Beyond Price Taker: Optimizing Integrated Energy Systems Considering Market/Grid Interactions

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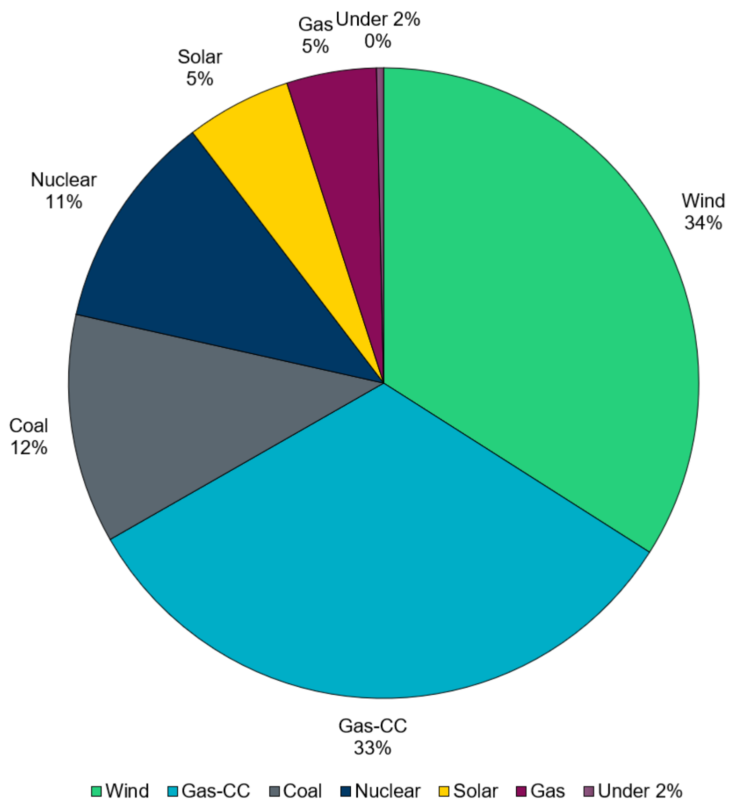
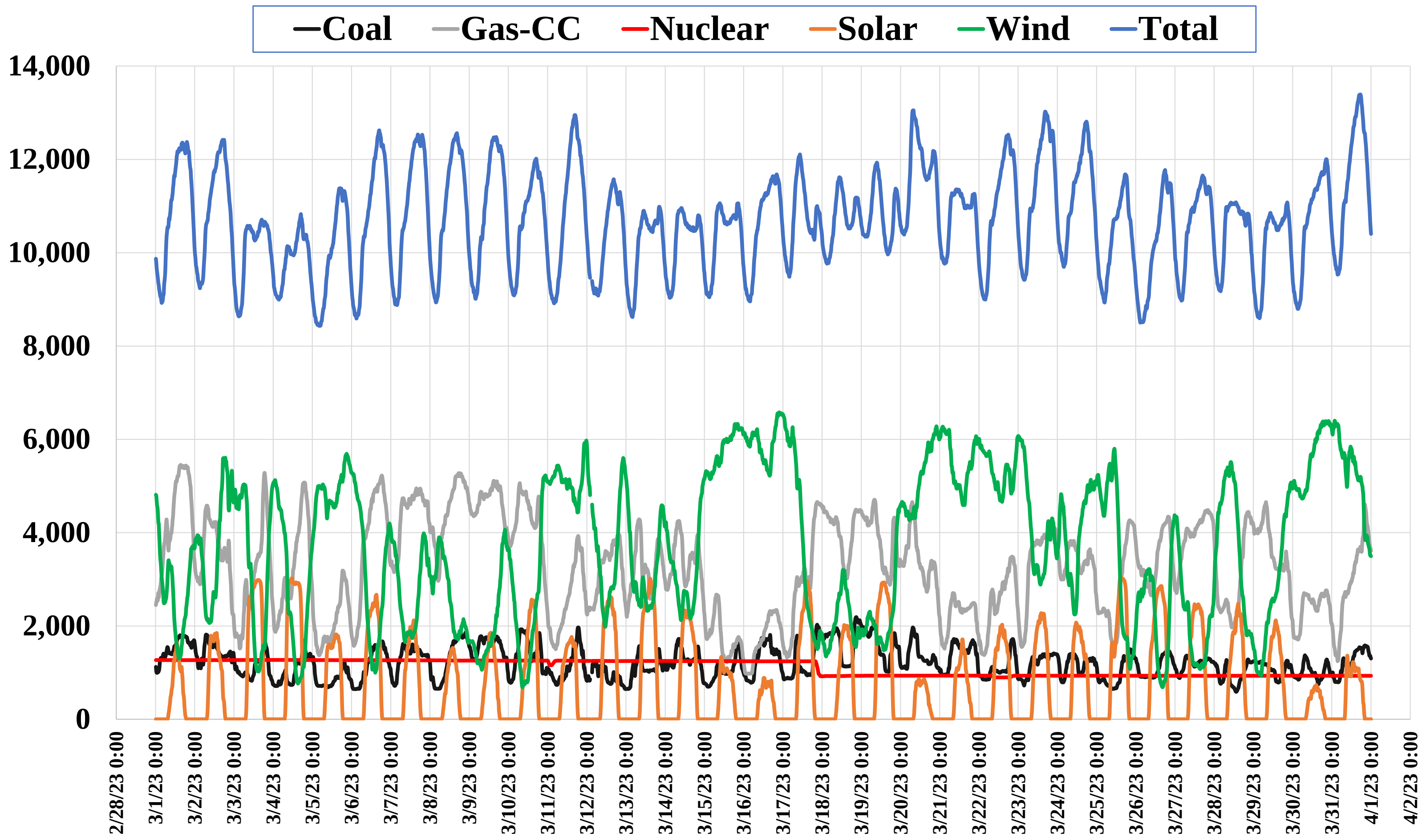
Evolving Grid Increasingly Requires Flexibility

Data for Electric Reliability Council of Texas (ERCOT) ISO

Energy by Fuel for 2023



ERCOT Generation Mix - March 2023



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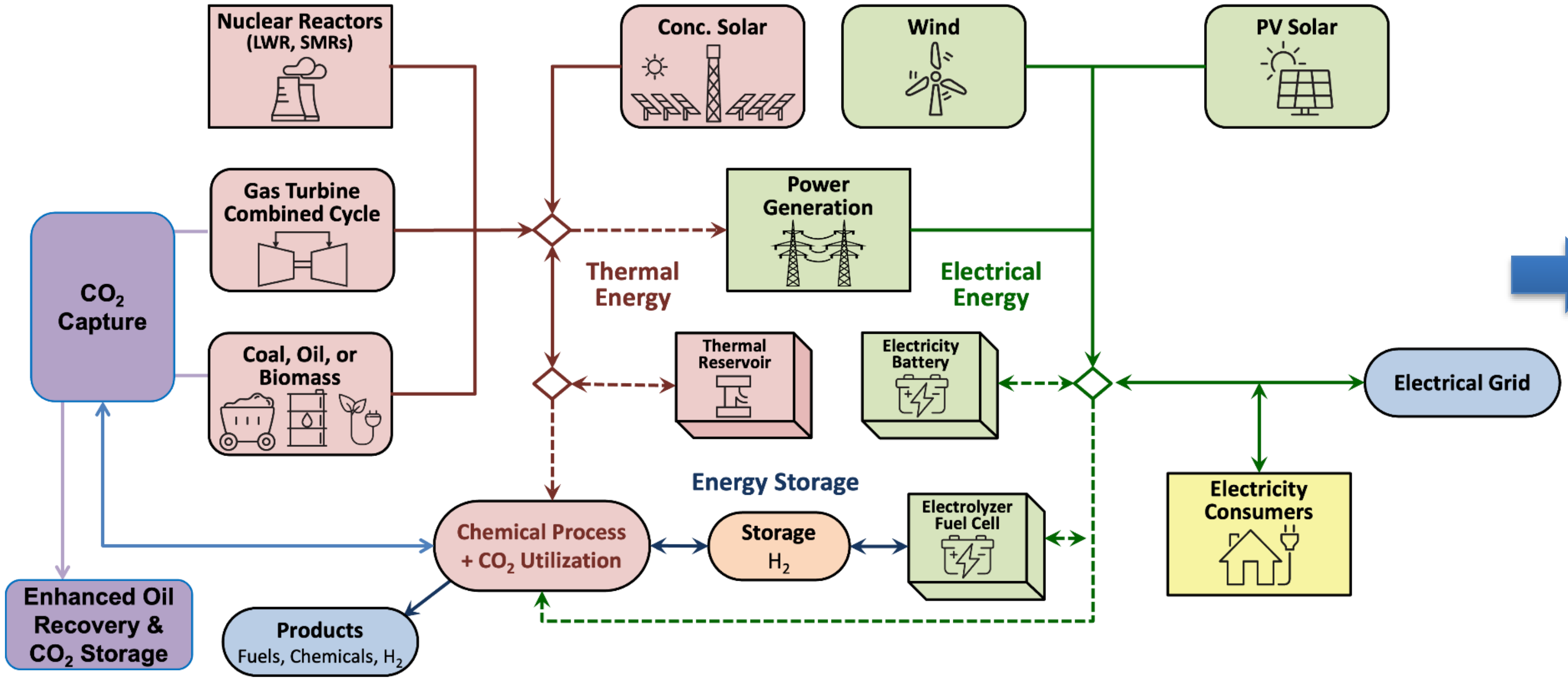
Source: https://www.ercot.com/gridinfo/generation

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 integration of multiple energy sources
Reduce grid operation costs
Increases grid reliability and resiliency

Challenge:

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

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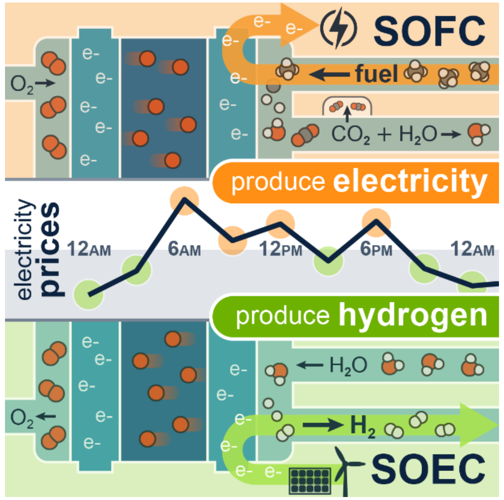
Figure adapted from: Arent, Douglas J., et al. "Multi-input, multi-output hybrid energy systems." *Joule* 5.1 (2021): 47-58.

Presentation Outline

How to **co-optimize** IES design and operation considering **dynamic markets**

<u>Price Taker</u>

Solid oxide fuel cell IESs that co-produce H_2 and electricity

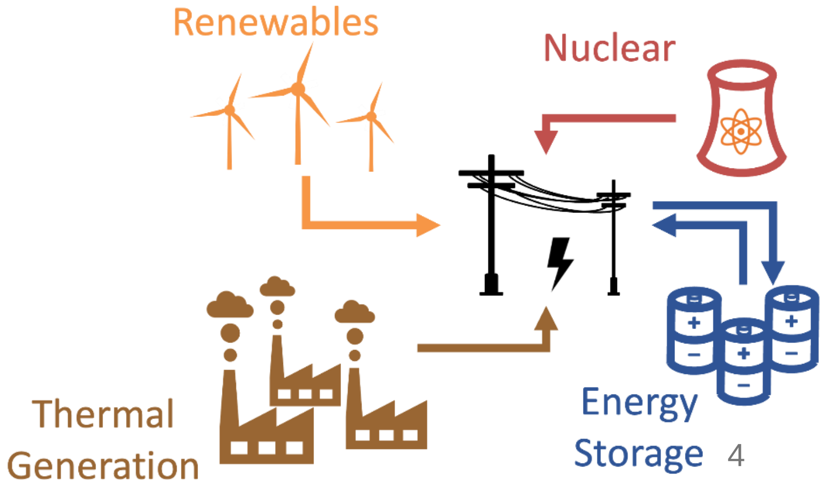


<u>Beyond Price Taker</u>

Nuclear and electrolyzer IESs that co-produce H_2 and electricity

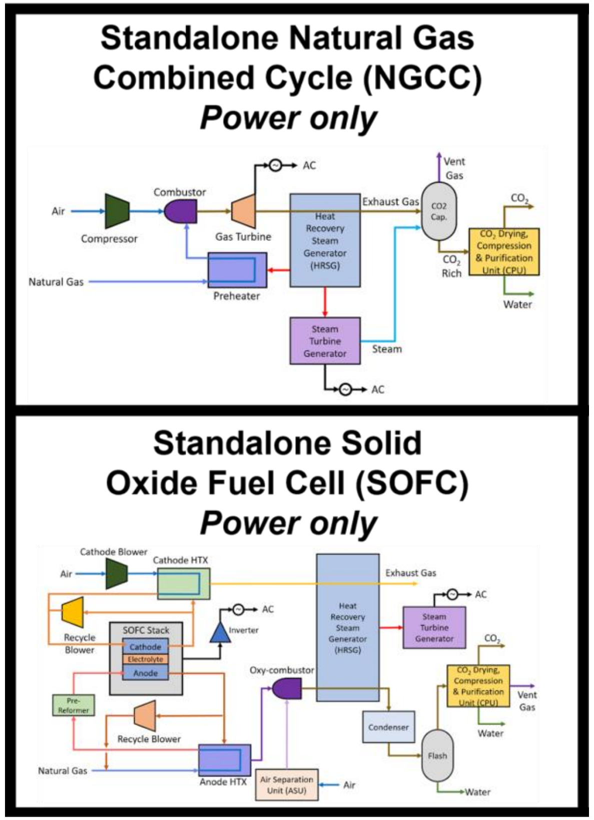
Wind and electrolyzer IESs that co-produce H_2 and electricity

Wind and battery IESs



Compare Solid Oxide Cells (Emerging Technology) with Legacy Technology (NGCC)

- Analyze the viability of SOFCs against legacy technology (NGCCs)



Which generators/technologies should be retired?

Which emerging technologies are worth research/scale-up investment?

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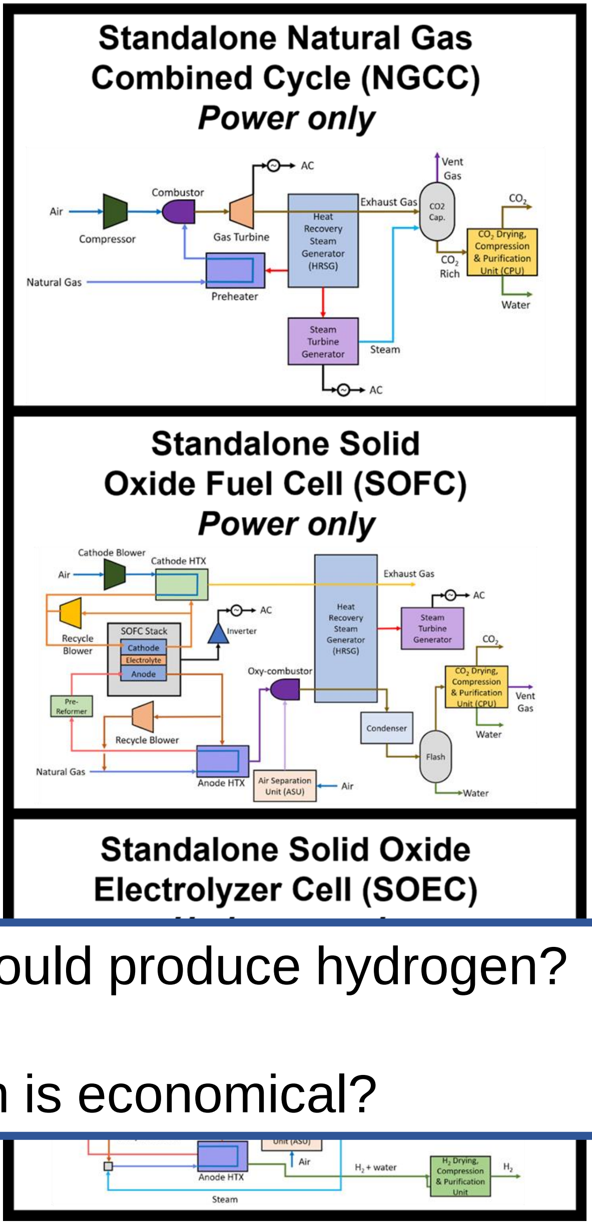
Evaluate Production of Alternative Fuels

- Analyze the viability of SOFCs against legacy technology (NGCCs)

- Evaluate the viability of alternative fuel production (e.g., Hydrogen from SOEC)

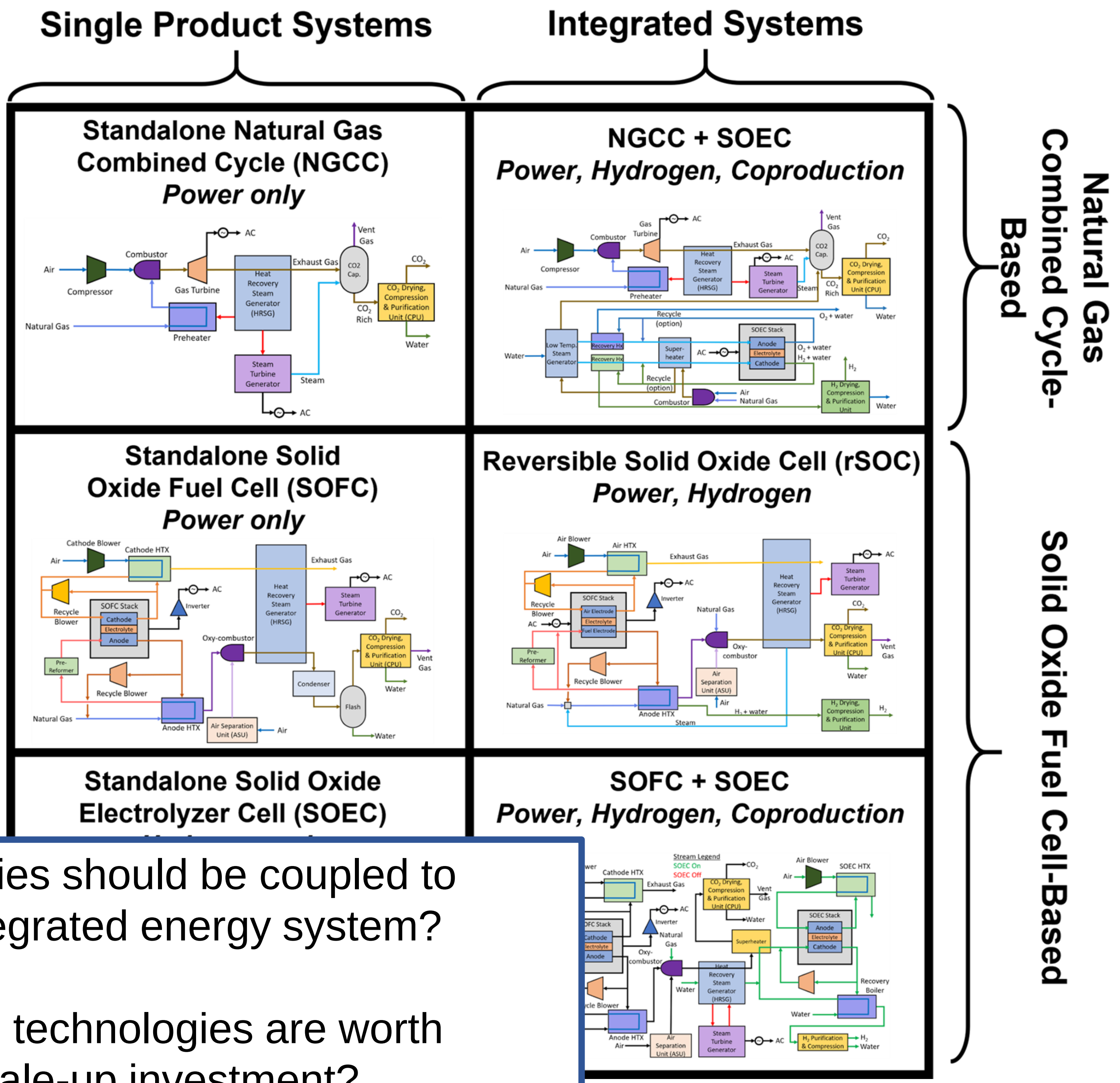


Which technologies should produce hydrogen?

What price of hydrogen is economical?

Evaluate Coproduction

- Analyze the viability of SOFCs against legacy technology (NGCCs)
- Evaluate the viability of alternative fuel production (e.g., hydrogen from SOEC)
- Evaluate integrated energy systems (IESs)
    - Coproduction:
        - Power (NGCC
        - Hydrogen (SO
        - Reversible sys



Which technologies should be coupled to comprise an integrated energy system?

Which emerging technologies are worth research/scale-up investment?

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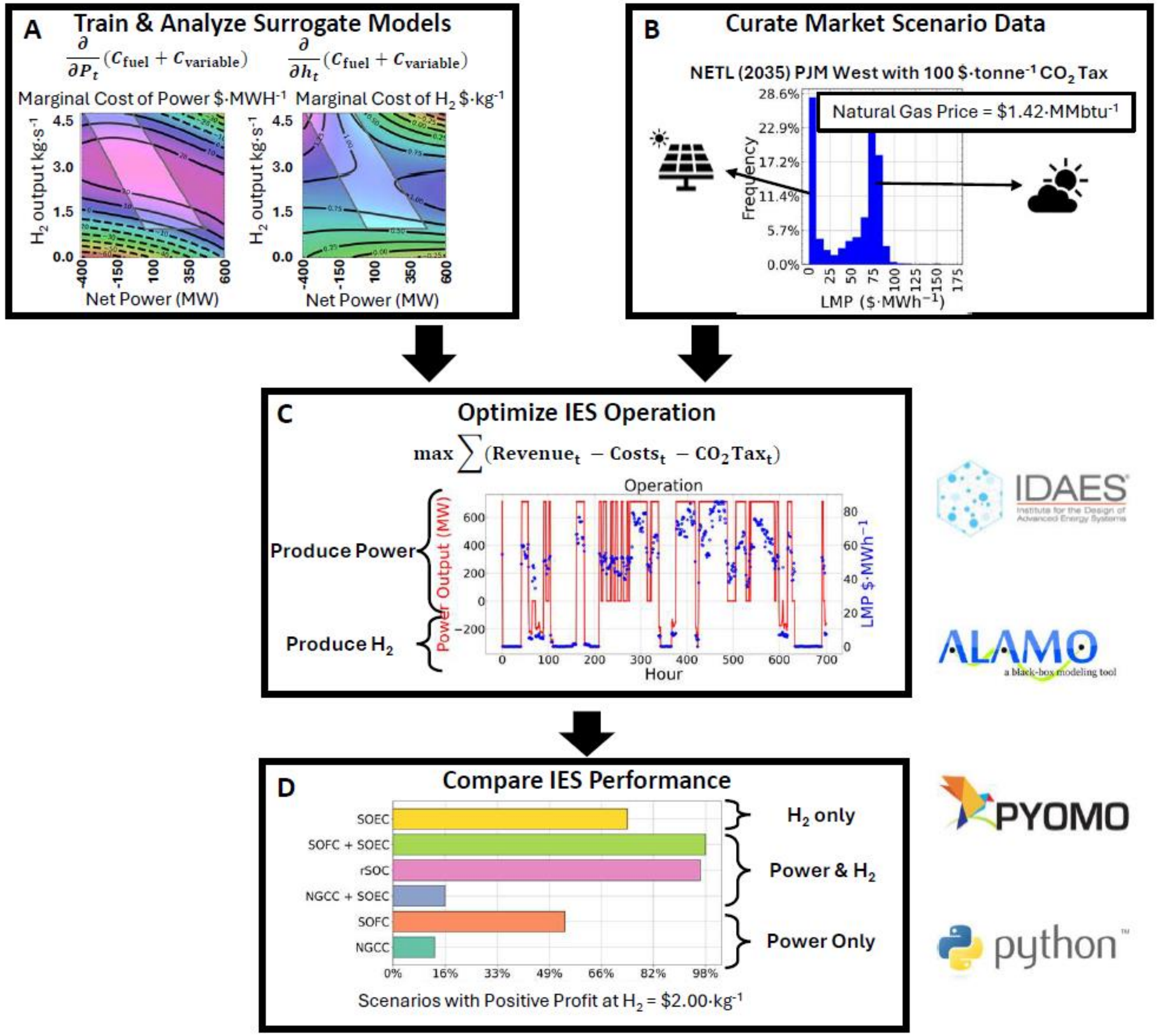
Grid-Wide Decisions for Locational Markets Require a Streamlined Evaluation Framework

Which technologies should produce hydrogen?

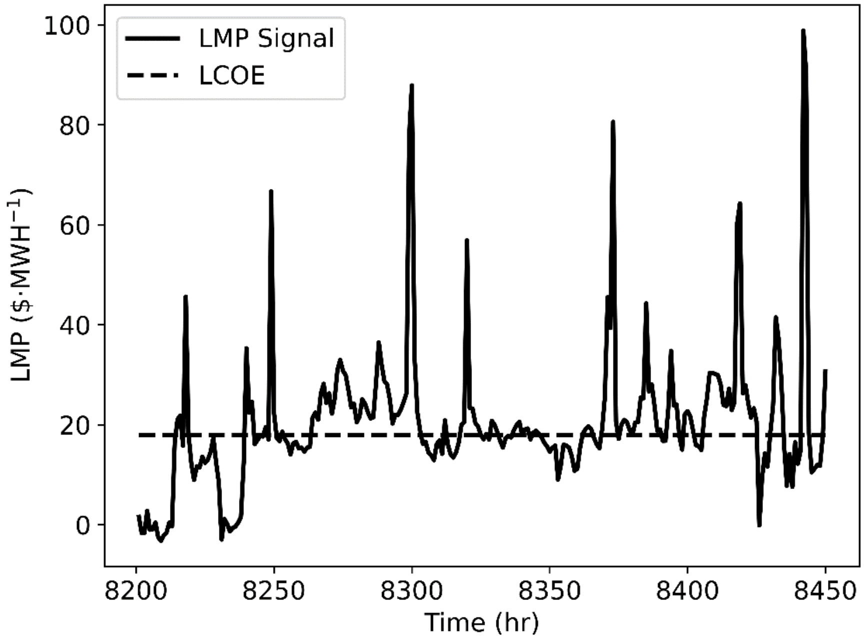
Which technologies should be coupled to comprise an integrated energy system?

Which generators/technologies should be retired?

Which emerging technologies are worth research/scale-up investment?



Price Taker Model Considers Dynamic Prices



Locational marginal price (LMP) changes dynamically, where traditional low-fidelity modeling only uses a static levelized cost of electricity (LCOE)

Objective options: NPV, Annualized NPV, Net Profit

Profit expression at each time period (e.g., hour)

$$f_t^{\text{profit}} = \pi_t^e p_t - \frac{\pi^g}{\bar{\pi}^g} f^{\text{fuel}}(p_t) - f^{\text{var}}(p_t) - \pi^c f^{\text{carbon}}(p_t) - f_t^{\text{fixed}}(P^{\max}) \qquad \forall t \in \mathcal{T}$$

Capacity Constraints

$$P^{\min} y_t \leq P_t \leq P^{\max} y_t \qquad \forall t \in \mathcal{T}$$

Startup and Shutdown Constraints

$$y_t \leq z_{\text{build}} \qquad \forall t \in \mathcal{T}$$

$$\sum_{t-\tau^u+1}^{t} v_j = y_t \qquad \{t|\ t > \tau^u\}$$

$$\sum_{t-\tau^d+1}^{t} w_j = (1 - y_t) \qquad \{t|\ t > \tau^d\}$$

$$y_t - y_{t-1} = v_t - w_t \qquad \{t|\ t > 1\}$$

Ramping Constraints

$$\frac{(P_t - P_{t-1})}{P^{\max}} \leq (r_{\text{su}} - r_{\text{op,u}}) v_t + r_{\text{op,u}} y_t \qquad \forall t \in \mathcal{T}$$

$$\frac{(P_{t-1} - P_t)}{P^{\max}} \leq r_{\text{sd}} w_t + r_{\text{op,d}} y_t \qquad \forall t \in \mathcal{T}$$

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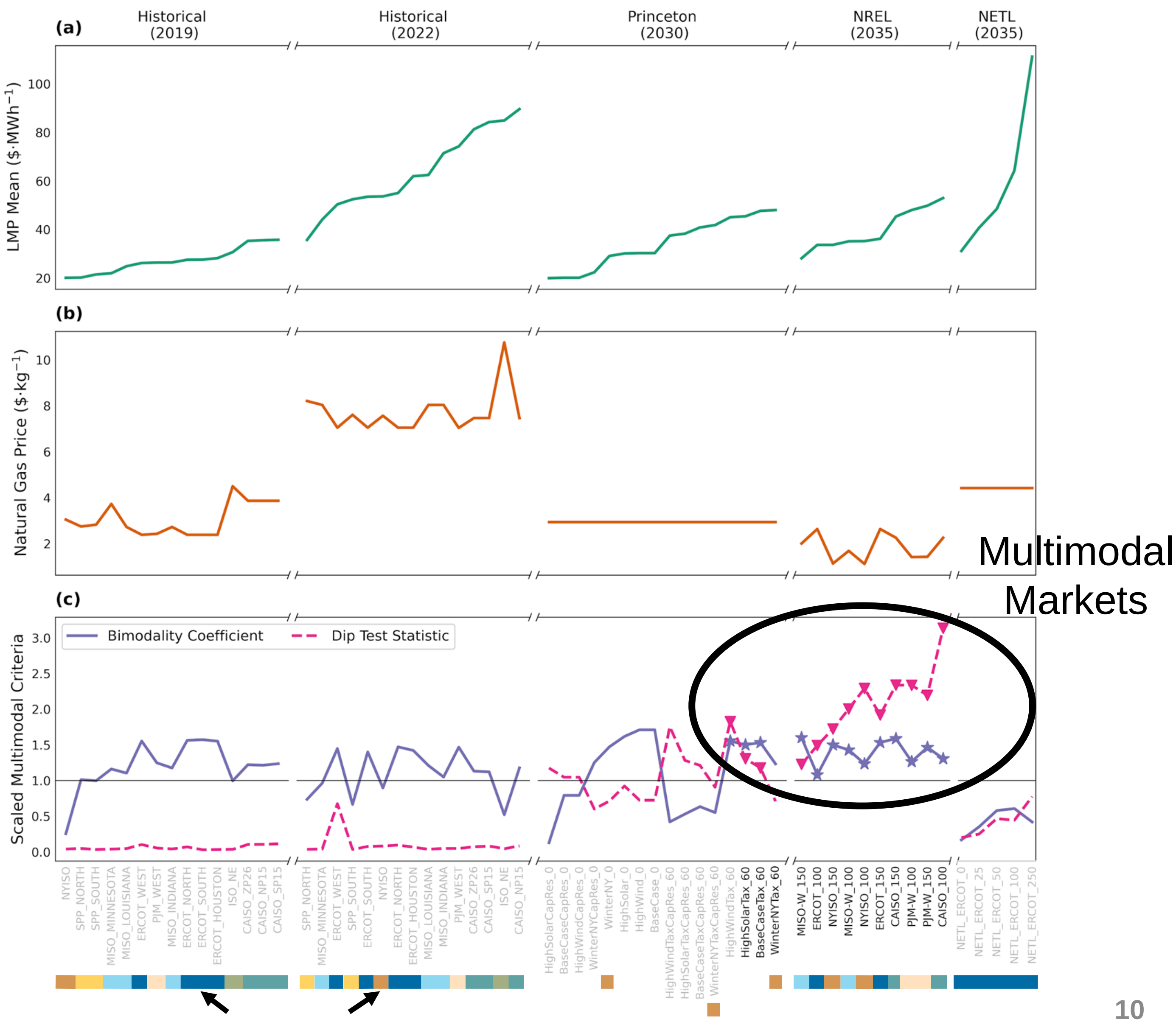
61 Markets Used to Evaluate Emerging Technologies

Figure from FERC (https://www.ferc.gov/electric-power-markets)

- 15 historical markets (2019)
- 15 “current” markets (2022)
- 16 forecasted scenarios (2030)
  - “Princeton”
- 10 forecasted scenarios (2035)
  - “NREL”
- 5 forecasted scenarios (2035)
  - “NETL”



Regional Market Association

Emerging Coproduction Technologies Make a Profit in Most Scenarios

Percentage of scenarios that make profit at each **hydrogen selling price** ($1.00 kg^{-1} to $3.00 kg^{-1})

Process Concept	$1.00\$\cdot kg^{-1}$	$1.50\$\cdot kg^{-1}$	$2.00\$\cdot kg^{-1}$	$2.50\$\cdot kg^{-1}$	$3.00\$\cdot kg^{-1}$
NGCC	13%	13%	13%	13%	13%
SOFC	54%	54%	54%	54%	54%
NGCC + SOEC	8%	11%	16%	62%	80%
rSOC	54%	77%	97%	100%	100%
SOFC + SOEC	46%	79%	98%	100%	100%
SOEC	10%	49%	74%	87%	98%

Takeaway: At sufficient hydrogen price ($2.50+), even the existing thermal generation technology with co-production (NGCC +SOEC) sees profit in over half of the market scenarios.

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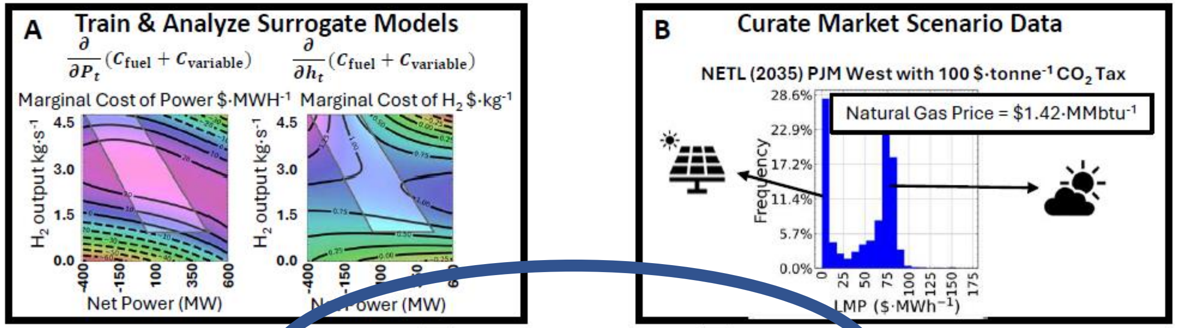
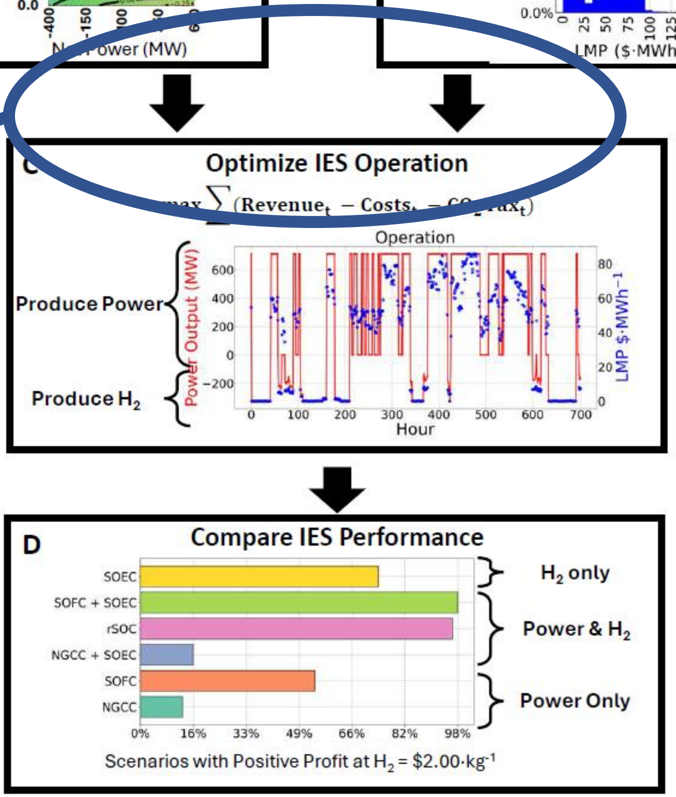
Price Taker Class Streamlines Optimal Operation Scheduling

- Automatically populates LMP (market data) in model
- Only need to specify costing equations and choose operational constraints for a representative time period
- Easily automated/scriptable using the IDAES ecosystem (Python, open-source)



Modeling effort lowered from weeks to hours



IDAES Documentation:
https://idaes-pse.readthedocs.io/en/main/reference_guides/apps/grid_integration/index.html

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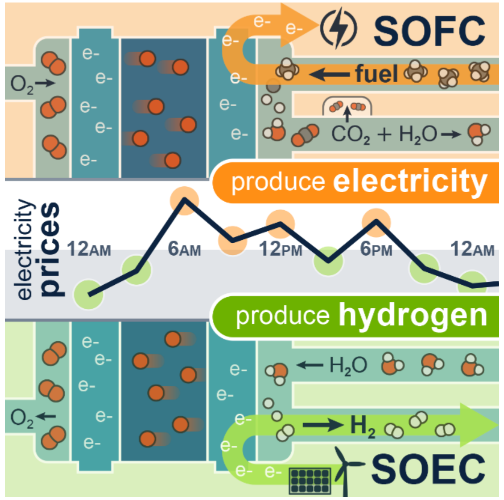
Presentation Outline

How to **co-optimize** IES design and operation considering **dynamic markets**.

Price Taker

Solid oxide fuel cell IESs that co-produce H_2 and electricity



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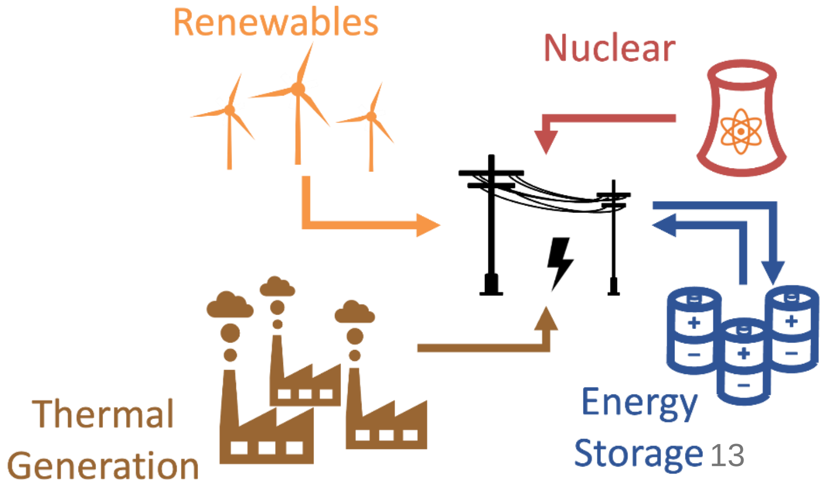

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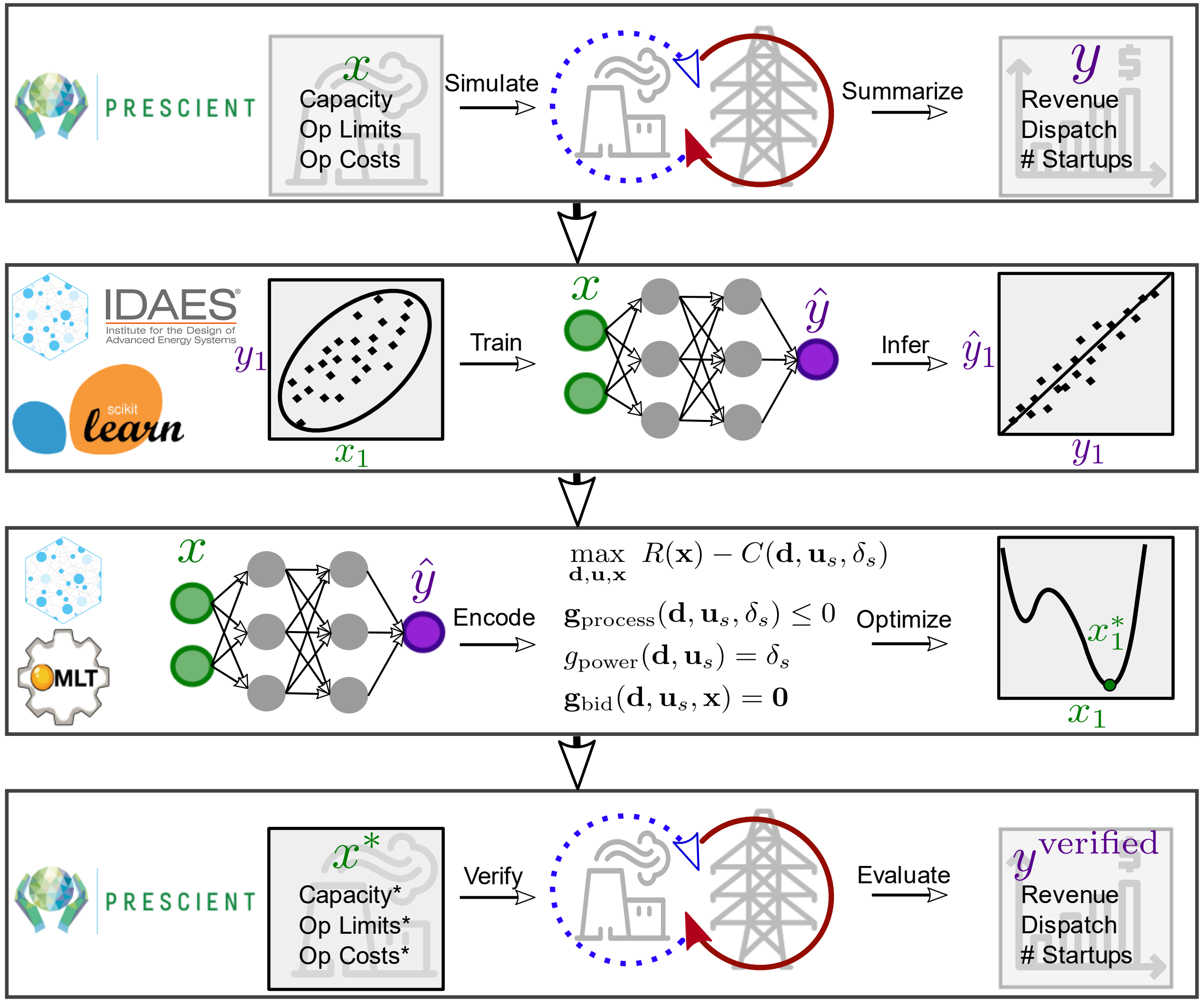
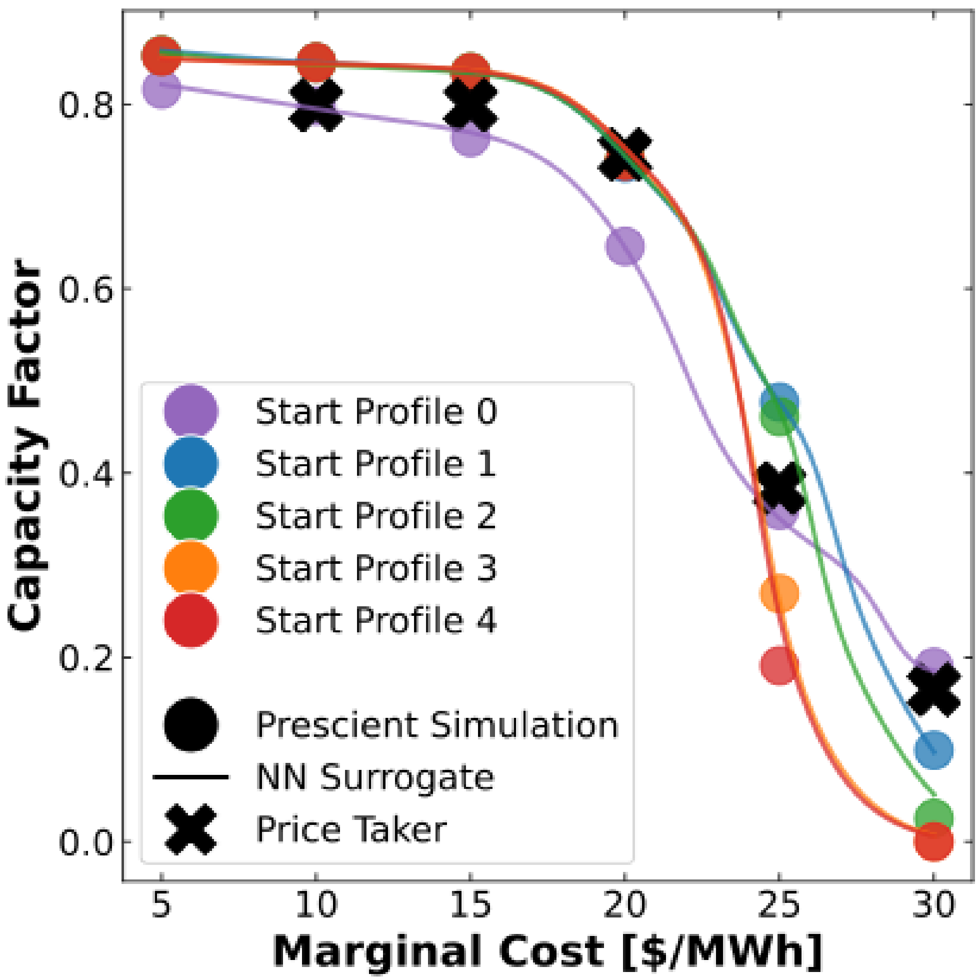
Moving Beyond Price Taker



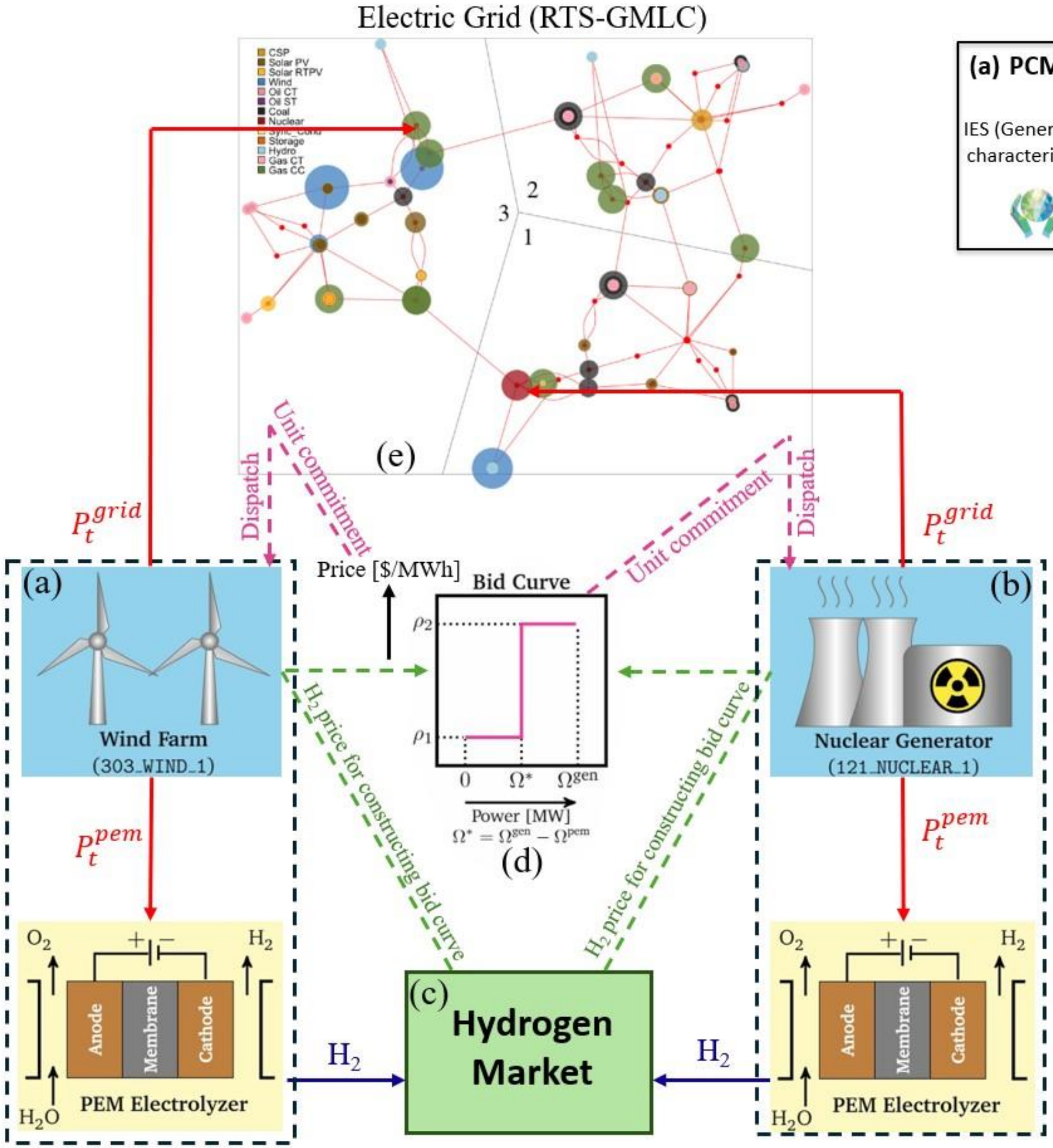


price taker breaks down

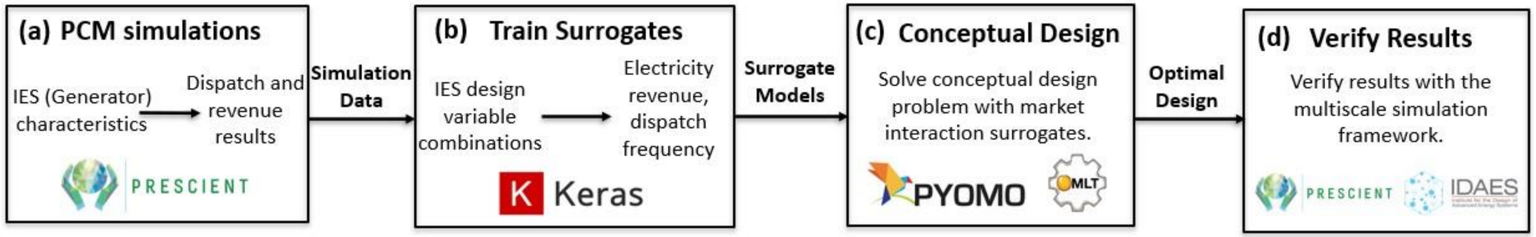
Jalving et al, *Applied Energy (2023)*

Beyond Price Taker: Co-Production of Electricity and H_2

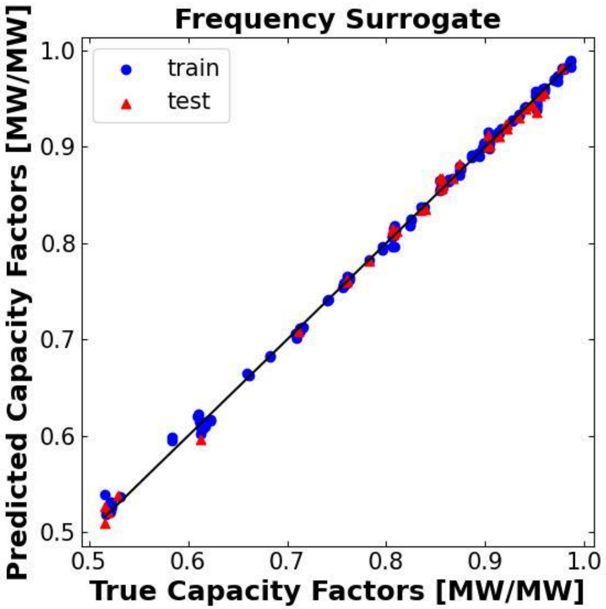
Problem Statement

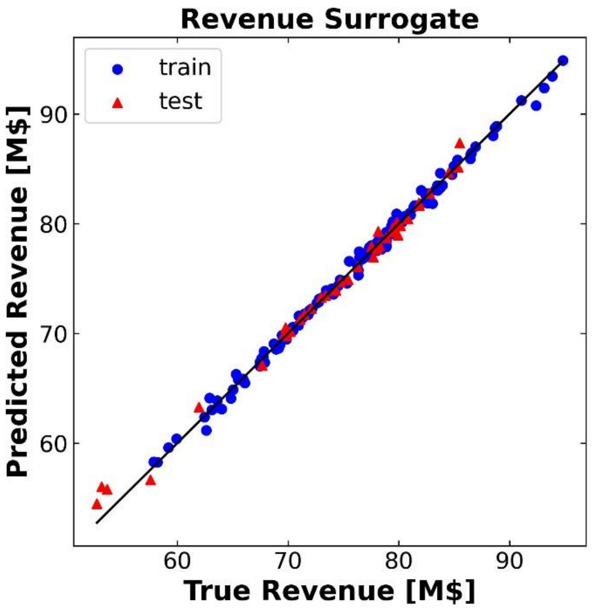


Overall Approach



Example Surrogates (Nuclear + PEM)

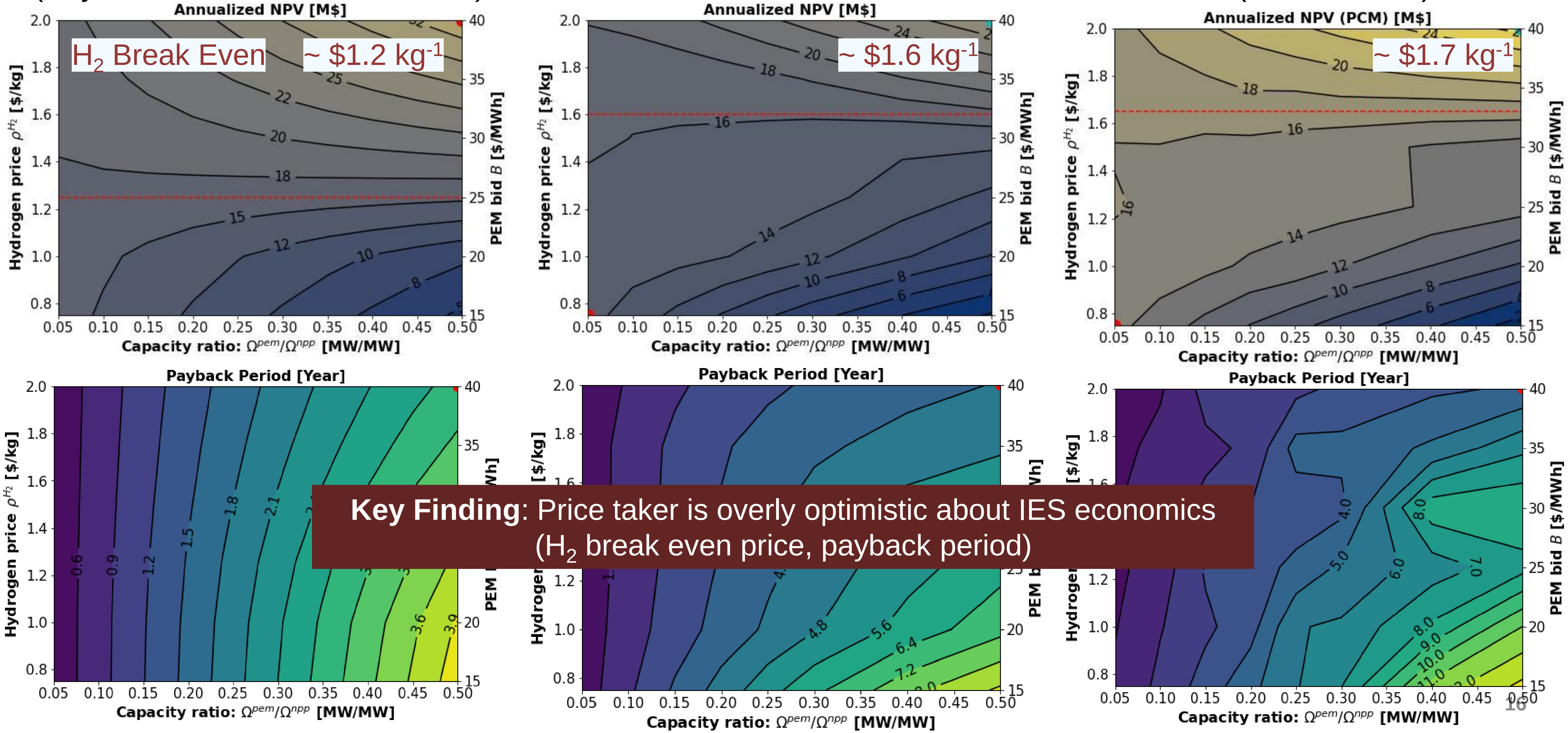




Chen et al, (2025) *in preparation*

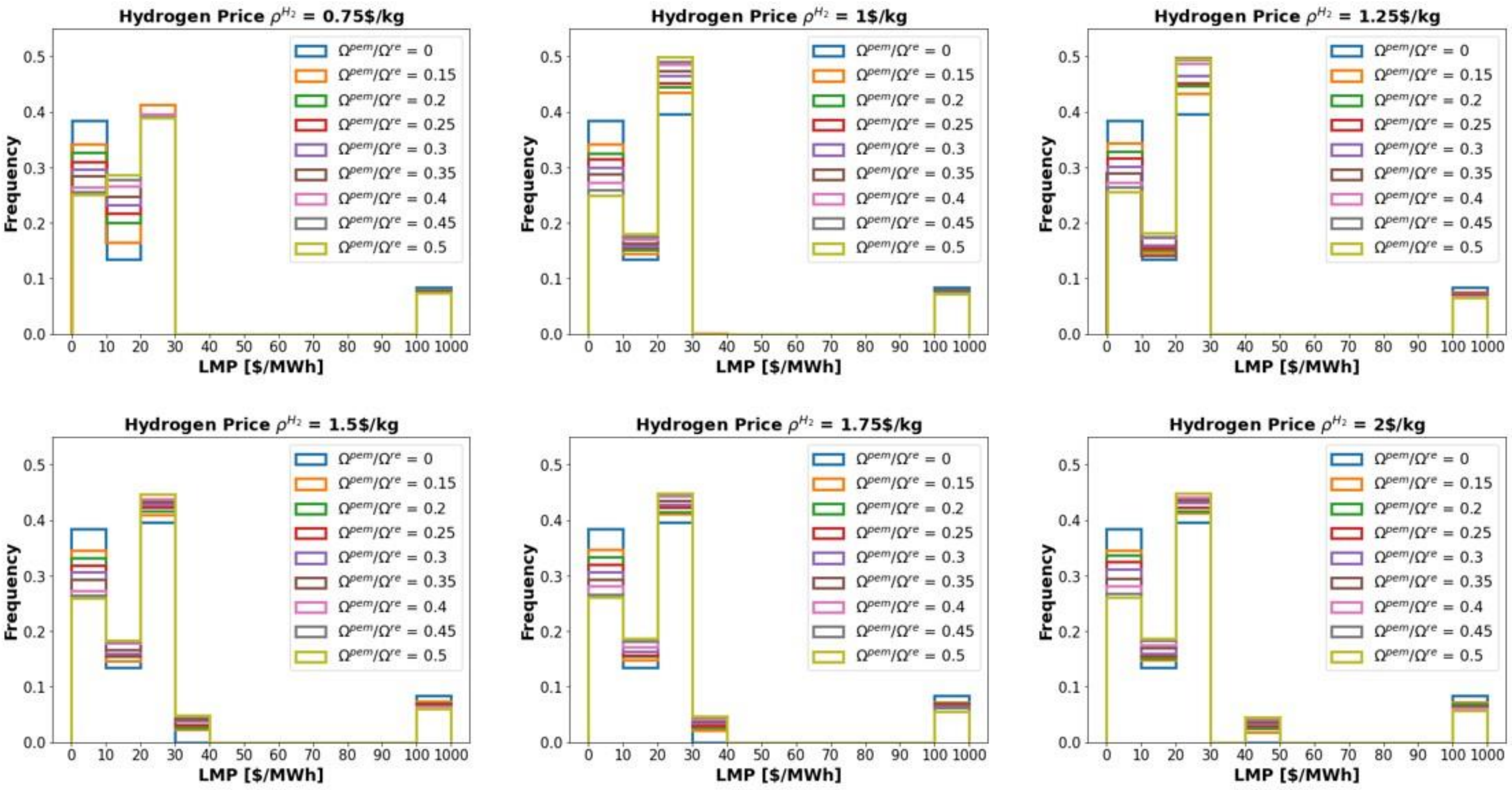
Nuclear + PEM Case Study

Price Taker (Day-Ahead + Real-Time Markets) | **Surrogates** | **Production Cost Model** (Ground Truth)



Key Finding: Price taker is overly optimistic about IES economics (H_2 break even price, payback period)

Renewables + PEM Case Study: Key Finding



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Key Finding: IES changes price (LMP) distribution

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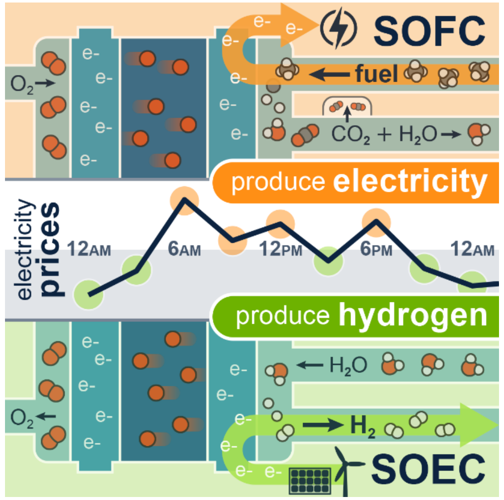
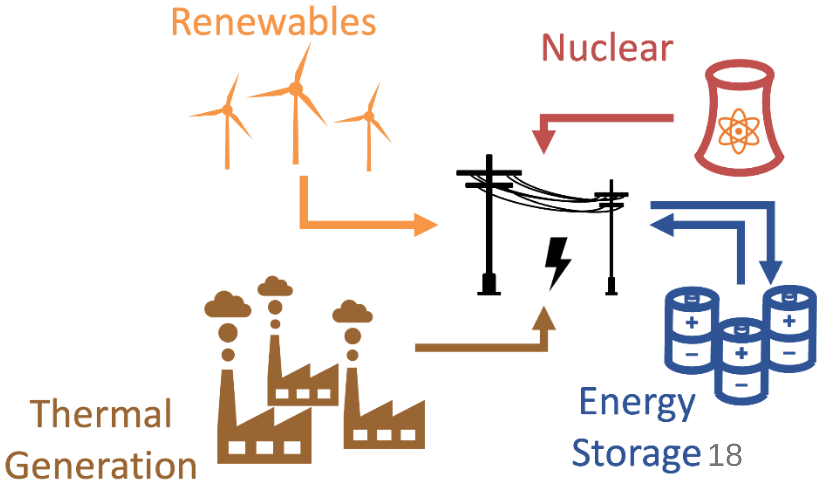
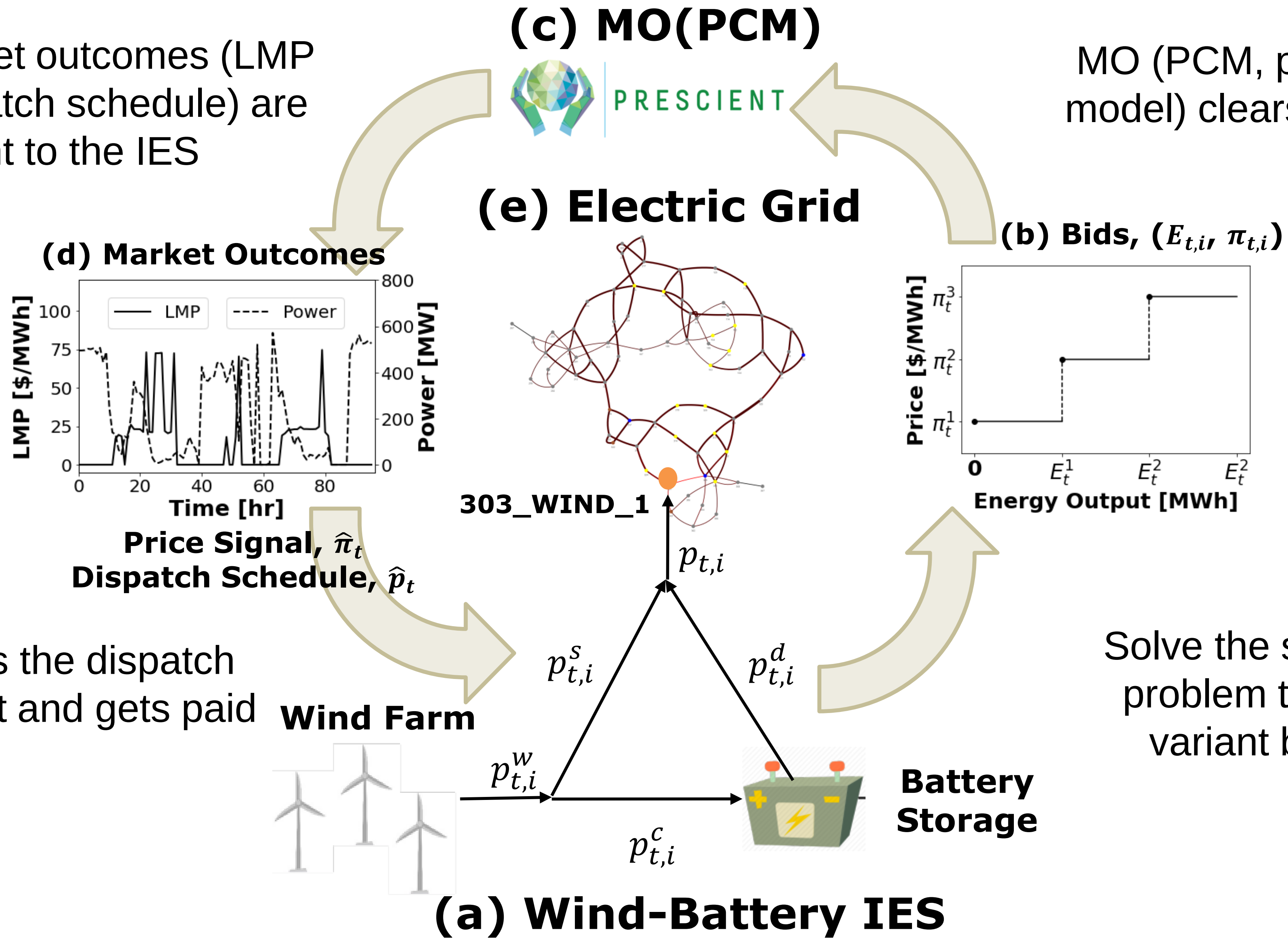




Multiperiod Optimization (MO) of the Wind-Battery IES

The market outcomes (LMP and dispatch schedule) are sent to the IES

MO (PCM, product cost model) clears the market



IES follows the dispatch commitment and gets paid

Solve the stochastic bidding problem to generate time-variant bids for the IES

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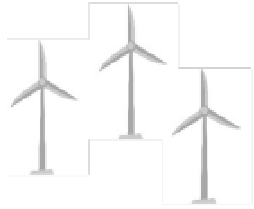
Price-taker (PT) with Perfect Information and Uncertainty

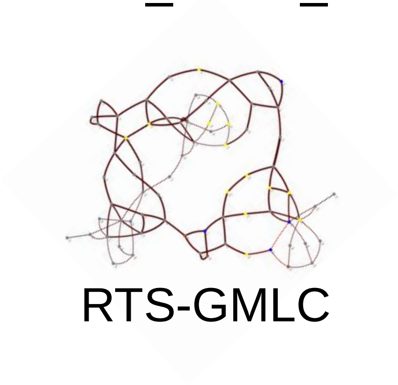
Choose wind farm '303_WIND_1' in the RTS-GMLC dataset



303_WIND_1

↓

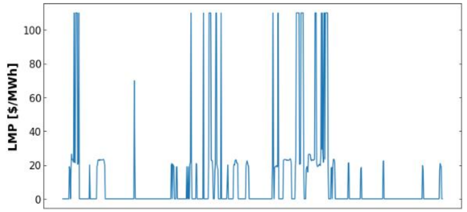
Product Cost Model (PCM)



RTS-GMLC

↓

Obtain the real-time LMP price signals



↓

Solve the price-taker optimization

Max Net Present Values of IES Investments

$s.t.$ Wind farm and battery operation constraints

Perfect Information Mode:

LMP signals are deterministic

$$R_{t,i} = (\hat{\pi}_{t,i} + \varepsilon) \cdot p_{t,i} \cdot \Delta t$$

Where $I = \{0\}, T = \{0, 1, .., 8783\}$

$R_{t,i}$: Total revenue at time t, scenario i.

$\hat{\pi}_{t,i}$: LMP at time t, perfect information.

$p_{t,i}$: IES power output at time t, scenario i.

ε: Small incentive (0.001 \$/MWh) to avoid degeneracy.

Δt: Time step, hour.

Uncertainty Mode:

Rolling horizon stochastic optimization and use historical prices as scenarios.

$$R_{t,i} = (\pi_{t,i} + \varepsilon) \cdot p_{t,i} \cdot \Delta t$$

Nonanticipativity constraints

$$p_{t,i} = p_{t,i'} \quad \forall t \in T_1', \forall i' \in I \backslash \mathrm{i}$$

Where $I = \{0, .., 9\}, T = \{T_1' \cup T_2'\}$

$\pi_{t,i}$: LMP at time t and scenario i.

T_1': Stage 1 time set, {0,…,23}.

T_2': Stage 2 time set, {24,…,71}.

After optimization is solved:

$$\hat{R}_d = \sum_{t \in T_1'} \hat{\pi}_t \cdot p_{t,0} \cdot \Delta t$$

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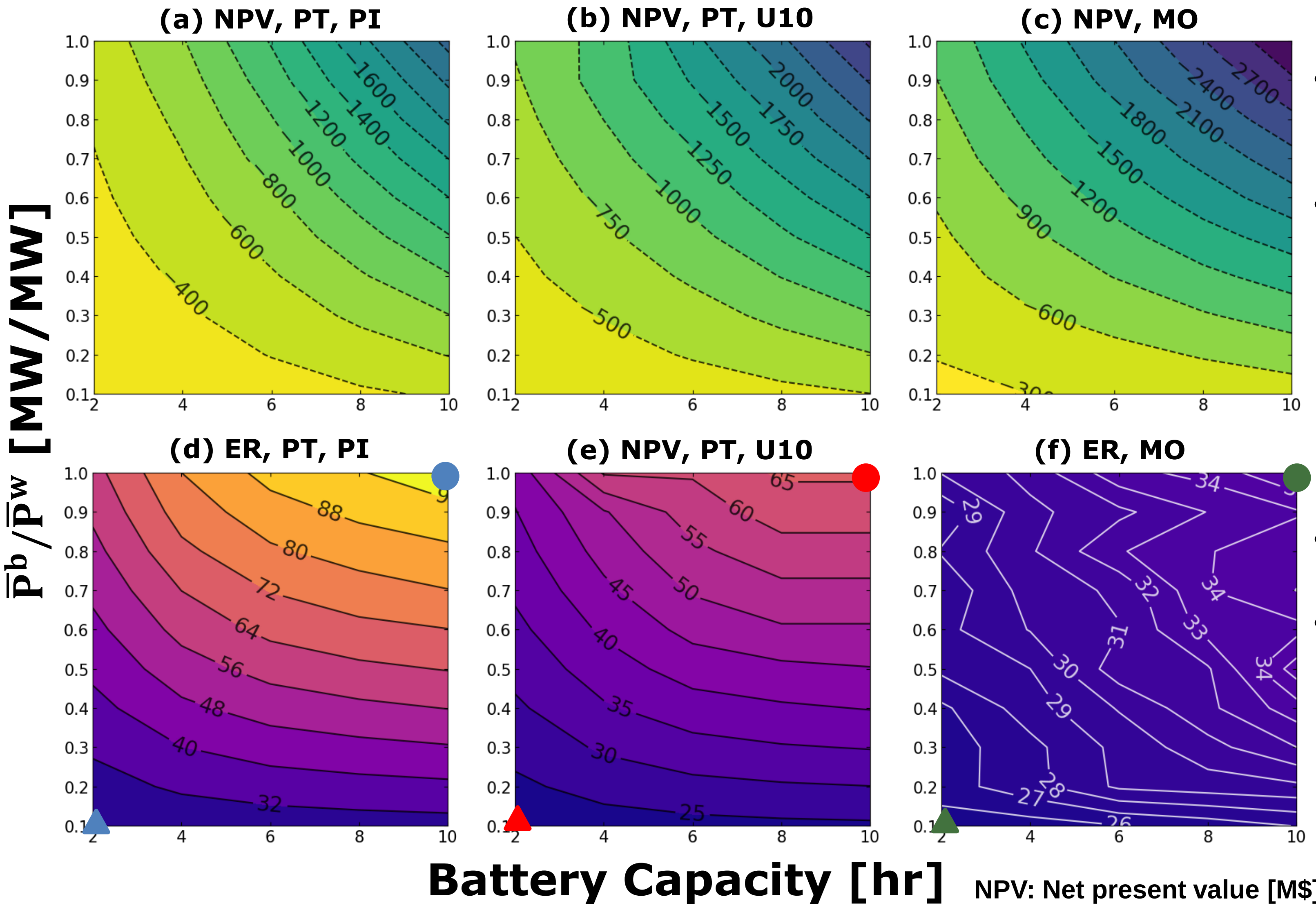
PT is Overly Optimistic on IES Economic Values



- All NPV values are negative in both PT and MO (overbuilt grid).
- Electricity revenue (ER), [M$]
  - ▲ Case 1 (PT, PI, smallest battery): 24.2
  - ● Case 2 (PT, PI, largest battery): 100.4
  - ▲ Case 3 (PT, U10, smallest battery): 21.2
  - ● Case 4 (PT, U10, largest battery):65.9
  - ▲ Case 5 (MO, smallest battery): 25.5
  - ● Case 6 (MO, largest battery): 36.0
- PT overestimates the NPV and ER.
- NPV and ER and more sensitive to the maximum battery power $\bar{P}^b$ ($\bar{P}^w$: maximum wind power, parameter)

NPV: Net present value [M$]
ER: Annual electricity revenue [M$]
PI: Perfect information
U10: Uncertainty with 10 scenarios

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Take Away Messages

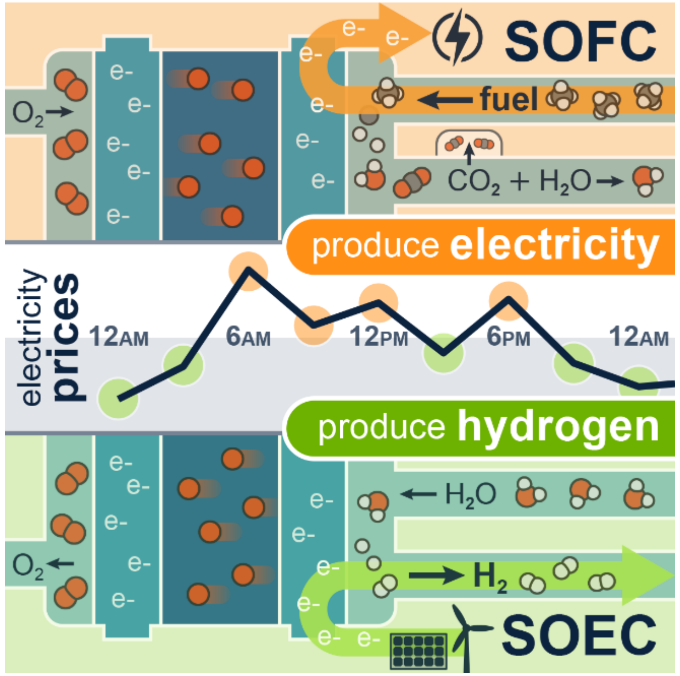
Optimization is a powerful tool to analyze integrated energy systems (IESs) in dynamic energy markets.

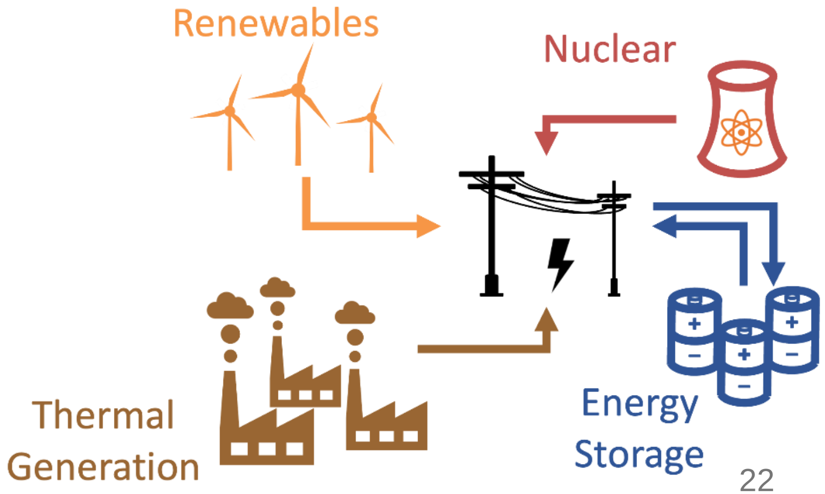
Price taker assumes IES decisions do not impact market prices.

- Surrogates and PriceTaker class in IDAES makes this analysis fast and easy.

Need to go beyond price taker (with IDEAS)!

- Price taker is often overly optimistic.
- IES decisions shift market prices.





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2025 Joint IDAES/CCSI$_2$/PrOMMiS/WaterTAP Technical Team Meeting
University of Notre Dame

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