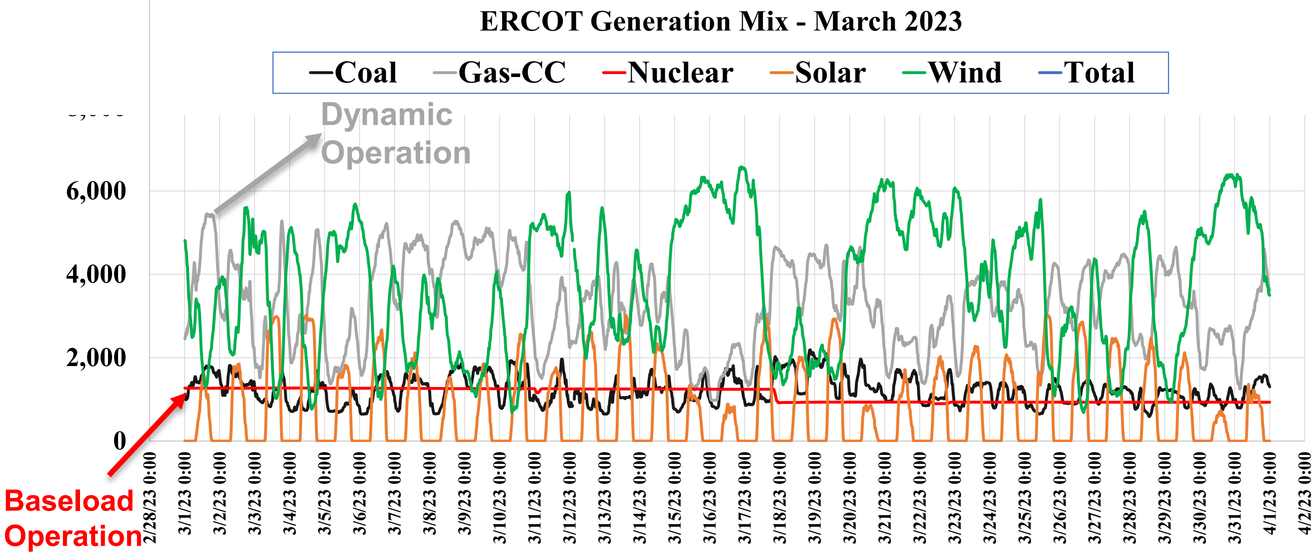
- Allows for reverse interaction to inform process design

Market Interaction Approach

- Considers both forward and reverse interactions

Traditional Techno-Economic Analysis – Levelized Cost Analysis





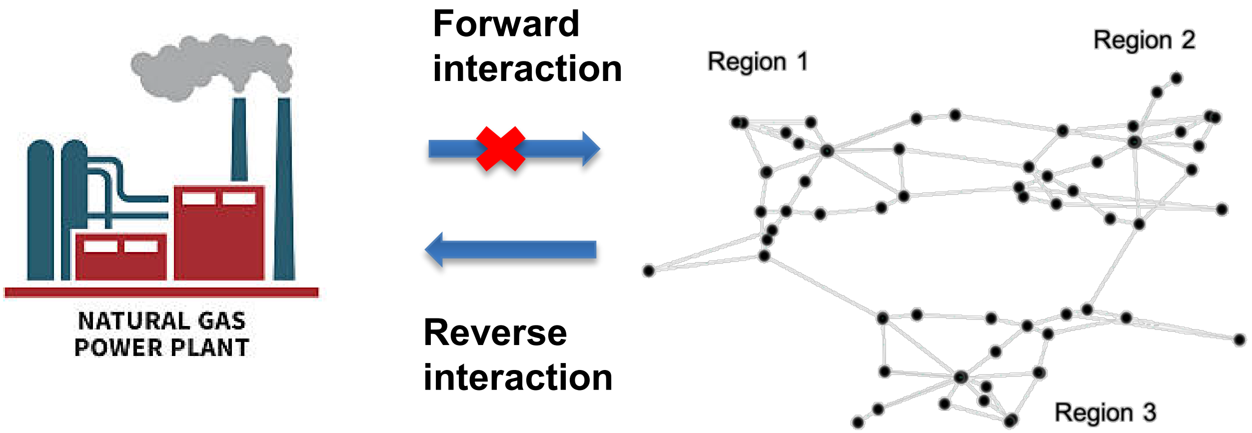
Pros:

- Optimizes design assuming steady state operation throughout
- Suitable for baseload plants

Cons:

- Not suitable for flexible systems
  - Price volatility is not included
  - Capacity factor is not known a priori
  - Startup/shutdown costs are neglected
- Not ideal for storage systems

Price-taker Approach



Locational marginal prices (LMPs) serve as a representative of the grid behavior

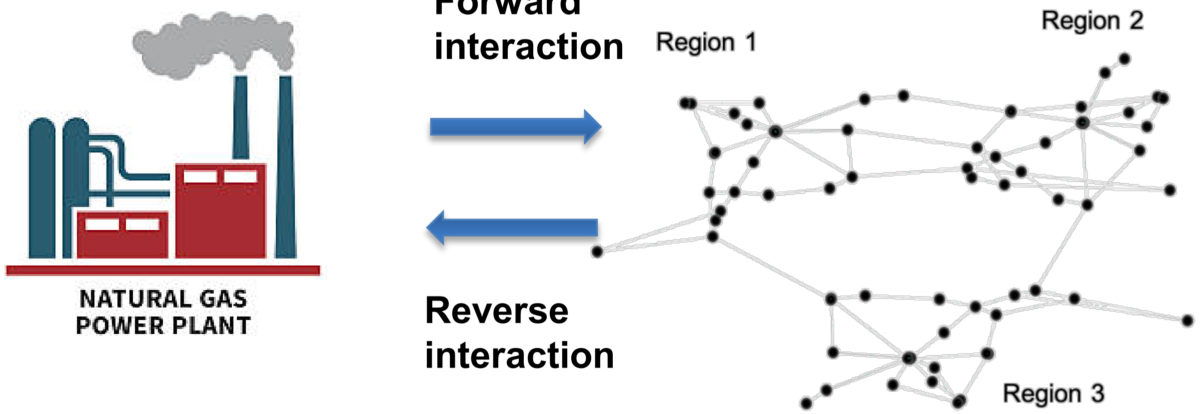
Pros:

- Design optimization while considering (simplified) dynamic operation
- Suitable for load-following plants, storage systems, co-production systems, etc.
- Accounts for price volatility, ramping limits, startup/shutdown constraints, etc.

Con:

- May not be suitable when the system’s power is a significant portion of the node capacity

Market Interaction Approach



Forward interaction

Reverse interaction

Pros:

- All advantages of price-taker
- Impact of the generator on the grid behavior is included (active bidding)

Cons:

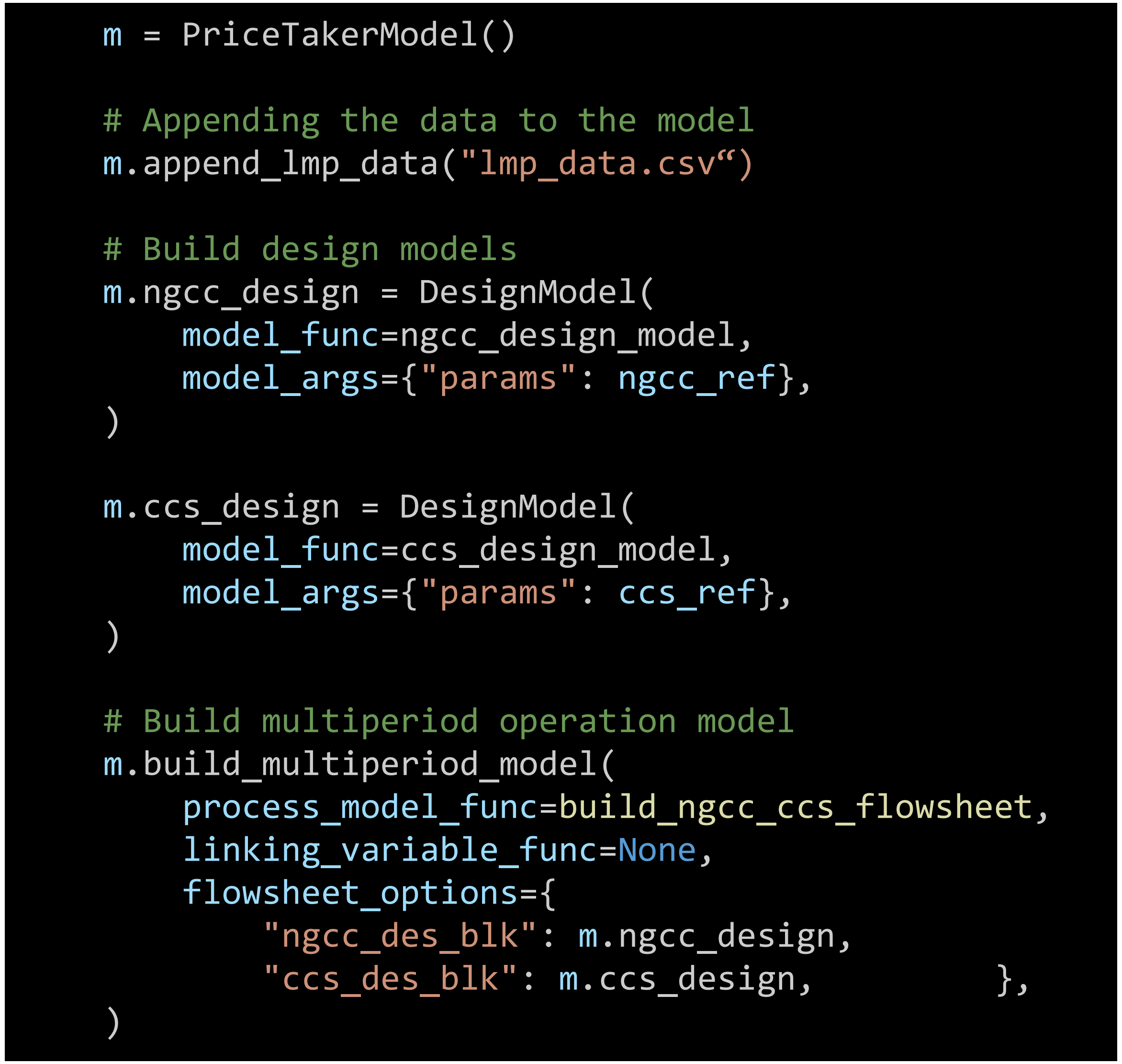
- Requires detailed grid information
- Computationally intensive

IDAES Grid Integration Tools

- **Goal**: Simplify the implementation of price-taker models

- Developed “PriceTakerModel” class
  - Constructs a multi-period model of a given flowsheet (supports surrogate models and detailed IDAES process models)
  - Clusters time-varying price data
  - Method for tracking storage levels

  - Method for adding minimum up-time and down-time, startup and shutdown constraints
  - Method for adding ramp rates
  - Method for calculating detailed cash flows



```
m = PriceTakerModel()

# Appending the data to the model
m.append_lmp_data("lmp_data.csv“)

# Build design models
m.ngcc_design = DesignModel(
    model_func=ngcc_design_model,
    model_args={"params": ngcc_ref},
)

m.ccs_design = DesignModel(
    model_func=ccs_design_model,
    model_args={"params": ccs_ref},
)

# Build multiperiod operation model
m.build_multiperiod_model(
    process_model_func=build_ngcc_ccs_flowsheet,
    linking_variable_func=None,
    flowsheet_options={
        "ngcc_des_blk": m.ngcc_design,
        "ccs_des_blk": m.ccs_design,         },
)
```

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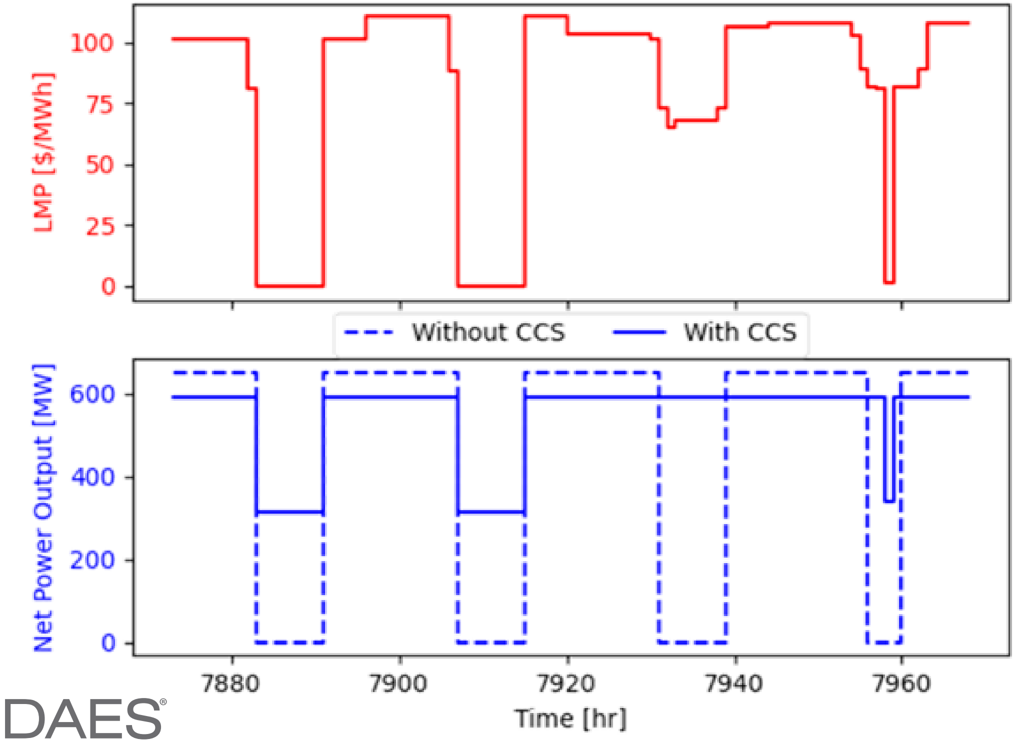
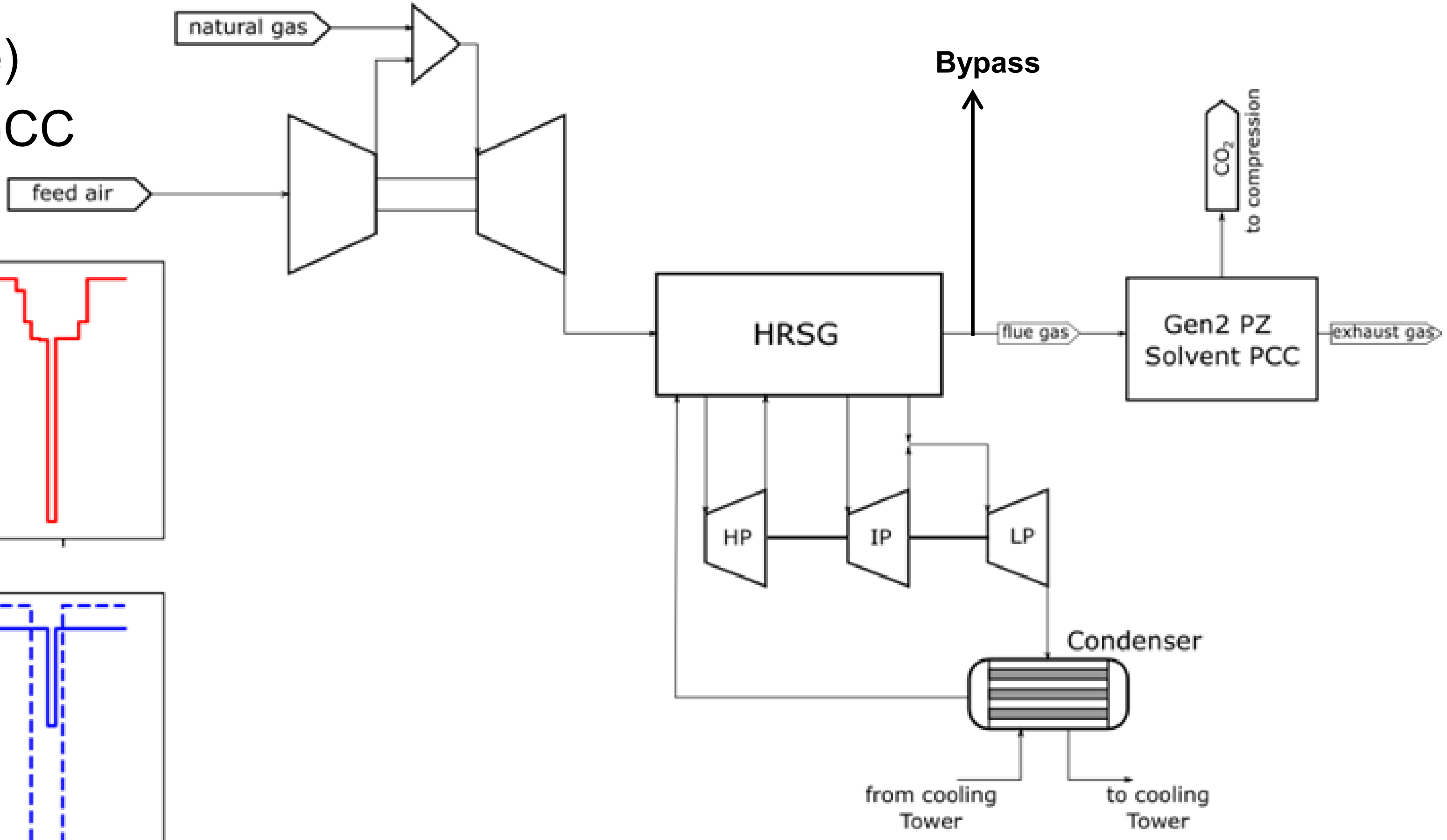
Flexible Operation of NGCC with CCS

- **Goal**: To find the set of conditions that provide optimal NPV. Conditions include:
  - System design (Capture rate)
  - Plant dispatch (CCS and NGCC separately)

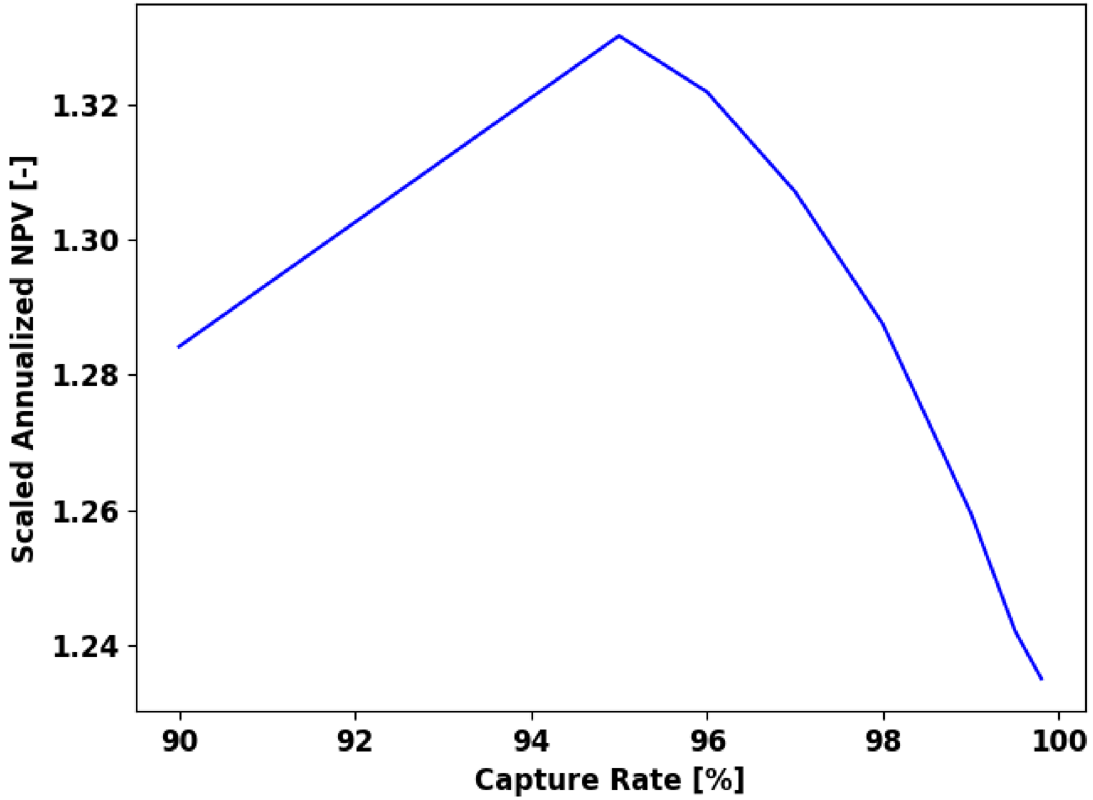


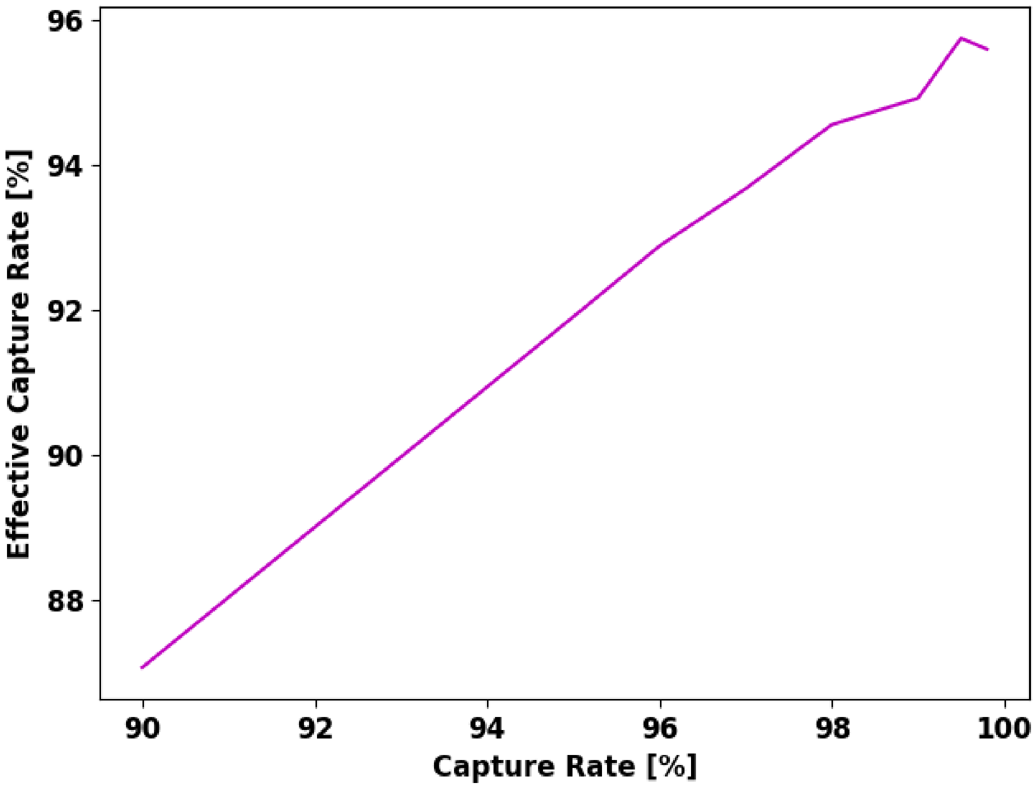


Optimal Capture Rate for most Scenarios is ~95%

NREL’s CAISO_$150/tonne scenario: **Capture system increases NPV**

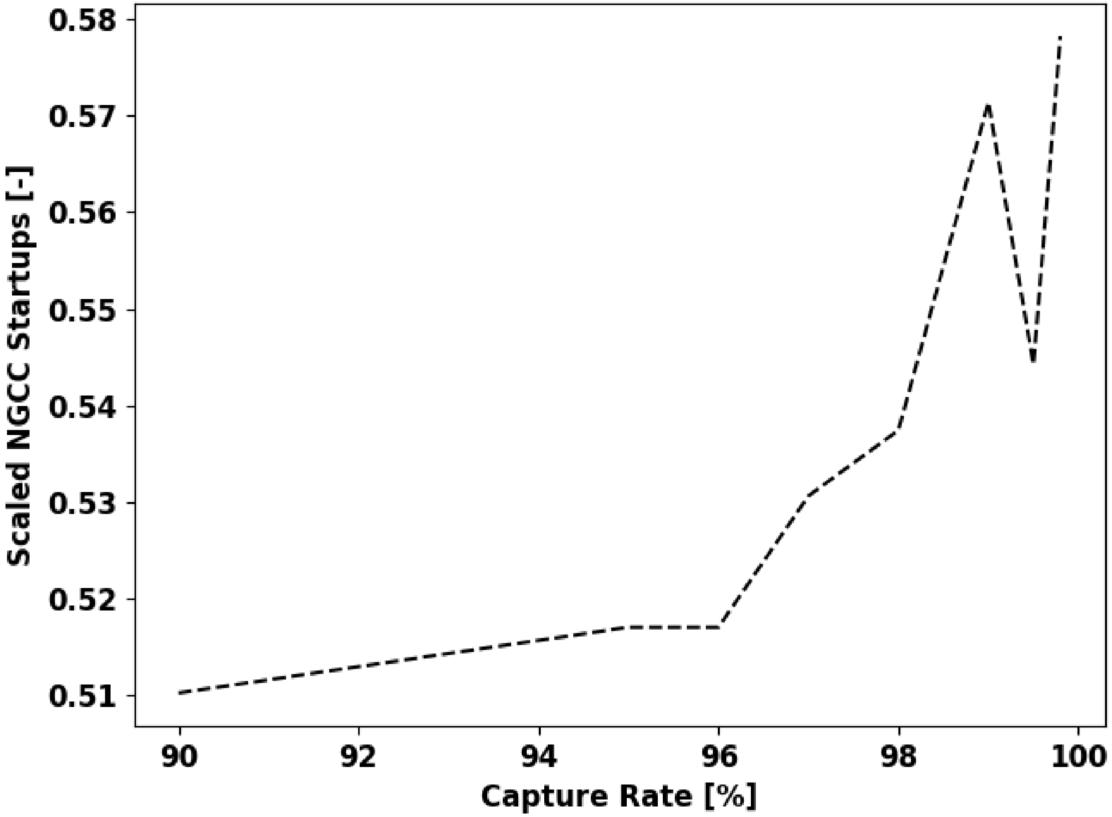
- Capture system increases the capacity factor by ~9.5%
- Effective capture rate is lower than the design capture rate



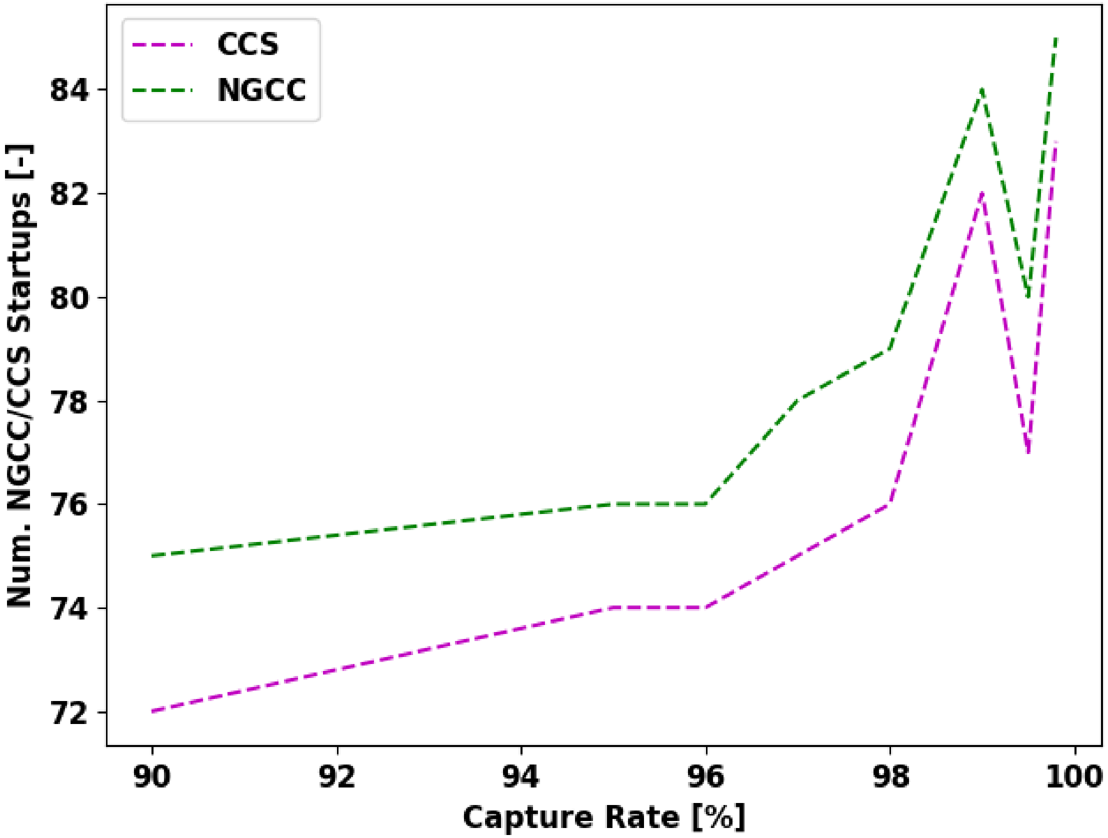


Numbers are scaled with those corresponding to the case without CCS

CCS Significantly Reduces Number of NGCC Shutdowns

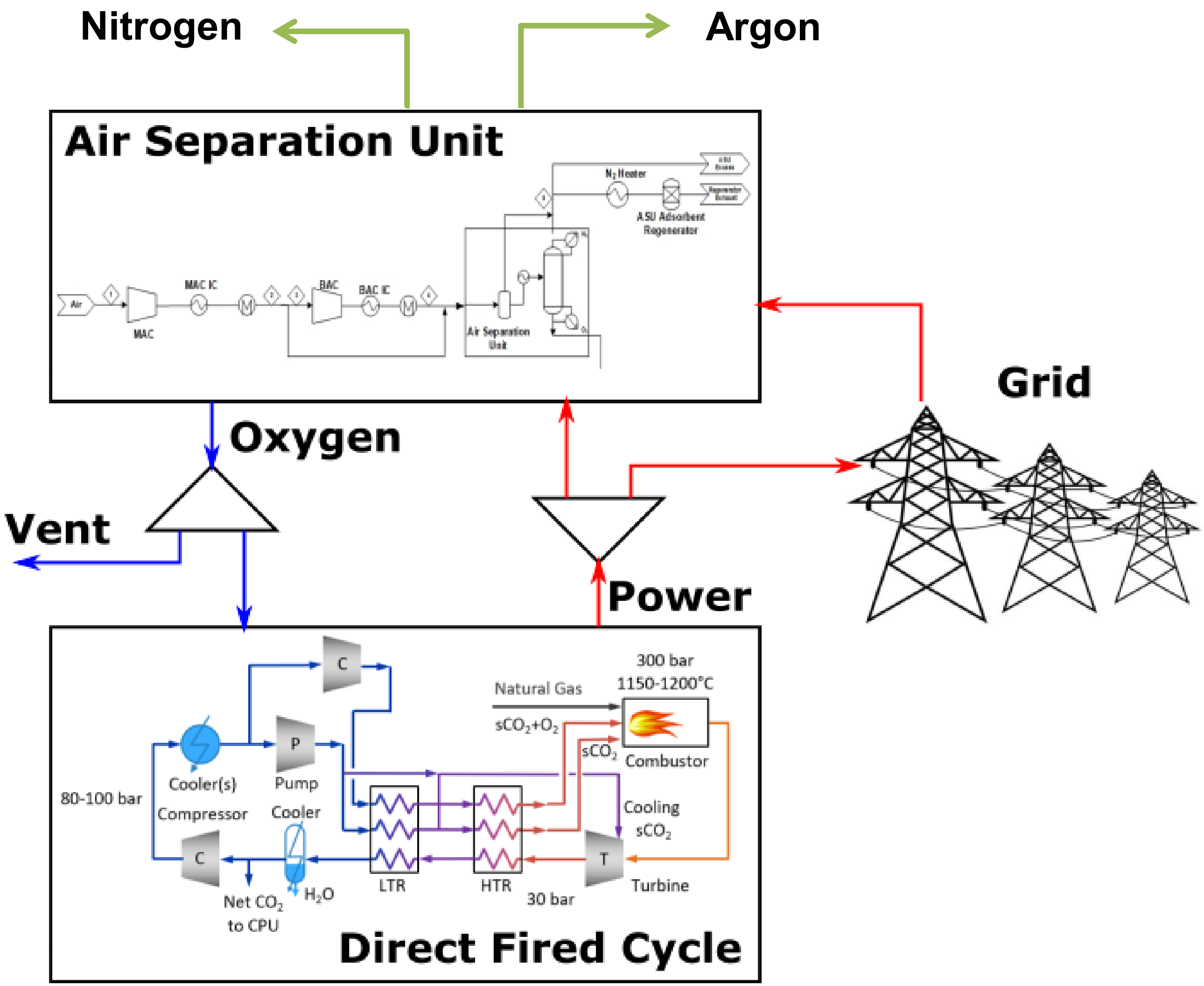


Numbers are scaled with those
corresponding to the case without CCS



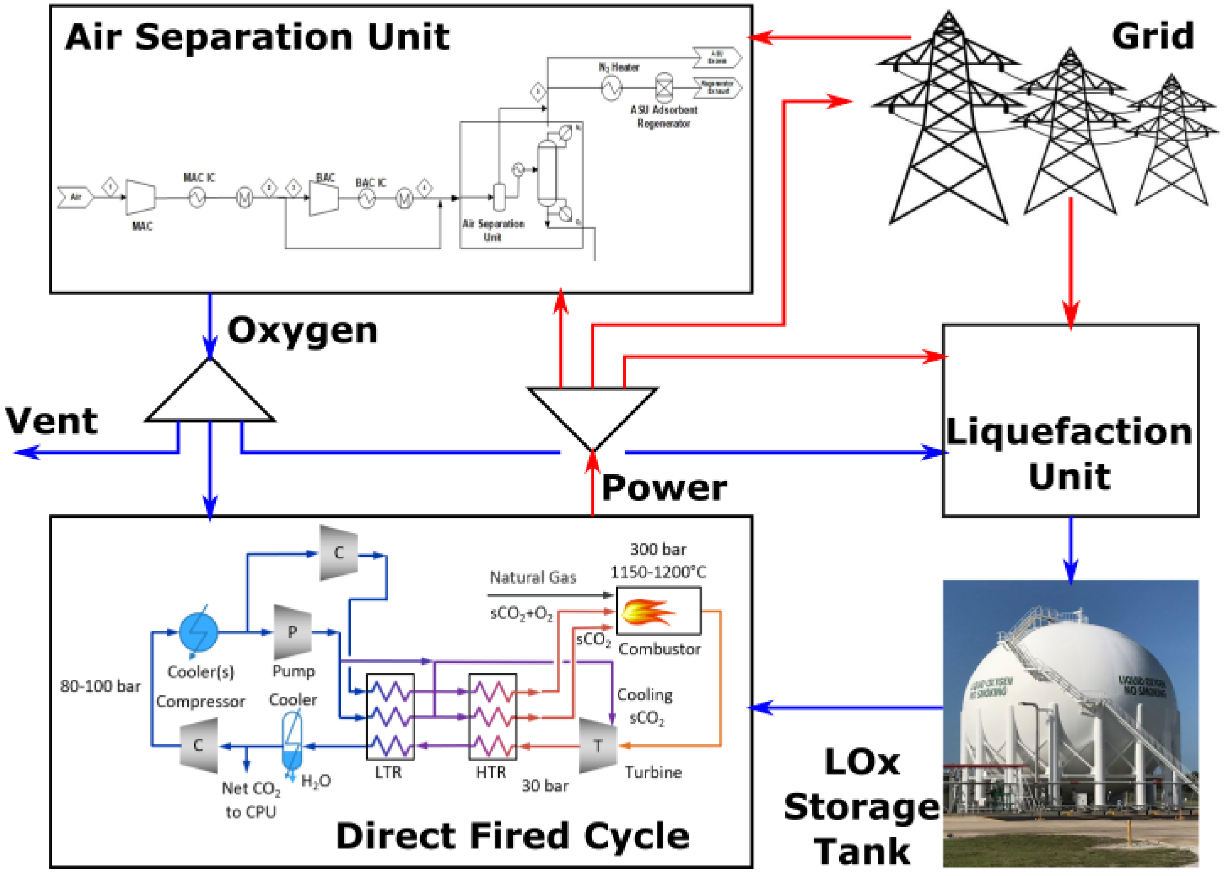
NGCC may operate without CCS

Direct-fired Supercritical CO_2 Power Cycle



- Power cycle requires oxygen instead of air
  - ☑ Capture is inherent – zero/near-zero emissions
  - ☑ Co-produce nitrogen and argon – Increases revenue and helps decarbonize the air products industry
  - ☒ Less flexible – Slow ramping and long startup time associated with ASU

Onsite Liquid Oxygen (LOx) Storage Improves Flexibility



Install a liquefaction unit (LU) and a storage tank

- **During off-peak period**
  - Ramp down/shutdown Direct Fired Cycle
  - Operate Air Separation Unit (ASU) and store the produced O_2
  - Power for liquefaction can be borrowed either from the grid or from the DFC
- **During high demand**
  - Ramp down ASU and use stored O_2
  - Inject more power into the grid

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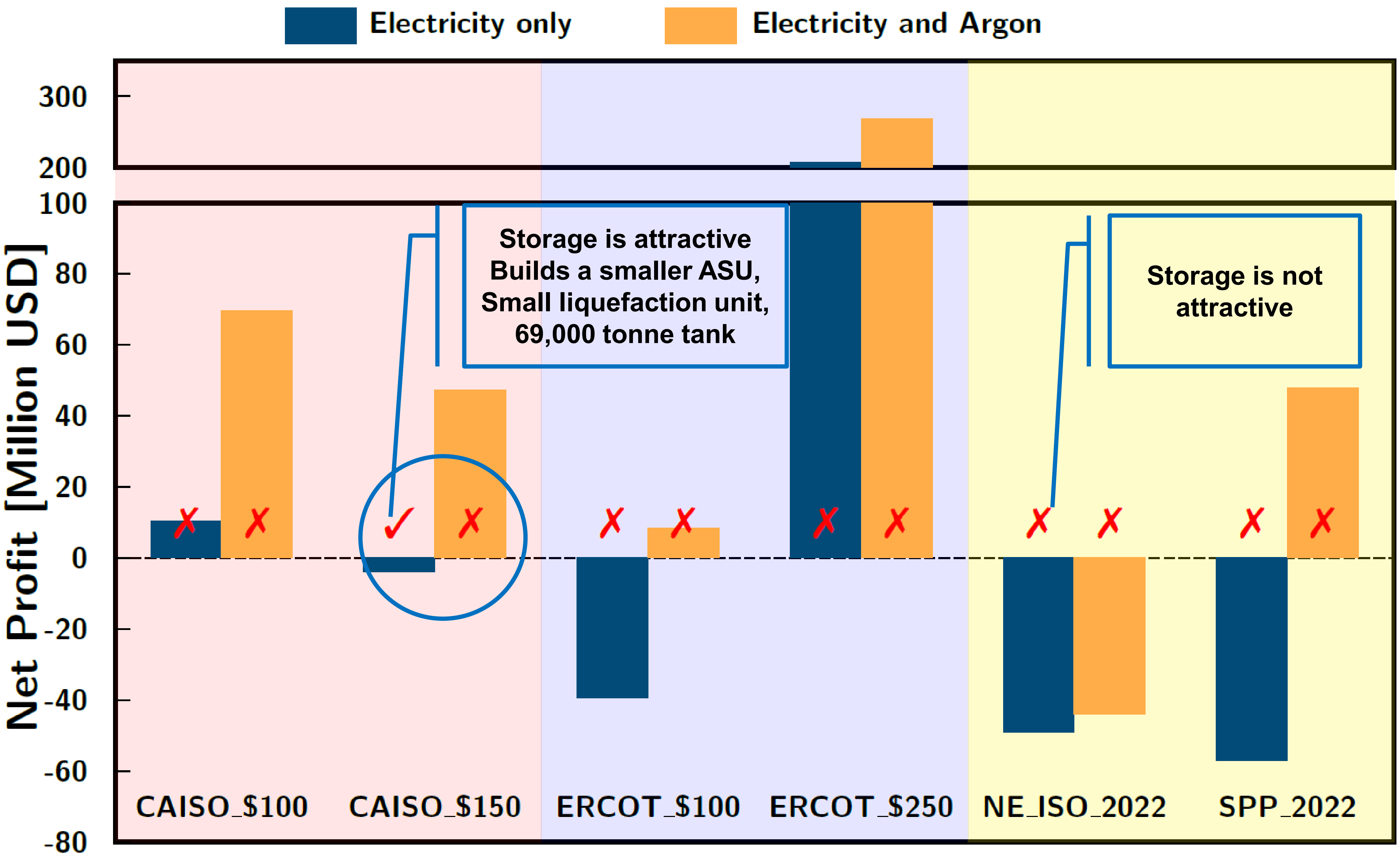
Key Research Questions

For a given electricity market:

- Does storage improve overall economics? What is the optimal size of the storage system?
  - Participate in electricity market alone
  - Participate in both electricity and argon markets

- Does storage improve flexibility?
  - Impact on number of startups and shutdowns

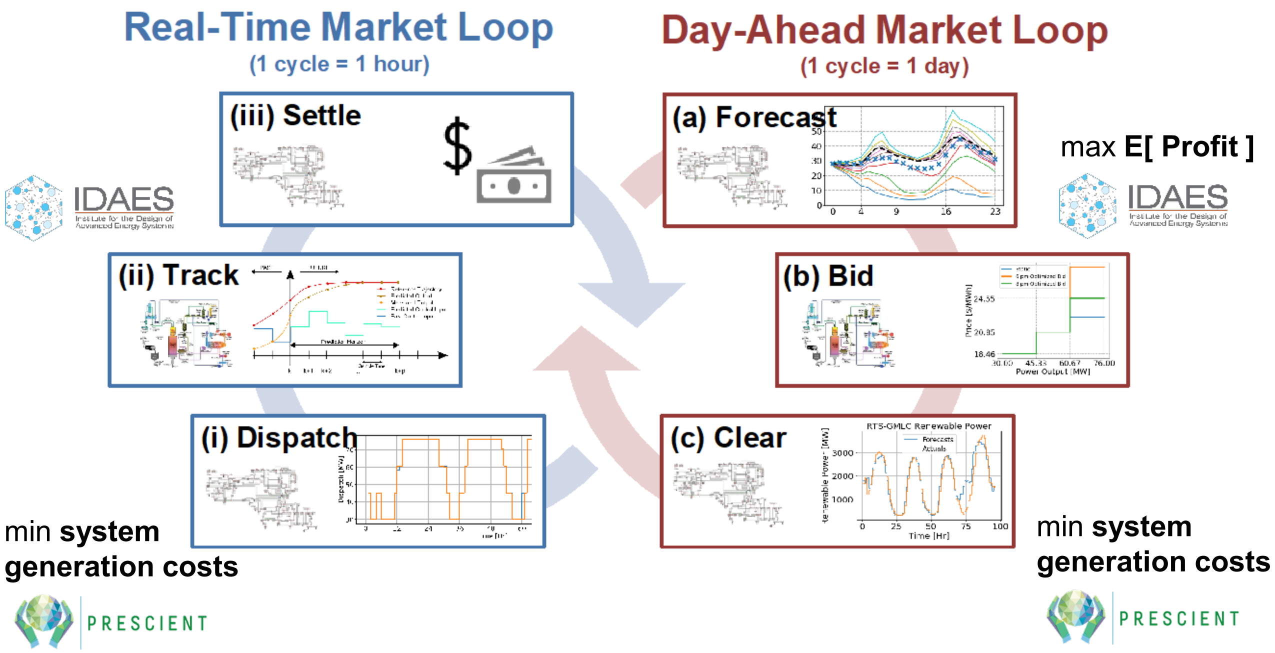
Highly Profitable Argon Market Discourages Storage



Storage is attractive
Builds a smaller ASU,
Small liquefaction unit,
69,000 tonne tank

Storage is not attractive

Market Interaction Approaches



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

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

(iii) Settle

(ii) Track

(i) Dispatch

(a) Forecast

(b) Bid

(c) Clear

max **E[Profit]**

min **system generation costs**

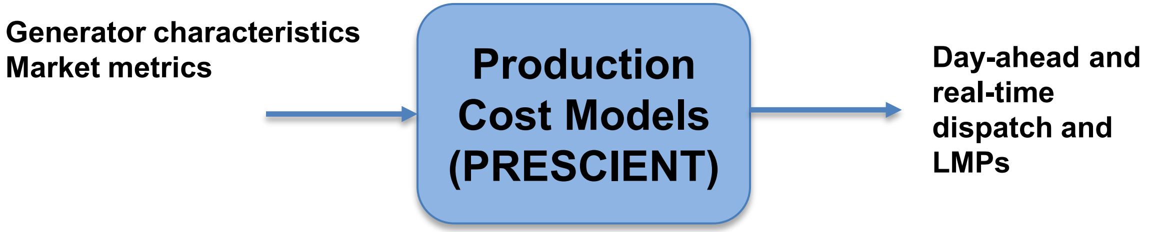
min **system generation costs**

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

Gao, X., B. Knueven, J.D. Siirola, D.C. Miller and A.W. Dowling (2022). "Multiscale simulation of integrated energy system and electricity market interactions." Applied Energy **316**: 119017, https://doi.org/10.1016/j.apenergy.2022.119017.

Code examples: https://github.com/gmlc-dispatches/dispatches

- **Step 1:** Generate training data

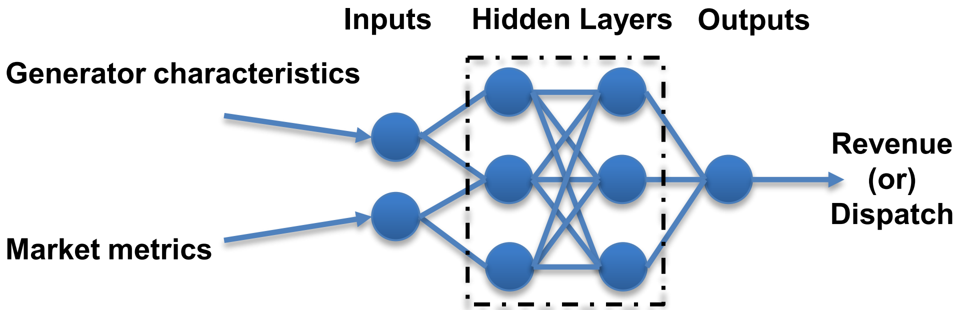


Generator characteristics
Market metrics

Production Cost Models (PRESCIENT)

Day-ahead and real-time dispatch and LMPs

- **Step 2:** Train neural network surrogate model



Inputs **Hidden Layers** **Outputs**

Generator characteristics

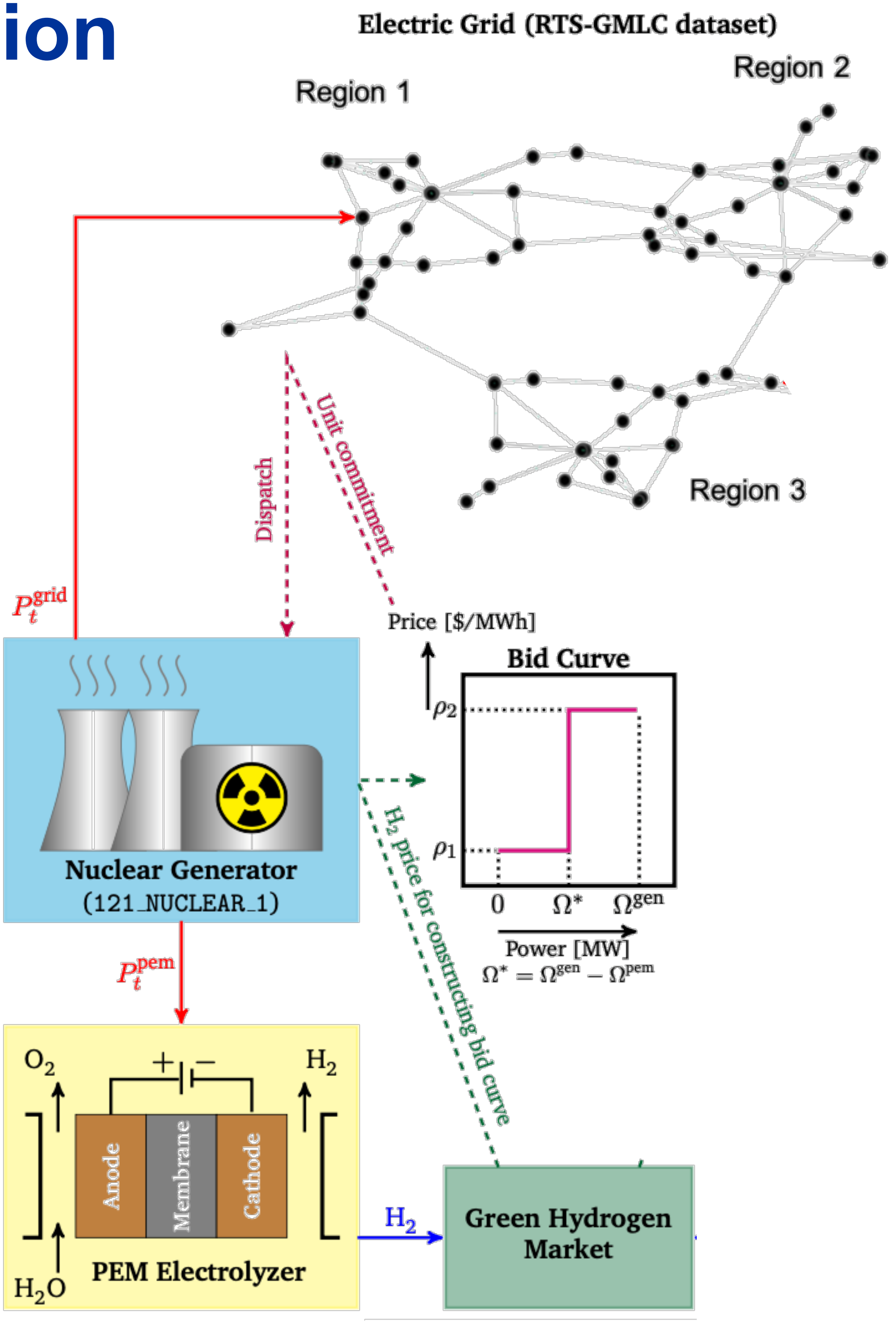
Market metrics

Revenue (or) Dispatch

- **Step 3:** Formulate and solve the design problem by embedding market surrogates

Power and Hydrogen Co-production

- **Increasing renewables → volatile grid conditions**
  - Nuclear generators cannot respond
- **Participate in alternate markets, e.g., H_2**
  - Increases profitability, efficiency, flexibility
  - Decarbonize other sectors
- **Need to co-optimize design and operating decisions of IES due to dynamic markets**
- **Need to consider how the IES influences markets, e.g., change electricity prices**



Nuclear Case Study Summary (Flexibility from Co-Products)

Problem Statement

How to improve the flexibility and economics of baseload nuclear generators?

What is the optimal electrolyzer size and minimum H_2 selling price?

Co-optimize design and operation

Method

Compare two modeling approaches:

Price-taker: assumes no impact on market behavior, de facto standard

Multiscale Simulation: accounts for changes in market behavior, novel contribution

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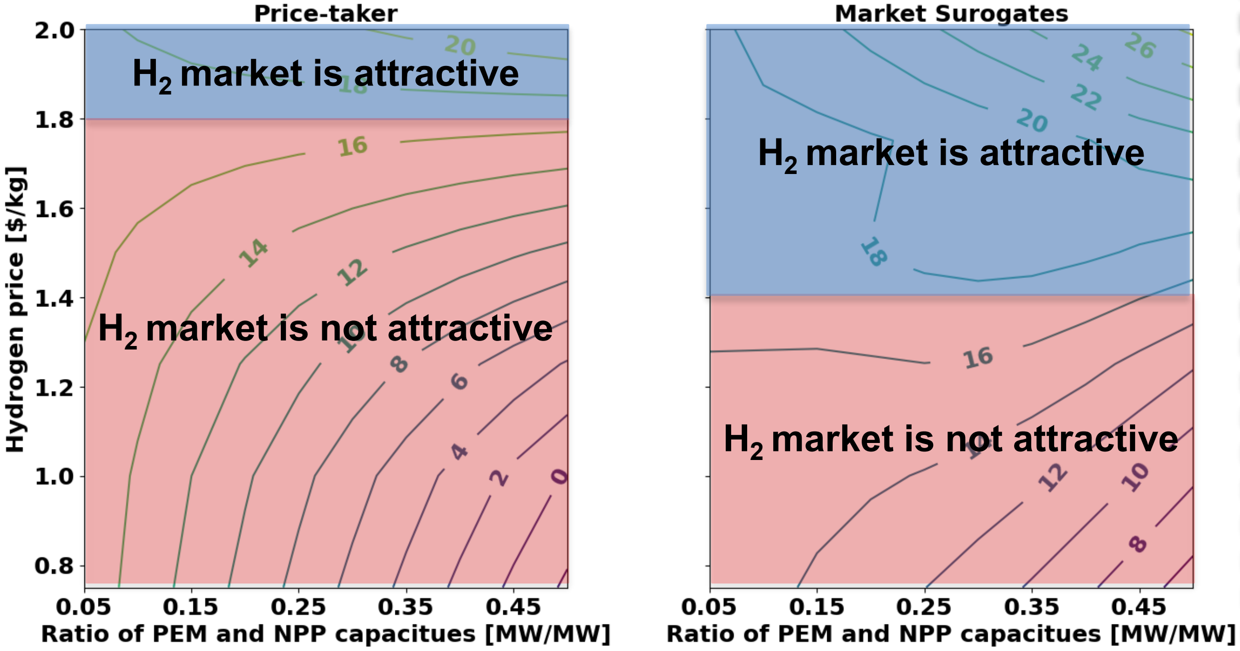
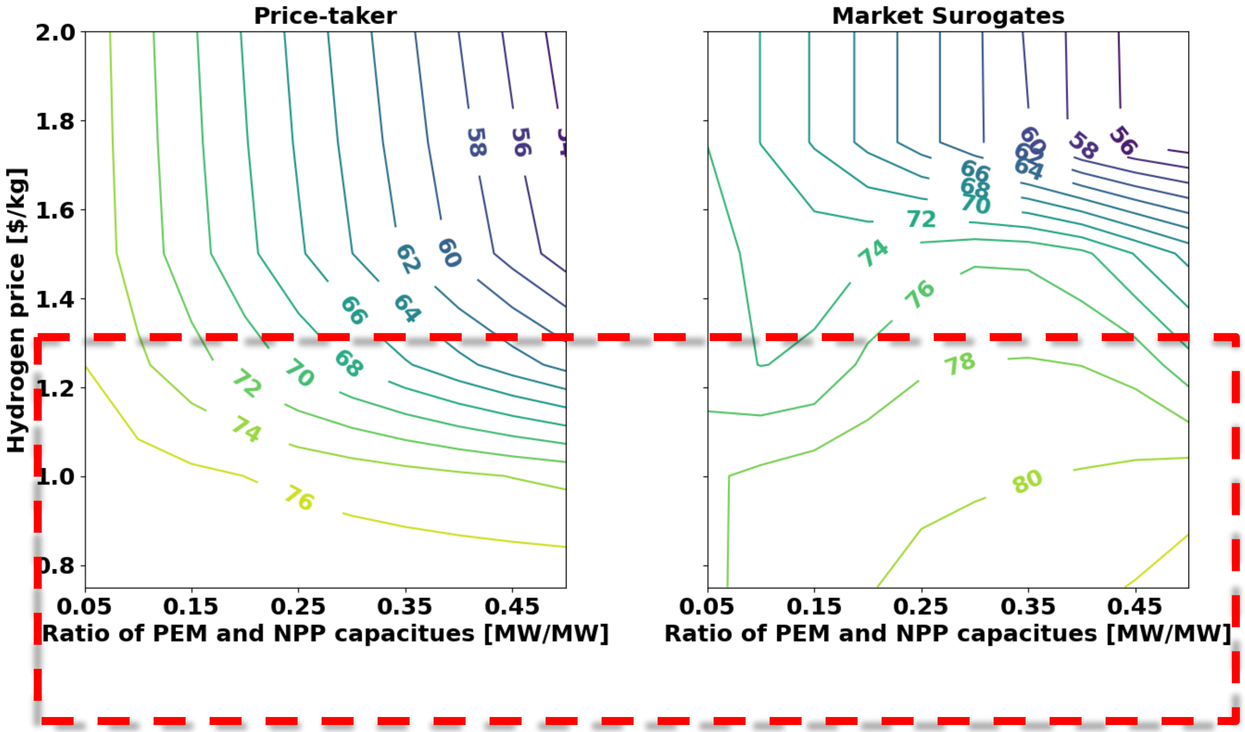
Nuclear Case Study Results: Price-taker vs Market Interaction

- Difference in the net present value and breakeven H_2 price: \$1.8/kg vs ~\$1.4/kg



Price-taker overestimates the breakeven H_2 price

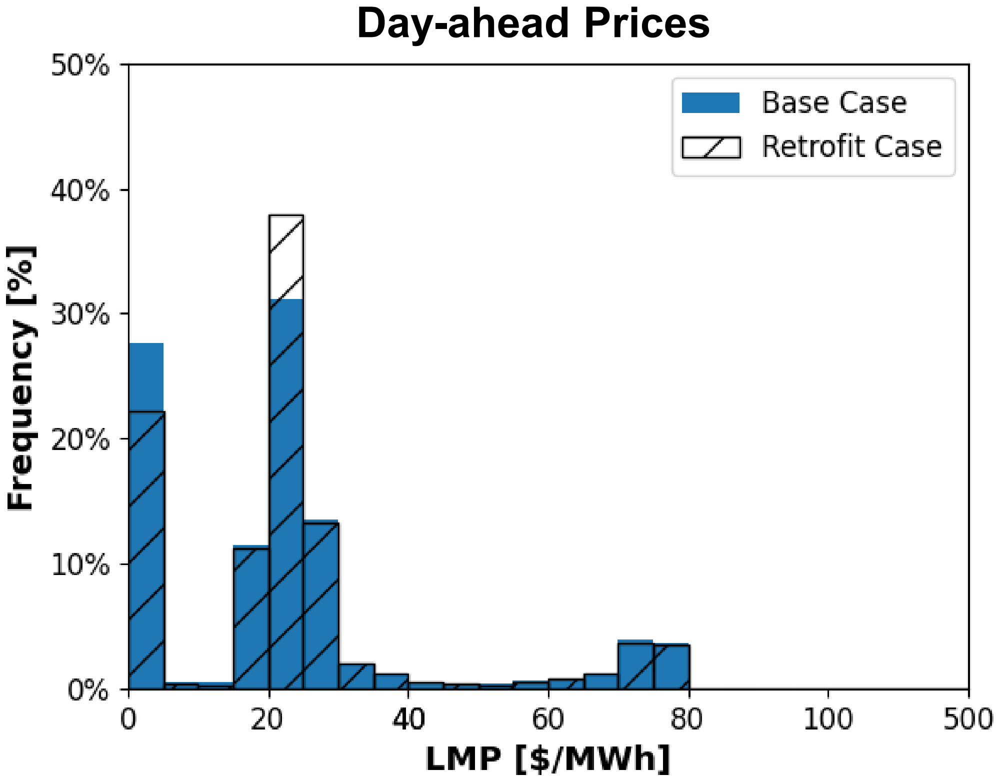
- Difference in electricity revenue

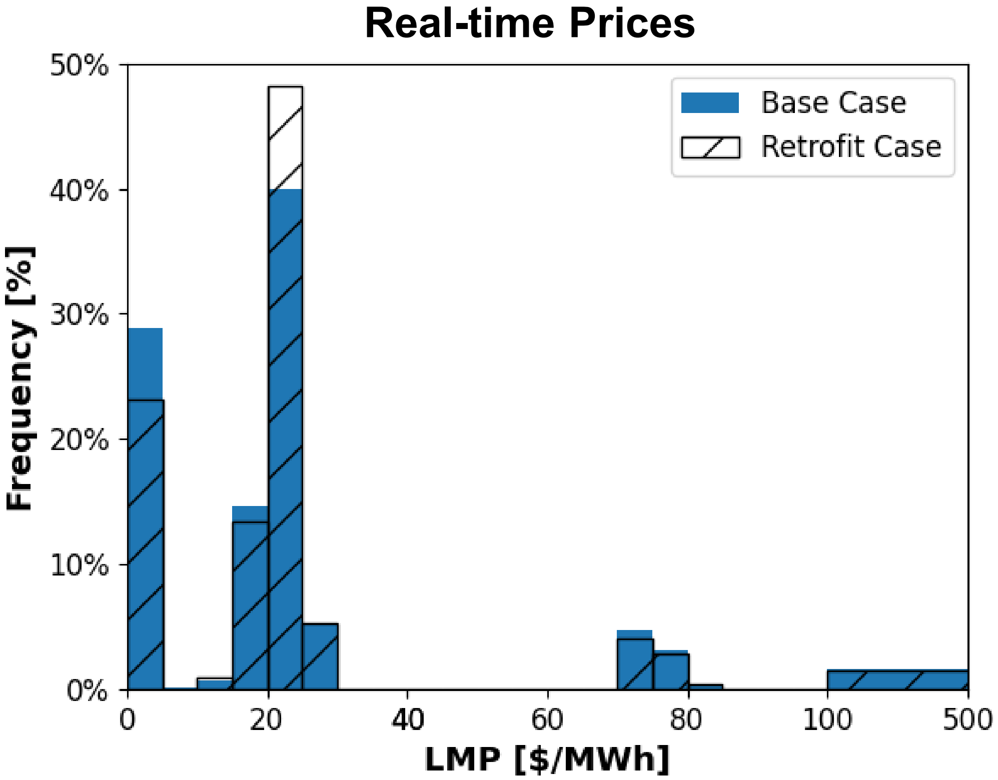


Electricity revenue depend on H_2 vs electricity production schedule – nuanced interactions

Electricity Prices Vary with the Size of Electrolyzer and H_2 Price

- **Base case (400 MW baseload nuclear generator without an electrolyzer)**
- **Retrofitted case (400 MW nuclear generator equipped with a 200 MW electrolyzer – H_2 sold at \$1/kg)**





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What is the optimal electrolyzer size and minimum H_2 selling price?

Co-optimize design and operation

Method

Compare two modeling approaches:

Price-taker: assumes no impact on market behavior, de facto standard

Multiscale Simulation: accounts for changes in market behavior, novel contribution

Key Findings

Hybridizing nuclear with PEM to produce hydrogen increases flexibility and profitability

Price-taker overestimates the breakeven H_2 price

Market surrogates accurately capture iterations

Impact

Method applies to other baseload generators, e.g., large coal or gas-fired generators with carbon capture

Easy to adapt to other electrolysis technologies – solid oxide electrolyzer cell (SOEC)

Conclusion

- **Developed novel capabilities for analyzing flexible and load-following systems**
  - Need to go beyond traditional techno-economic analysis

- **Two approaches two include grid interactions**
  - Price-taker (multi-period) approach
  - Multiscale simulation and optimization approach

- **Applied to multiple case studies**: additional examples include
  - Integrated solid oxide fuel cell + electrolyzer systems
  - Retrofitting renewables with green hydrogen gas turbines (industrial case study)
  - Economics of a fuel cell peaker (industrial case study)
  - Design and operation of flexible desalination systems

Acknowledgement and Disclaimer

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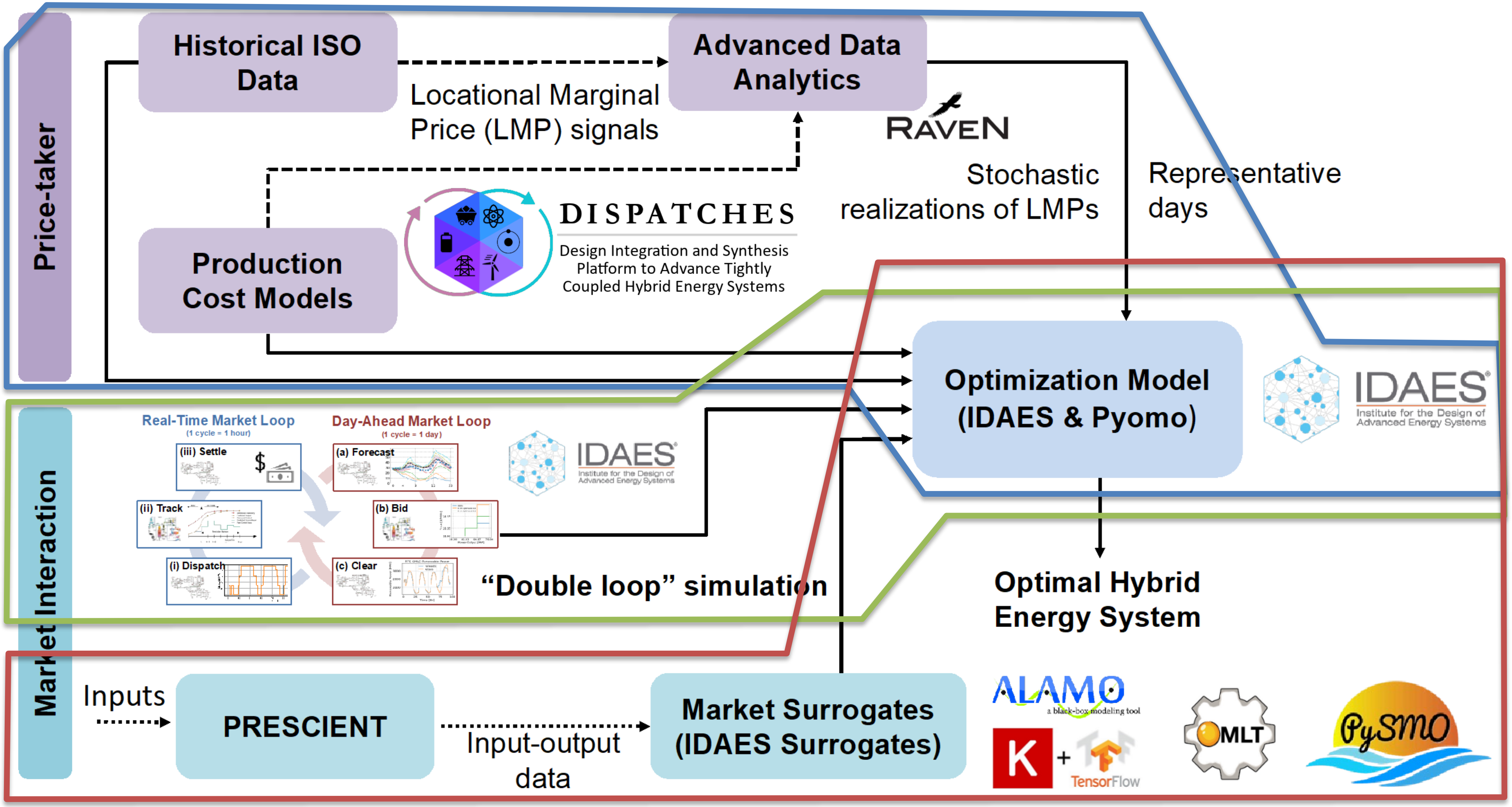
Multi-period Optimization Workflows



Price-taker

Historical ISO Data

Locational Marginal Price (LMP) signals

Advanced Data Analytics

RAVEN

Stochastic realizations of LMPs

Representative days

Production Cost Models

DISPATCHES

Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

Optimization Model (IDAES & Pyomo)

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Market Interaction

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

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

(iii) Settle

(ii) Track

(i) Dispatch

(a) Forecast

(b) Bid

(c) Clear

"Double loop" simulation

Optimal Hybrid Energy System

Inputs

PRESCIENT

Input-output data

Market Surrogates (IDAES Surrogates)

ALAMO a black-box modeling tool

K + TensorFlow

OMLT

PySMO