Multiperiod Conceptual Design of Integrated Energy Systems with Market Interaction Surrogate Models

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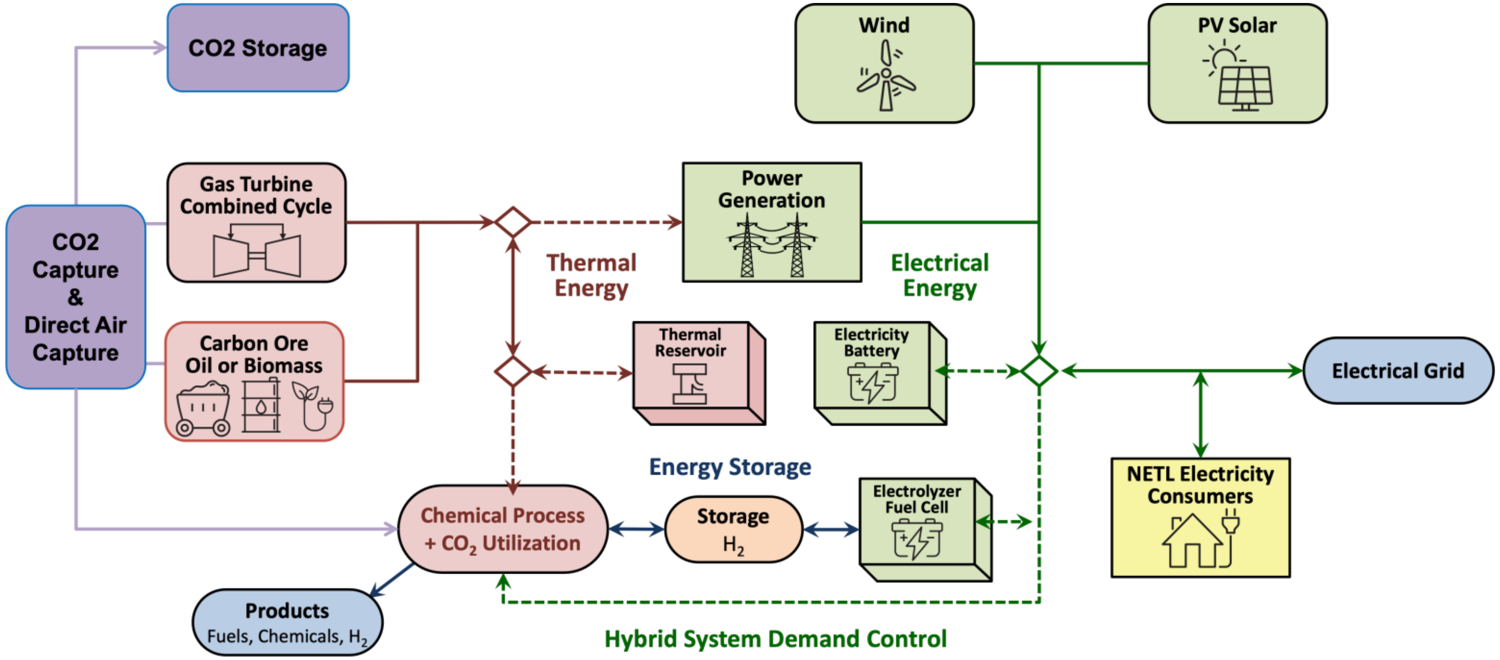
Integrated Energy Systems (IES) Provide Dynamic Flexibility

Multiple inputs and technologies:

Nuclear
Gas turbine
Fossil fuels
(w/ carbon capture)
Solar
Wind
Batteries
PEM electrolyzer



Multiple outputs and markets:

Electricity
Energy Storage
Ancillary Services
Heating/Cooling
Chemicals

Advantages:
Provide operation flexibility
Facilitate renewable integration
Reduce carbon emissions
Reduce grid operation costs

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

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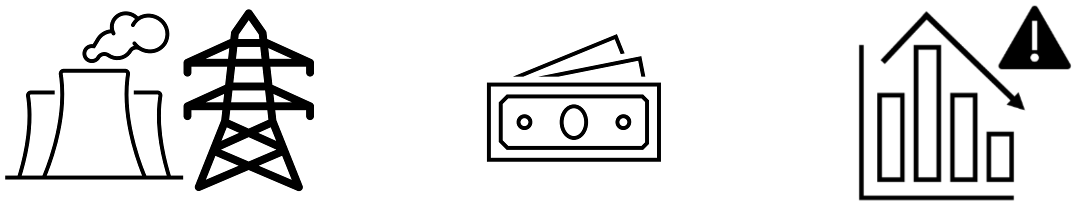
Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

Figure adapted from: Arent, Douglas J., et al. "Multi-input, multi-output hybrid energy systems." *Joule* 5.1 (2021): 47-58.

Traditional IES Optimization Approaches Have Limitations

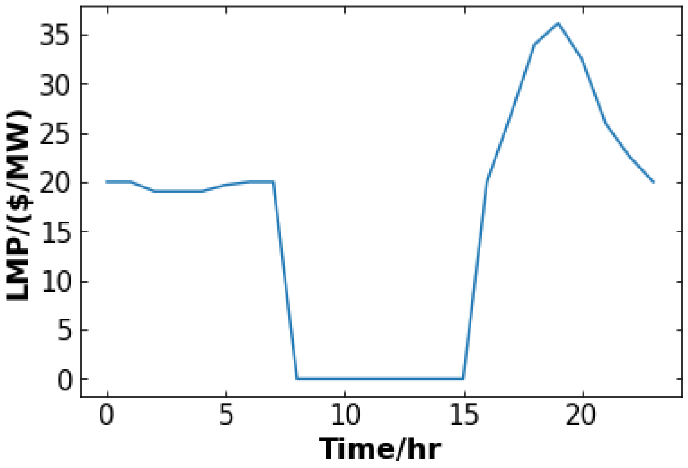
Traditional Techno-Economic Analysis:

- Fixed selling price of electricity and IES capacity factor.
- Lack information about the electricity grid.
- Static analysis that assumes the constant input parameters.



Technical Analysis | **Economic/Financial Analysis** | **Risk Analysis**

Price-taker Analysis:



Historical Locational Marginal Price $\pi_{s,t}$(LMP)

Data Analysis →

$$\max_{LMP} NPV$$

$s.t.$ Process Constraints

Economic Constraints

Environment Constraints

Price-taker Optimization Models

Solve →

Optimal design
Optimal operation
Net present value
…

Optimal Decisions

Both methods fail to consider **dynamic interactions** between market and IES.

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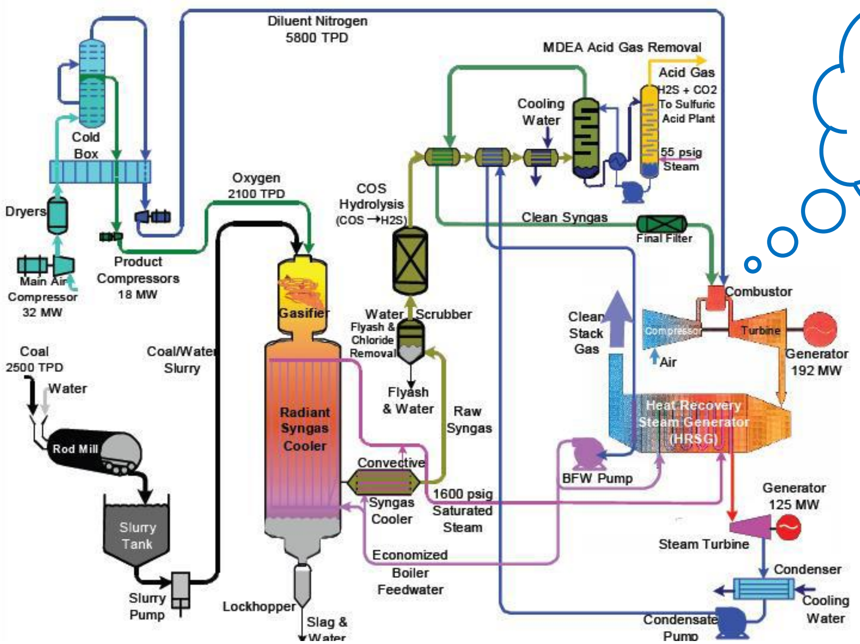
Gooty, Radhakrishna Tumbalam, et al. "Incorporation of market signals for the optimal design of post combustion carbon capture systems." *Applied Energy* 337 (2023): 120880.

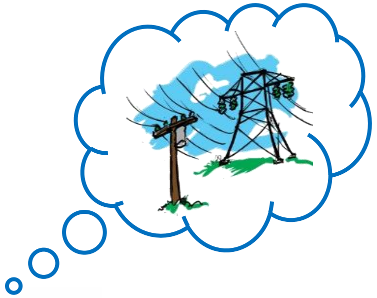
Developing Optimization Environments for Scale-bridging

Process-centric Modeling

Detailed plant model assuming grid as an infinite capacity bus

Price-taker model





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

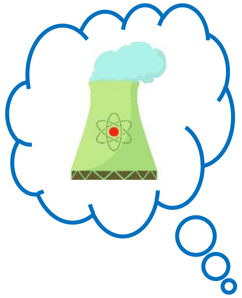
Market Interactions

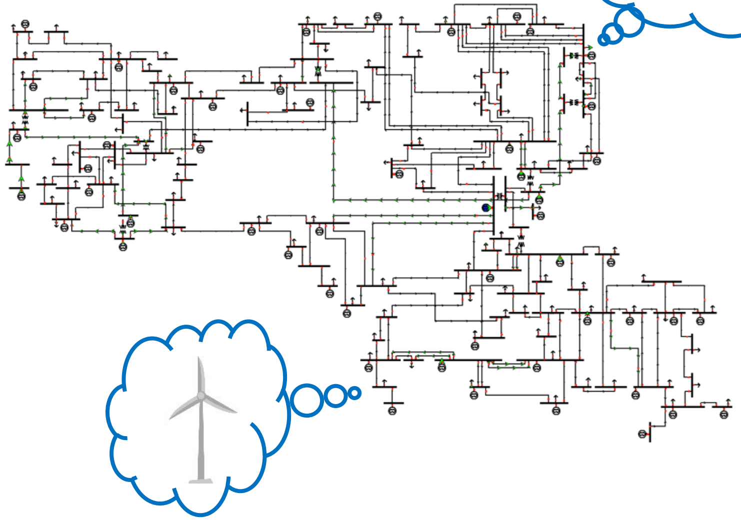
Hybrid System Operations

Grid-centric Modeling

Detailed power flow models,
with individual generators modeled

Product cost models (PCM)





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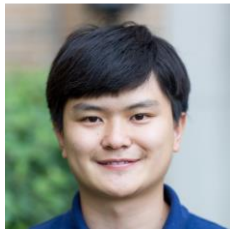
Multiscale Simulation Framework Moves Beyond Price-taker



Dr. Gao, Xian

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

PRESCIENT

(iii) Settle

balance:
- cost
- health
- tracking penalty

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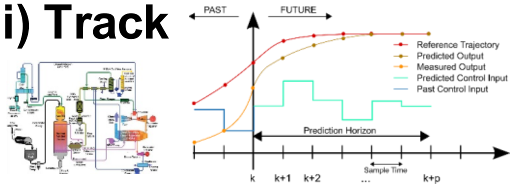
(ii) Track



min **system generation costs**
(economic dispatch)

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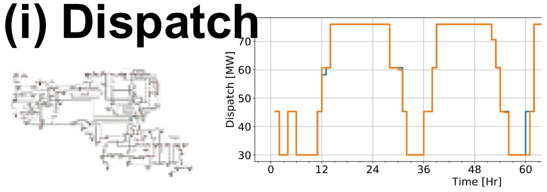
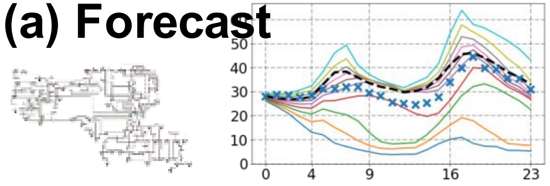
(i) Dispatch



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

(a) Forecast



Forecast the LMP for the certain time periods.

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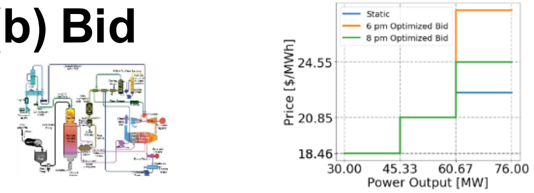
(b) Bid



max **E[Profit]**

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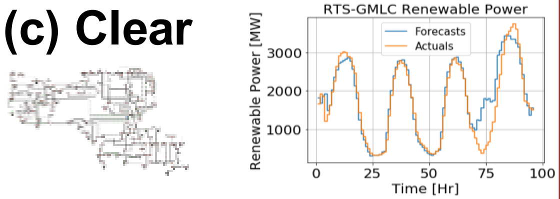
(c) Clear



min **system generation costs**
(unit commitment)

PRESCIENT

Key take away:

The multiscale simulation framework mimics how independent system operators (ISO) operate the U.S. wholesale electricity markets and provides generator-level operation information.

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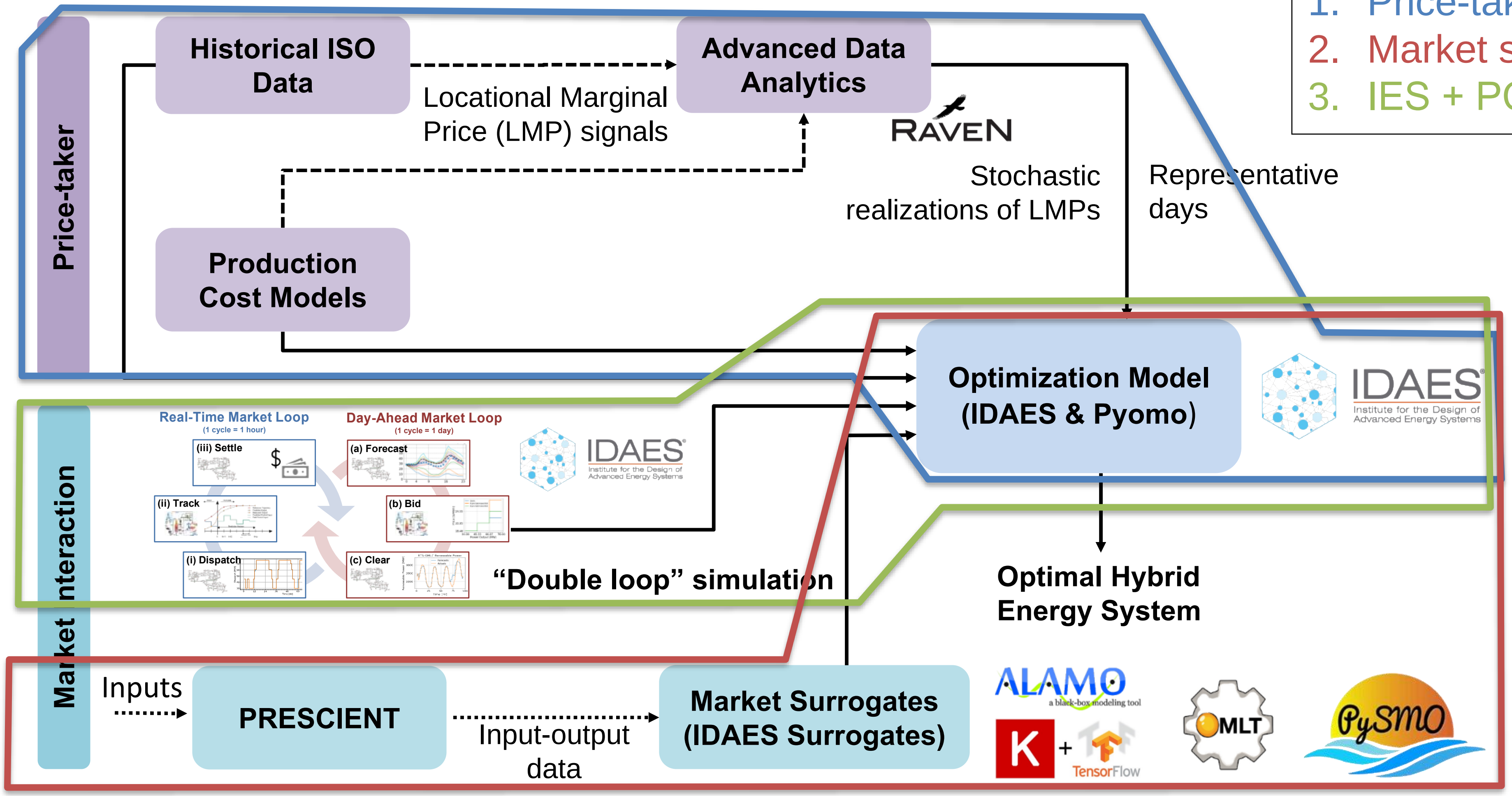
Gao, Xian, et al. "Multiscale simulation of integrated energy system and electricity market interactions." Applied Energy 316 (2022): 119017.

DISPATCHES Optimization Workflow



Three Workflows:

1. Price-taker
2. Market surrogates + design
3. IES + PCM "double-loop" optimization

Advantages of each workflow

Price-taker: Low complexity.

Surrogate: More accurate.

Double-loop: Provide insights into how operation (bidding) impacts the IES economics and the grid.

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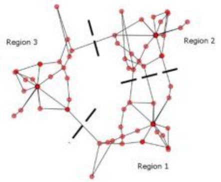
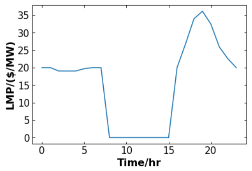
IES Conceptual Design Optimization with Surrogate Models



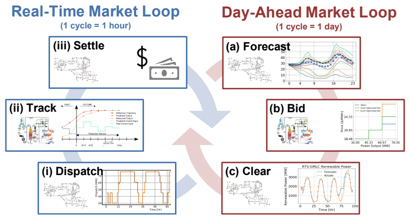
RTS-GMLC



LMP signals

$$\max_{d,u} E(NPV)$$
$$\text{s.t. } f(d,u,\pi_t) = 0$$
$$g(d,u,\pi_t) \leq 0$$

PYOMO



PCM Simulations → LMP Signals → Price-taker Optimization → PCM Verification

PCM Simulations → Train ML Surrogates → Optimization with Surrogates → PCM Verification

PRESCIENT

Keras

TensorFlow

OMLT

PYOMO

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Step 1. Generate training data

IES/Generator characteristics
- PEM Capacity
- Bid curve

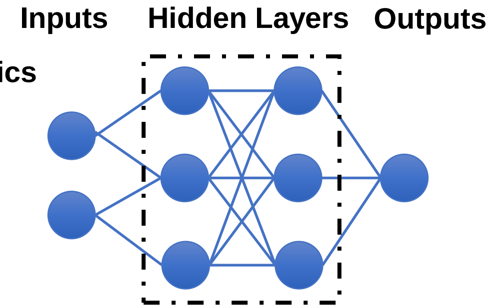
Market metrics
- Reserve
- Shortfall price

→ **Production Cost Models (PRESCIENT)** → **Day-ahead/ real-time dispatch signals and LMPs**

Step 2. Train neural network surrogate model

Generator characteristics
- PEM Capacity
- Bid curve

Market metrics
- Reserve
- Shortfall price



Revenue or frequency/capacity factor

Step 3. Formulate and solve the design problem by embedding market surrogates

Step 4. (Optional) Verify the optimal result using PCM.

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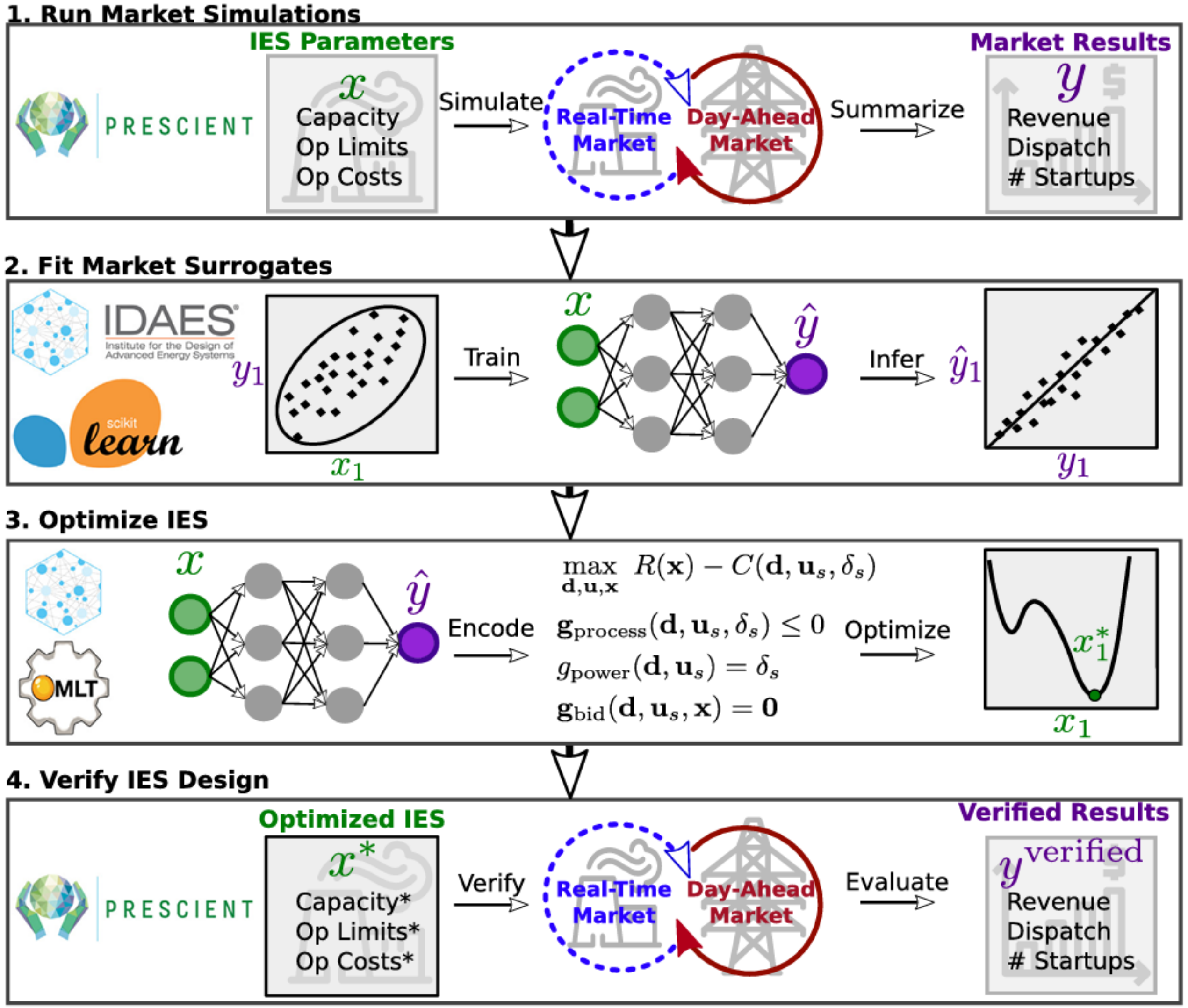
Recent Paper: Beyond Price-taker, Co-Optimization of a Thermal Power Plant (Power Only)



Totally 64000 annual PCM simulations of a **Rankine cycle** thermal power plant.

Three surrogate models (**revenue, start-up, frequency**) to model the IES/market interaction.

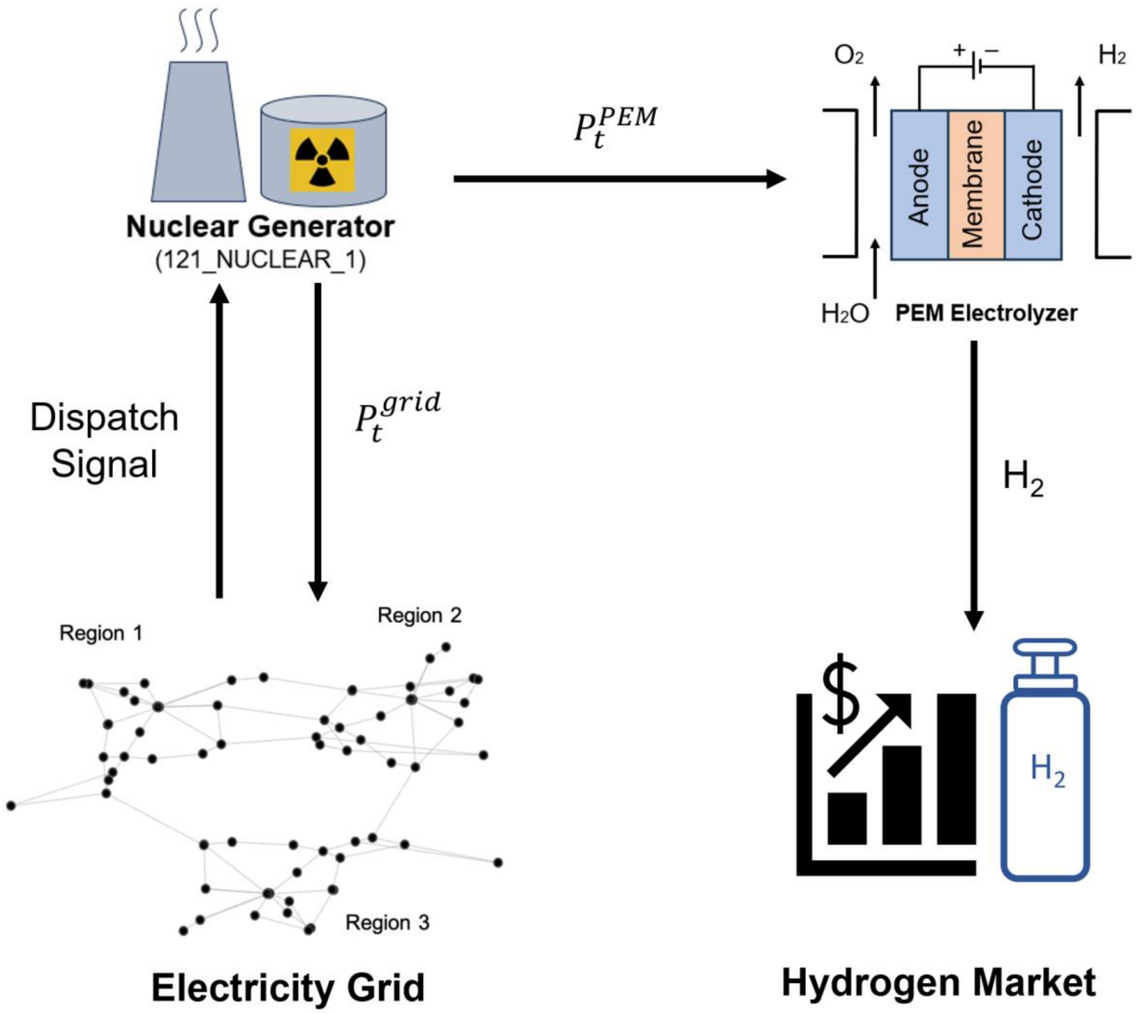
Price-taker **overestimates** the revenue because large generators will **suppress** the market electricity price .

Optimization with market surrogates is **accurate** over a wide range of conditions.

Jalving, Jordan, et al. "Beyond price taker: conceptual design and optimization of integrated energy systems using machine learning market surrogates." *Applied Energy* 351 (2023): 121767.

Nuclear Energy (NE) Model (Co-produce Power + Hydrogen)

- Increasing renewables → volatile grid conditions
  - Nuclear generators cannot respond (baseload)
- Participate in alternate markets, e.g., H_2
  - Increases profitability, efficiency and flexibility
- Need to co-optimize design and operating decisions of IES due to dynamic markets
- Need to consider how IES influence markets, e.g., change electricity prices
- Simplified H_2 market (constant H_2 price)
  - Price-taker



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Price-taker and Conceptual Design Optimization Model

Price-taker Model

$$\max_{d,u} \varphi \sum_{t\in T} \left(R(d,u_t,\pi_t) + R_{H2}(d,u_t) - C_{OPEX}(d,u_t)\right) - C_{CAPEX}(d)$$

$$s.t. \quad g_{process}(d,u_t) \le 0 \qquad t \in T$$

$$g_{process}(d,u_t) = 0 \qquad t \in T$$

Conceptual Design Model with Surrogates

$$\max_{d,u,\delta} \varphi\left[R(x) + \sum_{s\in S} \omega_s(x)\left(R_{H2}(d,u_s,\delta_s) - C_{OPEX}(d,u_s,\delta_s)\right)\right] - C_{CAPEX}(d)$$

$$s.t. \quad g_{process}(d,u_s) \le 0 \qquad s \in S$$

$$g_{power}(d,u_s) = \delta_s \qquad s \in S$$

$$R(x) = f_{rev}(x)$$

$$\omega_s(x) = f_{freq}(x) \qquad s \in S$$

Functions/Variables/Parameters/Sets	Description
f_{rev}	Revenue surrogate
f_{freq}	Frequency surrogate
R	Electricity revenue
R_{H2}	Hydrogen revenue
C_{OPEX}	Operation cost
C_{CAPEX}	Capital cost
d	IES design variables
u_s, u_t	IES Operation variables
ω_s	Weights of scenarios
x	Surrogate inputs
π_s	LMP signals
δ_s	Representative operation profiles
φ	NPV multiplier
S	Scenarios
T	Time periods

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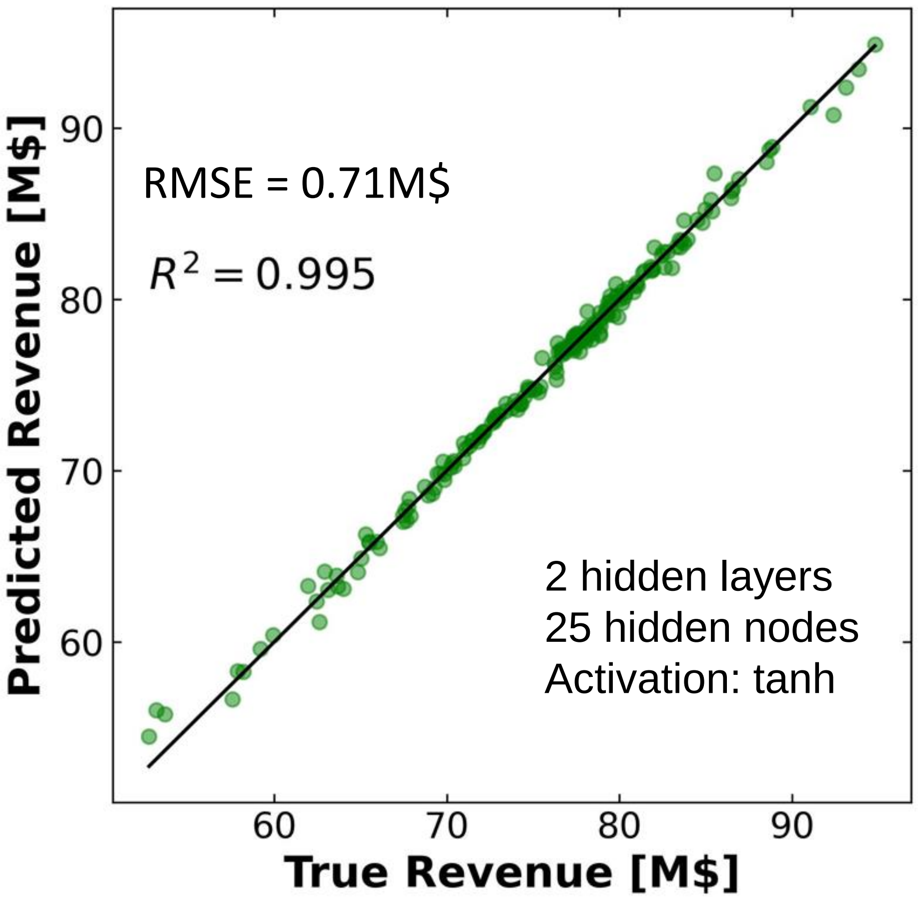
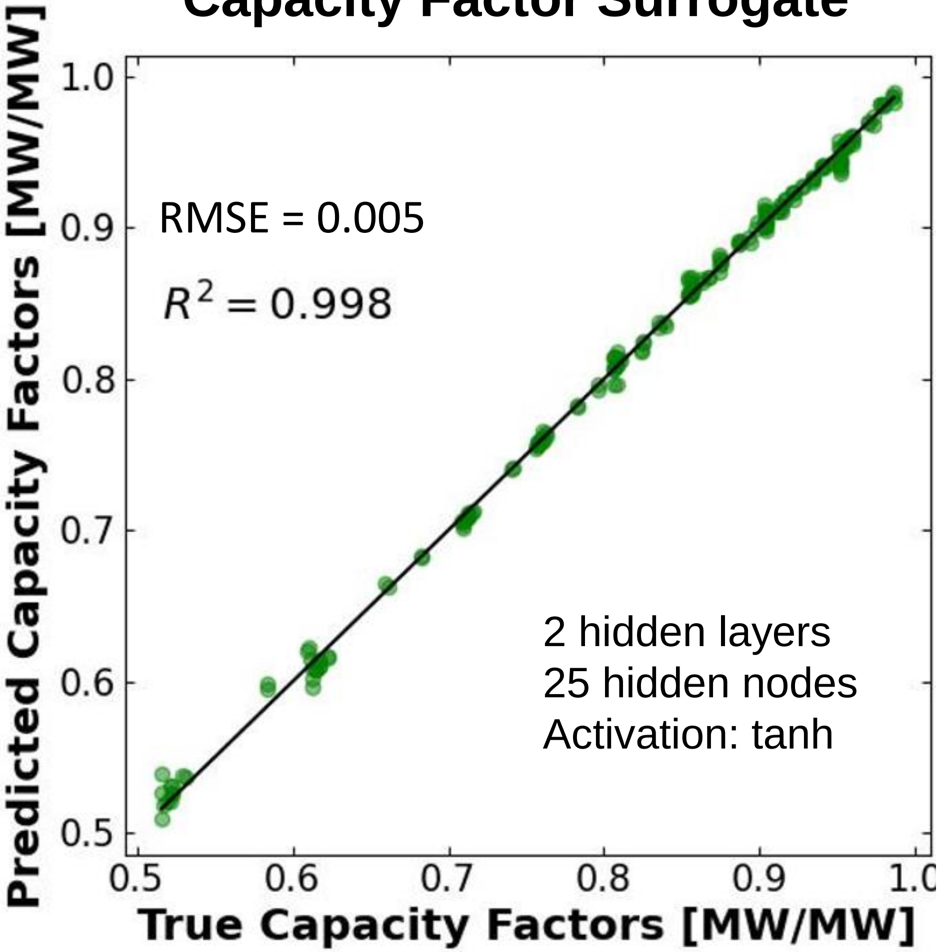
Surrogate Models Have Good Regression Performance

Revenue Surrogate



Predict the electricity revenue according to the IES design.

Capacity Factor Surrogate



Predict the annual capacity factor according to the IES design.

Keras

TensorFlow

OMLT

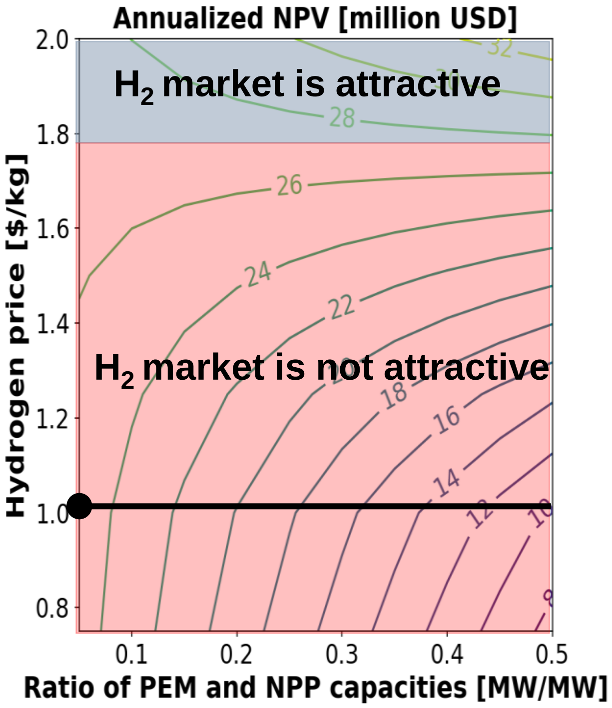
Price-taker Gives Inaccurate Economic Analyses

- Difference in the **net present value** and breakeven H_2 price

Price-taker **overestimates** the breakeven H_2 price

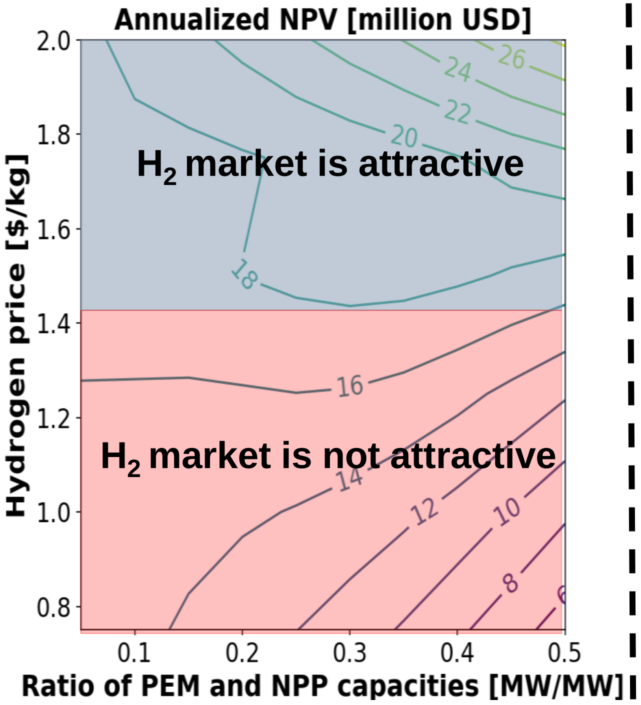
Price-taker

~$1.8/kg



Market Surrogate

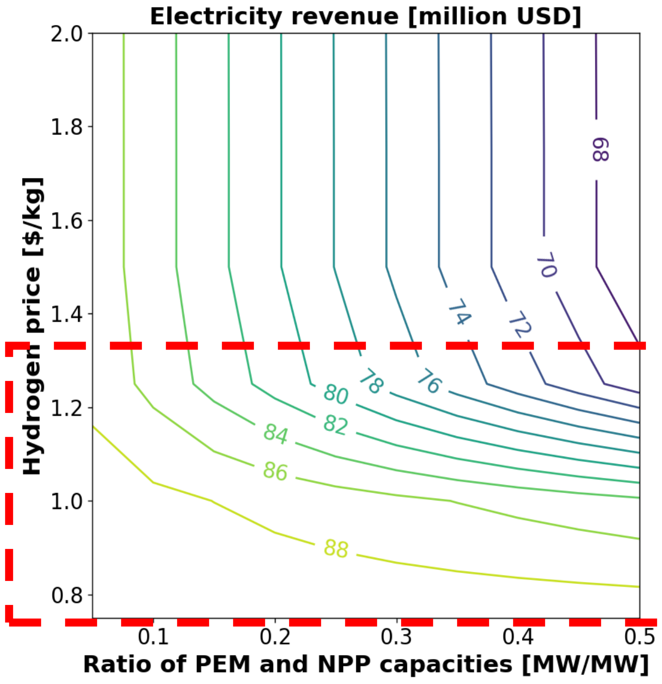
~$1.4/kg



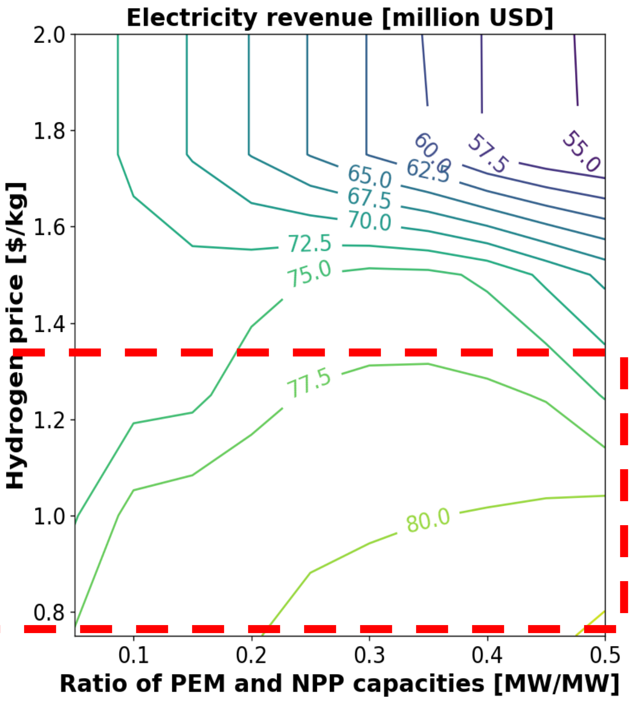
- Difference in **electricity revenue**

Electricity revenue depends on H_2 vs electricity production schedule – **nuanced interactions**

Price-taker



Market Surrogate



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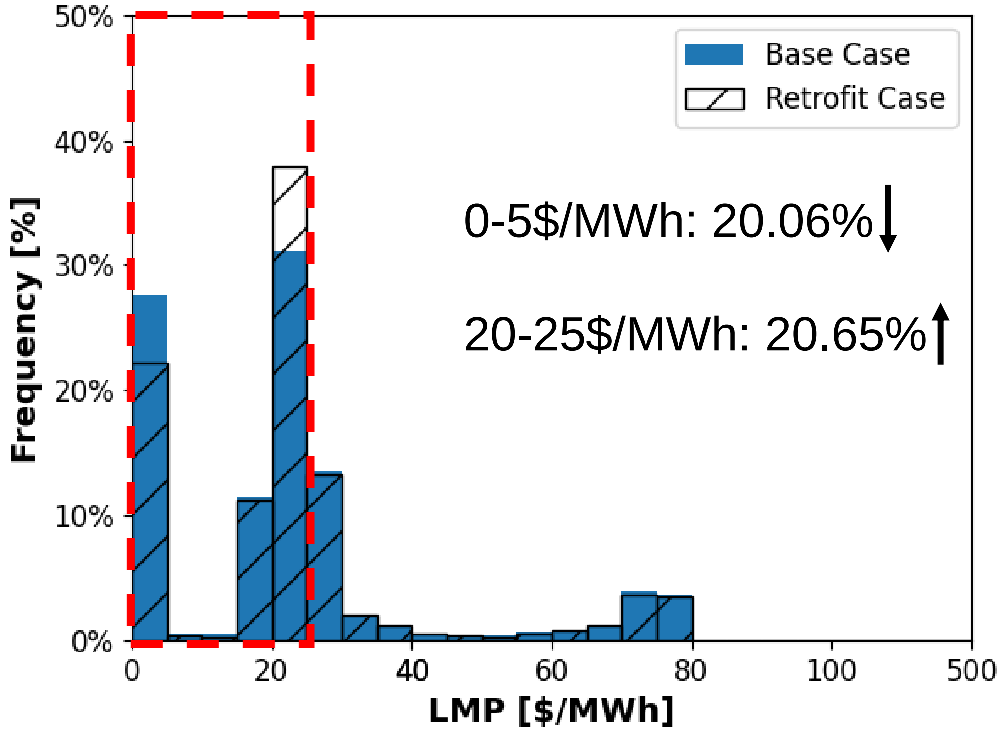
IES-Market Interactions Change the LMP Distribution

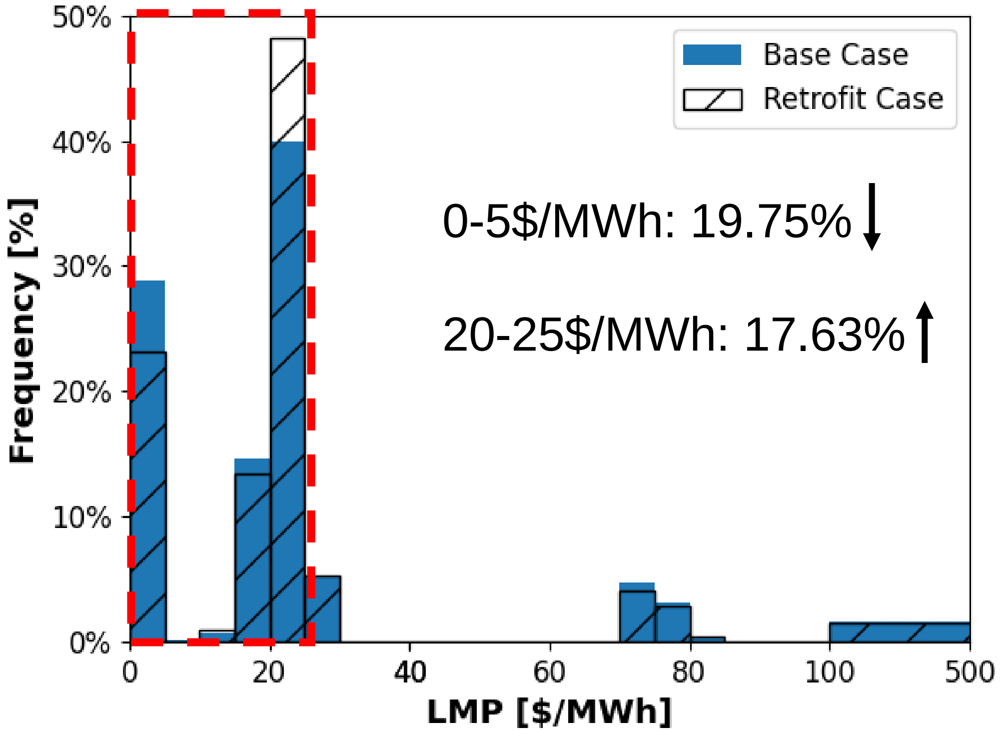
Base case (400 MW baseload nuclear generator without an electrolyzer)

Retrofitted case (400 MW nuclear generator equipped with a 200 MW electrolyzer – H_2 sold at \$1/kg)

Day-ahead Prices



Real-time Prices



Fewer periods near **0 \$/MWh** and **more** periods near **20 \$/MWh.**
IES **reduces** the electricity supply at low LMP periods and increases the price.

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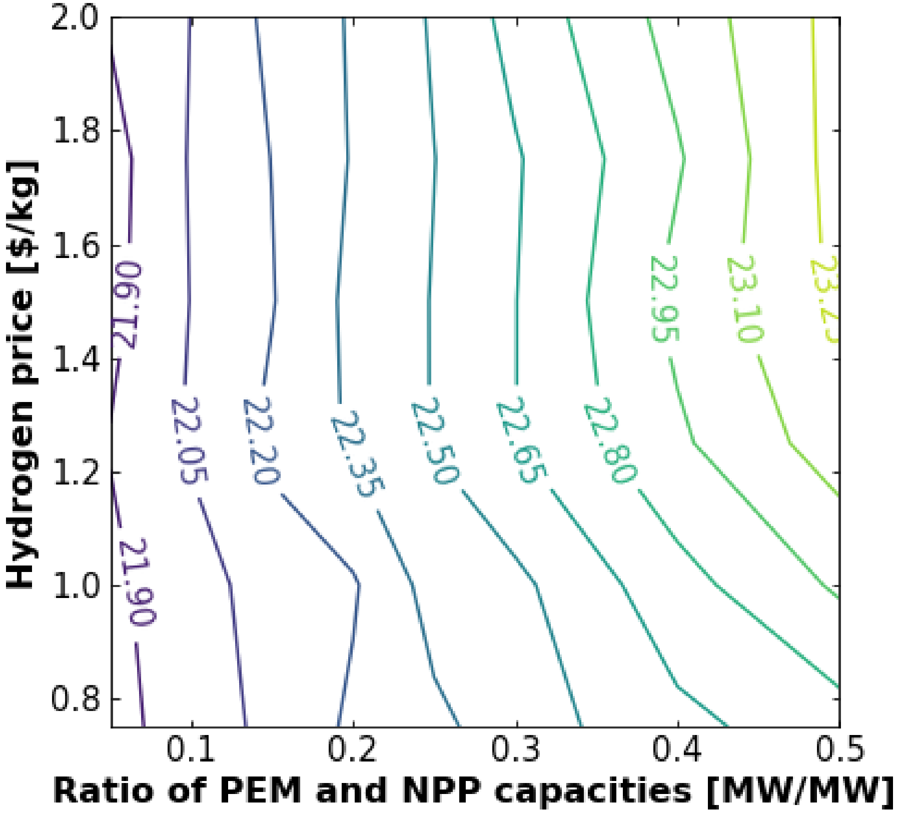
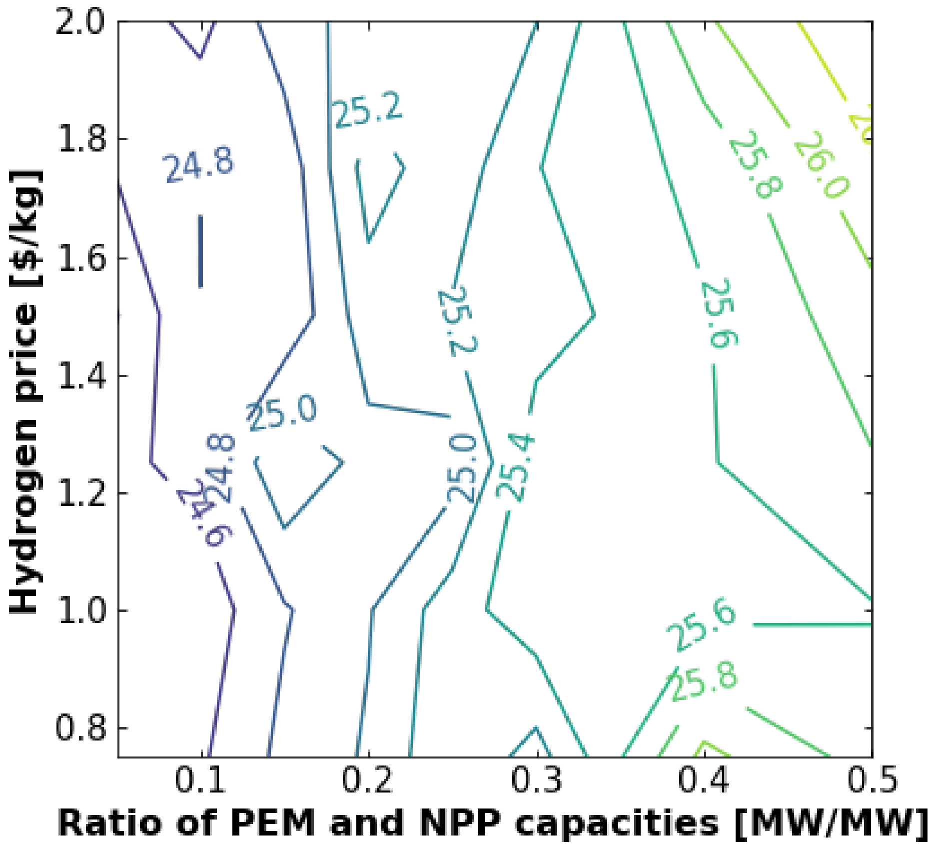
A Larger PEM Tends to Increase the Average LMP

Day-ahead Prices



Real-time Prices



The annual average LMP at the node is impacted by IES designs.
However, price-taker model ignores this interaction.

Conclusion

- The price-taker optimization overestimates the economic performance of IES, which may mislead the decision making.

- The interactions between IES and market will impact the electricity price and eventually affect the electricity revenue, where the price-taker model can’t capture this.

- Using the market surrogate framework will enable us to have a more accurate economic analysis of IES.

Future Work

- How to apply the surrogate-assisted workflow to the IES with storage systems.

- How to develop a general form of the surrogate model to describe all IES.

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