Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems

Optimization-based approaches to modeling, analyzing, and designing integrated energy systems

DISPATCHES

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

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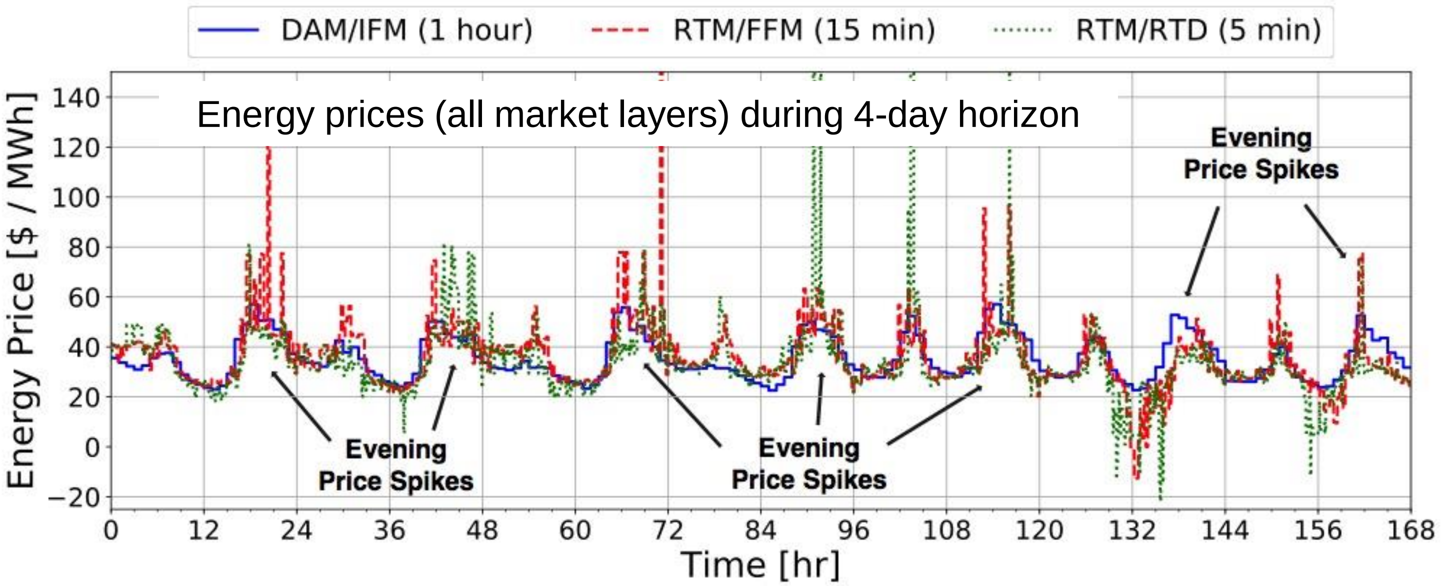
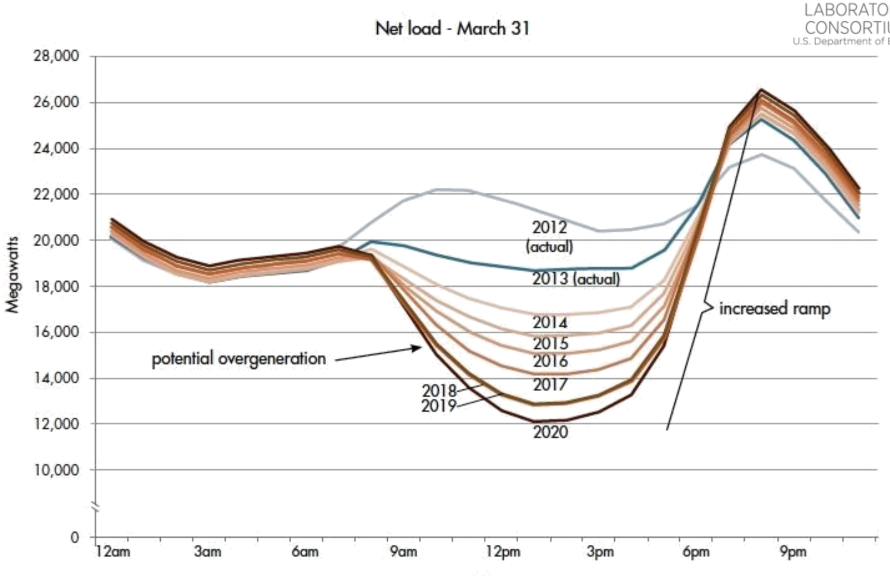
Evolving Grid Increasingly Requires Flexibility

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

California ISO (CAISO)



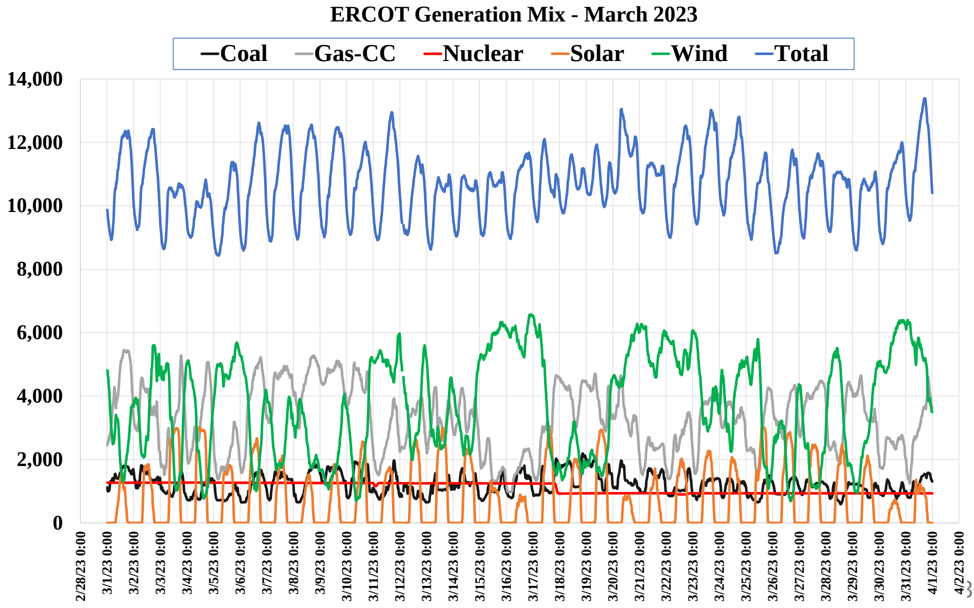
Dowling, Kumar, & Zavala (2017), *Applied Energy*
Dowling & Zavala (2018), *Comp. & Chem. Eng.*



https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf

Electric Reliability Council of Texas (ERCOT)

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



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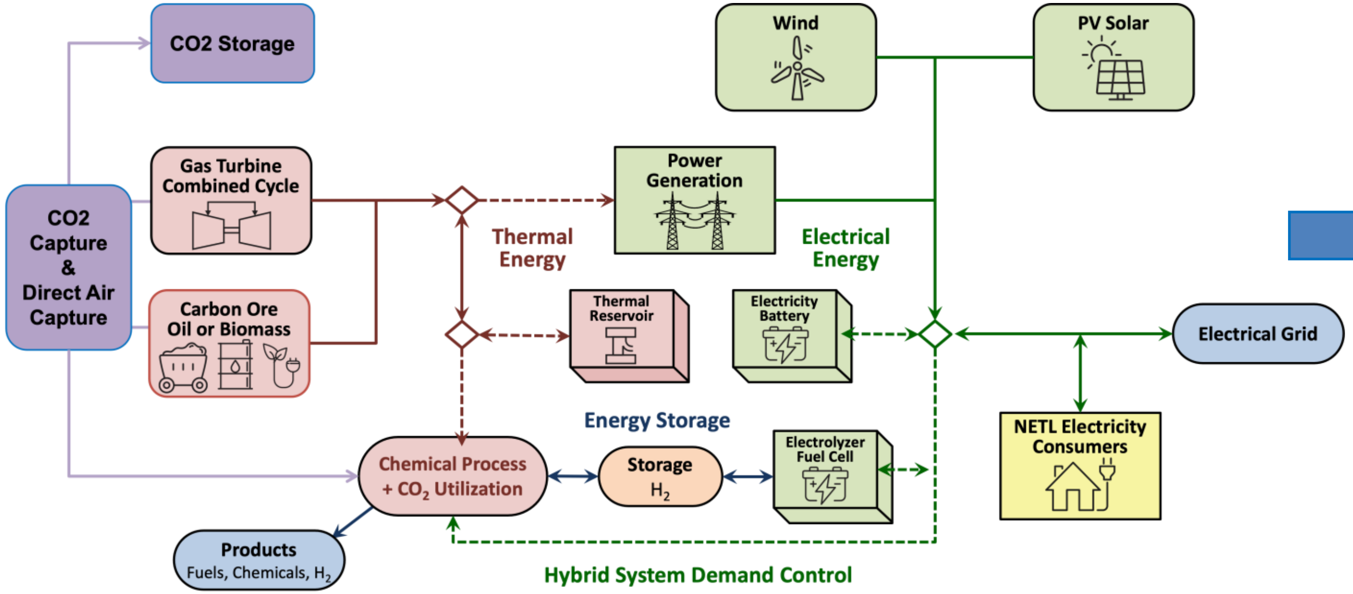
Integrated Energy Systems (IES) Provide Dynamic Flexibility

IESs provide **greater operational flexibility** by optimally coordinating material flows and energy conversions, **multiple value streams**

Multiple inputs and technologies:

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



Multiple outputs and markets:

Electricity energy
Ancillary services
H_2
Chemicals
Heating
Cooling

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

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

Developing Optimization Environments for Scale-bridging

Process-centric Modeling

Detailed plant model assuming grid / infrastructure as an infinite capacity bus

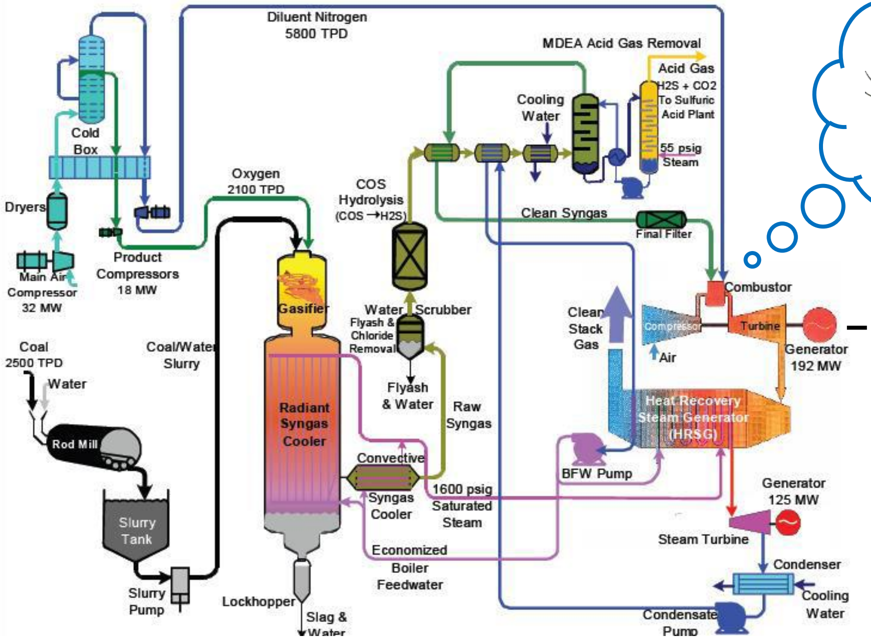
“Maximize efficiency”
“Minimize cost of hydrogen”

Grid-centric Modeling

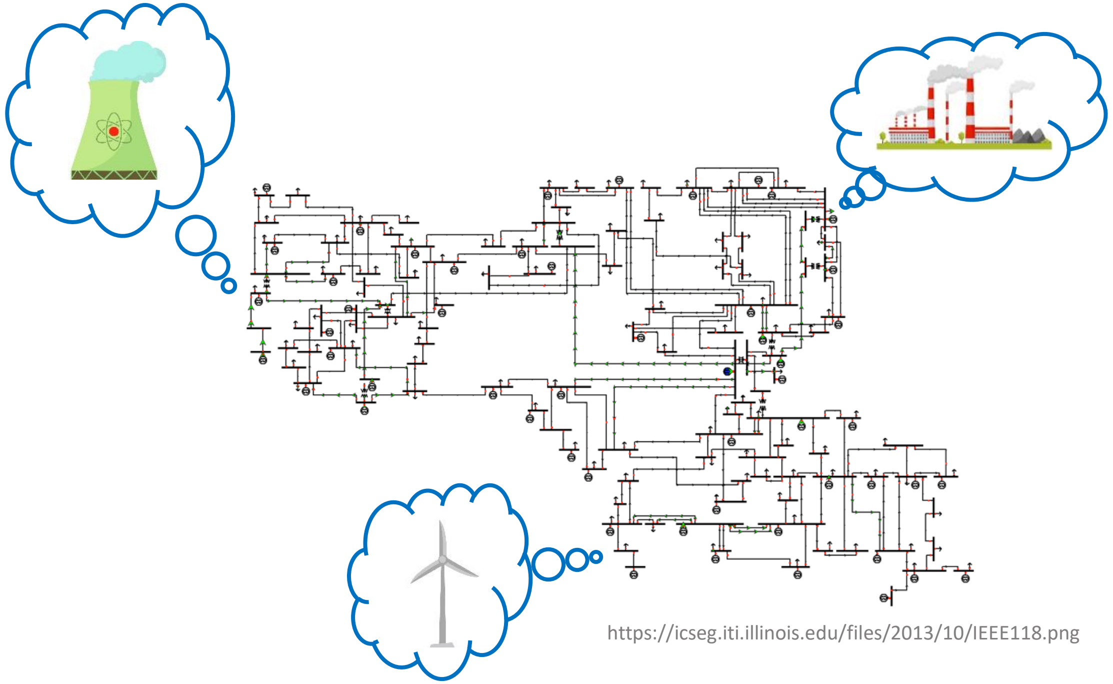
Detailed power flow models, with individual generators modeled as either dispatchable point sources or stochastic "negative loads"

“Minimize cost of electricity”

Market Interactions



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



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

Hybrid System Operations

Break Barriers & Move Beyond Price Taker:
Multiscale Process/Grid Simulation Enabling Capability

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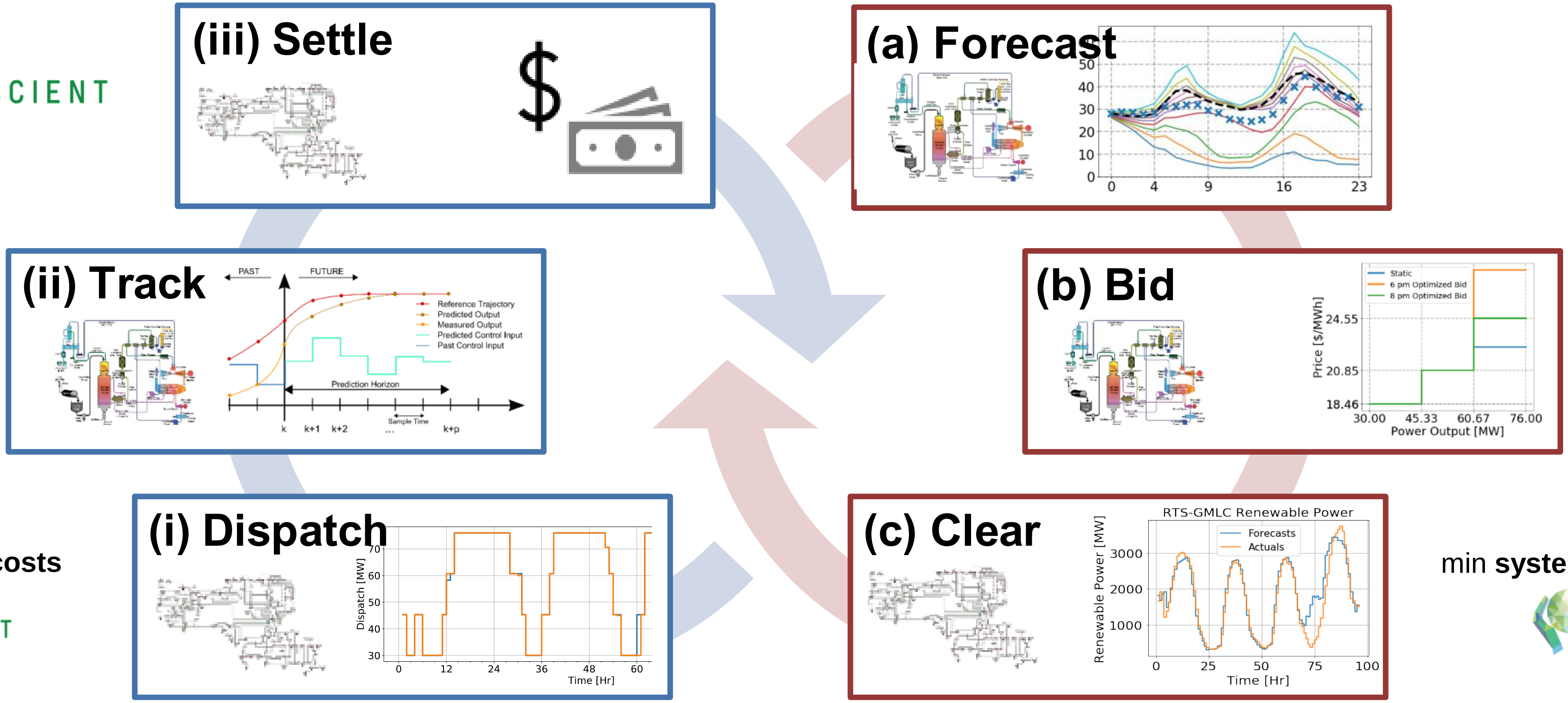
Real-Time Market Loop
(1 cycle = 1 hour)

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



PRESCIENT

Balance:
- cost
- equipment health
- tracking penalty

IDAES
Institute for the Design of Advanced Energy Systems

min **system generation costs**

PRESCIENT

max **E[Profit]**

IDAES
Institute for the Design of Advanced Energy Systems

min **system generation costs**

PRESCIENT

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

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

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.

Design & Optimization Infrastructure for Tightly Coupled Hybrid Systems

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Design Integration and Synthesis
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07/2020 to 12/2023

DISPATCHES is a collaboration among

- National Energy Technology Laboratory
- Sandia National Laboratories
- Idaho National Laboratory
- National Renewable Energy Laboratory
- Lawrence Berkeley National Laboratory
- University of Notre Dame

Value Proposition

- Conceptual design of novel hybrid systems in a way that enables **rigorous exploration of the design space**
- Values the output of the hybrid system within the **context of the grid** and region it is deployed

Project Objectives

- **Open, multi-lab computational platform** to support the design, optimization, and analysis of tightly coupled hybrid systems.
- Demonstrate and quantify the benefits of potential hybrid systems **based on case studies**
- **Build on DOE investments** in modeling and simulation capabilities to support a resilient, reliable, and cost-effective bulk power system.

Open-source, available on: https://github.com/gmlc-dispatches/dispatches

DISPATCHES Optimization Workflows

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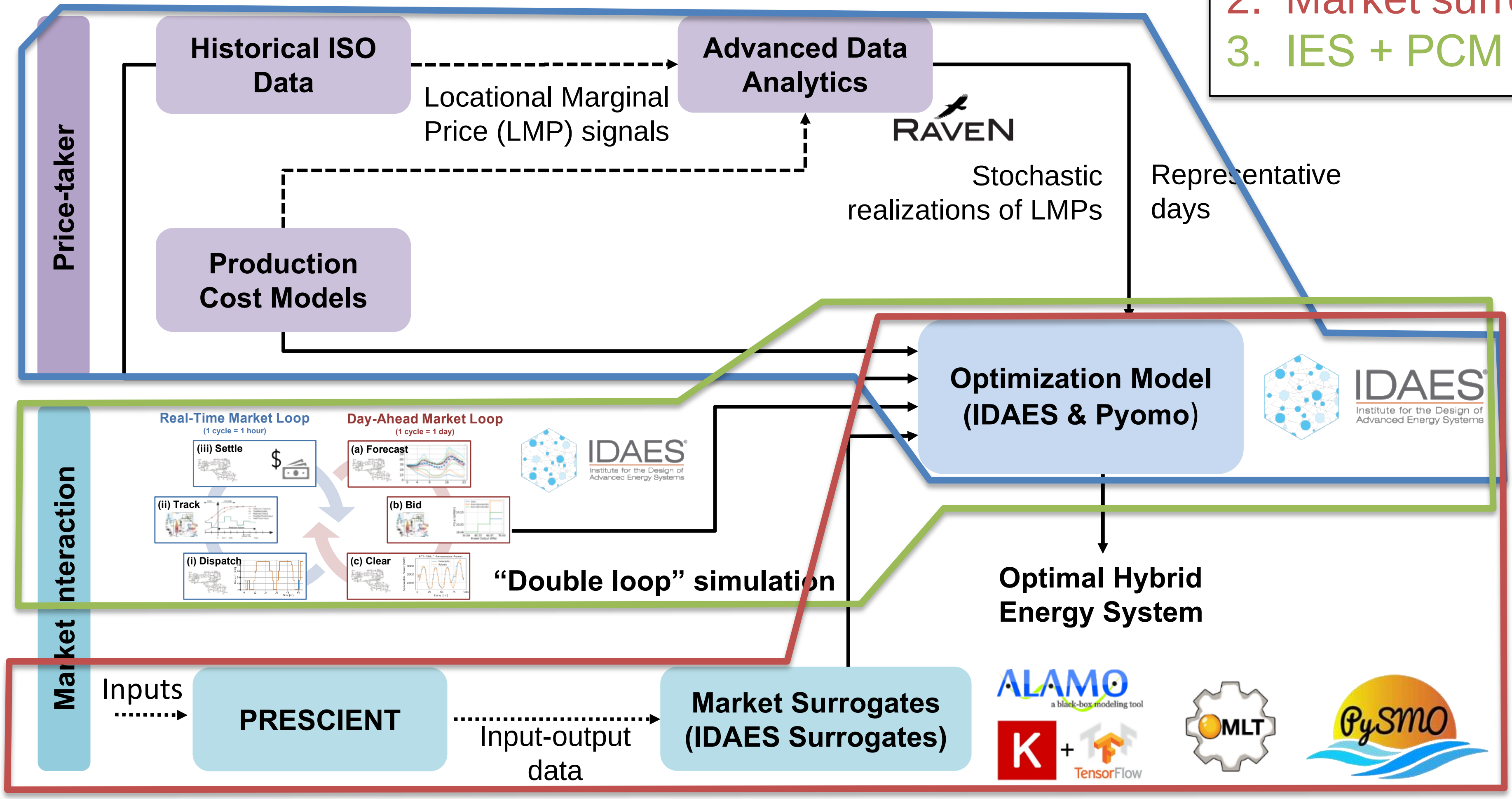
Three Workflows:

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



Price-taker

Historical ISO Data

Locational Marginal Price (LMP) signals

Advanced Data Analytics

Stochastic realizations of LMPs

Representative days

Production Cost Models

Market Interaction

"Double loop" simulation

Optimization Model (IDAES & Pyomo)

Optimal Hybrid Energy System

Inputs

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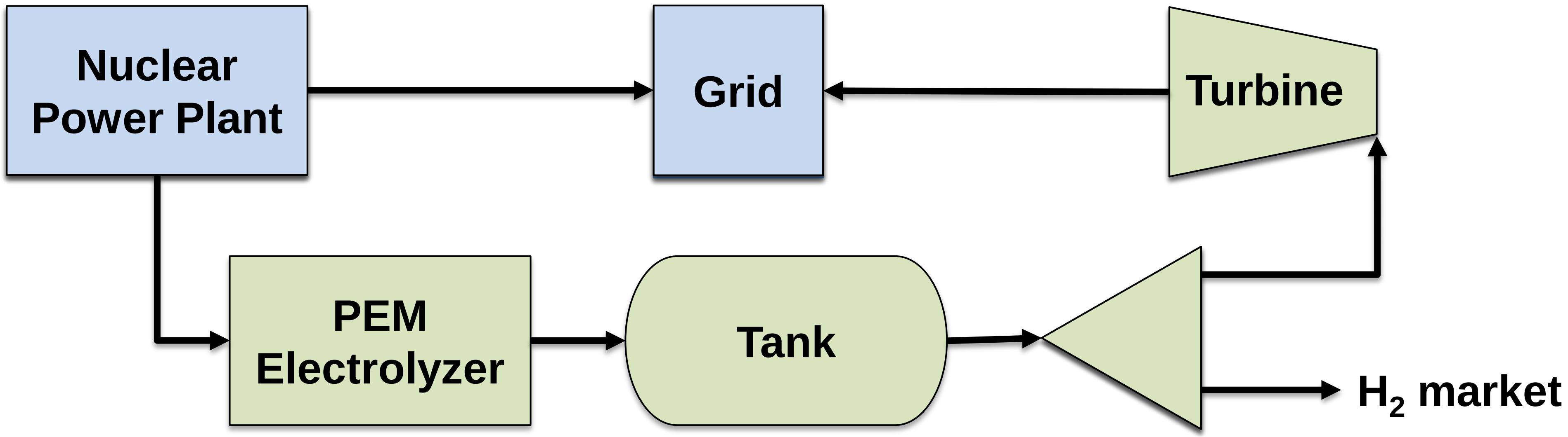
Input-output data

Market Surrogates (IDAES Surrogates)

DISPATCHES Case Study:

Nuclear Power Plant Integrated with Low-Temperature Electrolysis



Case study goals:

- Increase “flexibility” of nuclear power plant
- Exploit electricity price arbitrage
- Improve overall economics of low-temperature electrolysis via polymer electrolyte membrane (PEM) electrolyzer

Key findings

Hybridizing nuclear with PEM to produce hydrogen increases flexibility and profitability

Price-taker overestimates the breakeven H_2 price

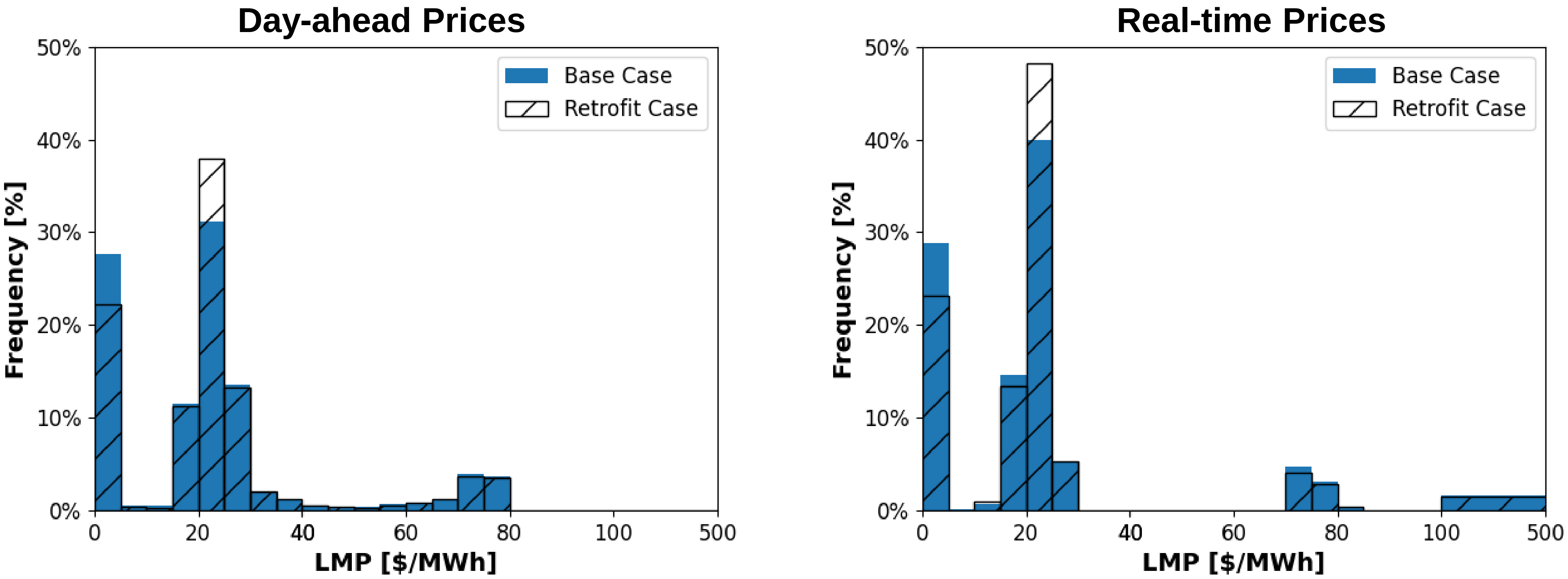
Market surrogates accurately capture interactions

For a given market,

- **Design decisions**: capacities of PEM, tank, and turbine
- **Operating decisions**: power input to PEM, flowrate of hydrogen to market and turbine

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 with a 200 MW electrolyzer; H_2 sold at $1/kg



- Changing a single generator in the system can impact both the average LMP and distribution
  - Flexibility reduces the observed frequency of near-zero LMPs, increases revenue from electricity
  - **Price-taker analysis does not capture this behavior**

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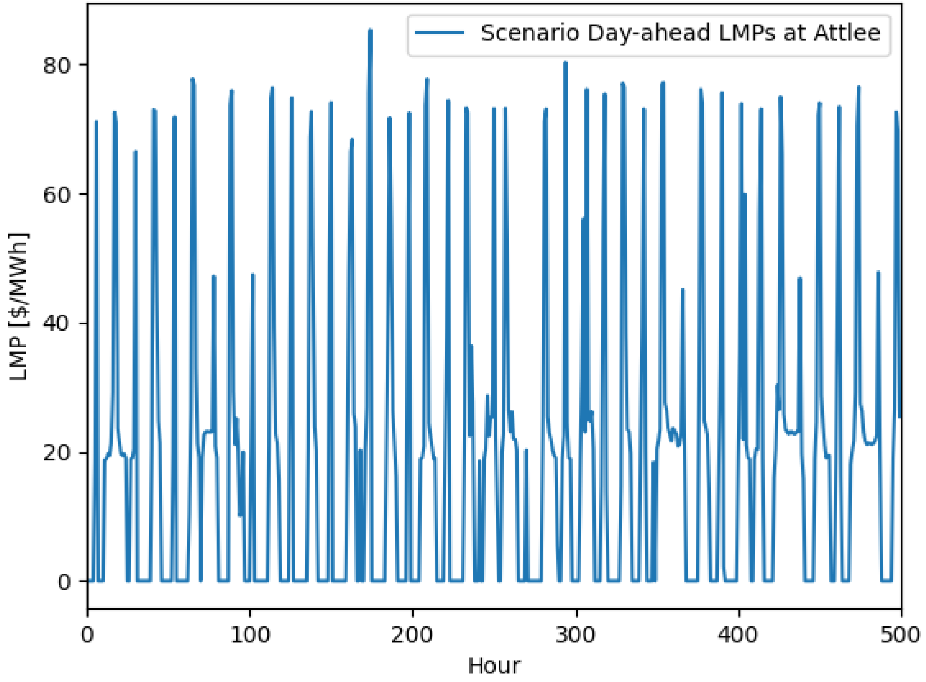
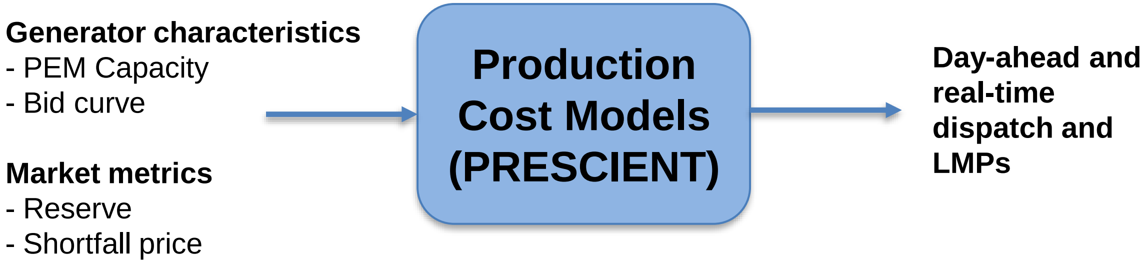
Price-taker (PT) Approach vs Market Surrogates (MS) Design Approach

- **PT1:** Generate LMP data (PCM or historical)



- **PT2:** Formulate and solve the price-taker design problem

- **MS1:** Generate training data



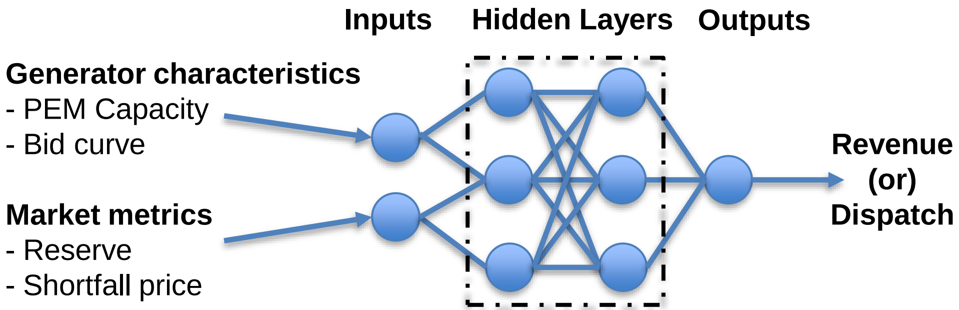
Generator characteristics
- PEM Capacity
- Bid curve

Market metrics
- Reserve
- Shortfall price

Production Cost Models (PRESCIENT)

Day-ahead and real-time dispatch and LMPs

- **MS2:** Train neural network surrogate model



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

Generator characteristics
- PEM Capacity
- Bid curve

Market metrics
- Reserve
- Shortfall price

Revenue (or) Dispatch

- **MS3:** Formulate and solve the design problem by embedding market surrogates

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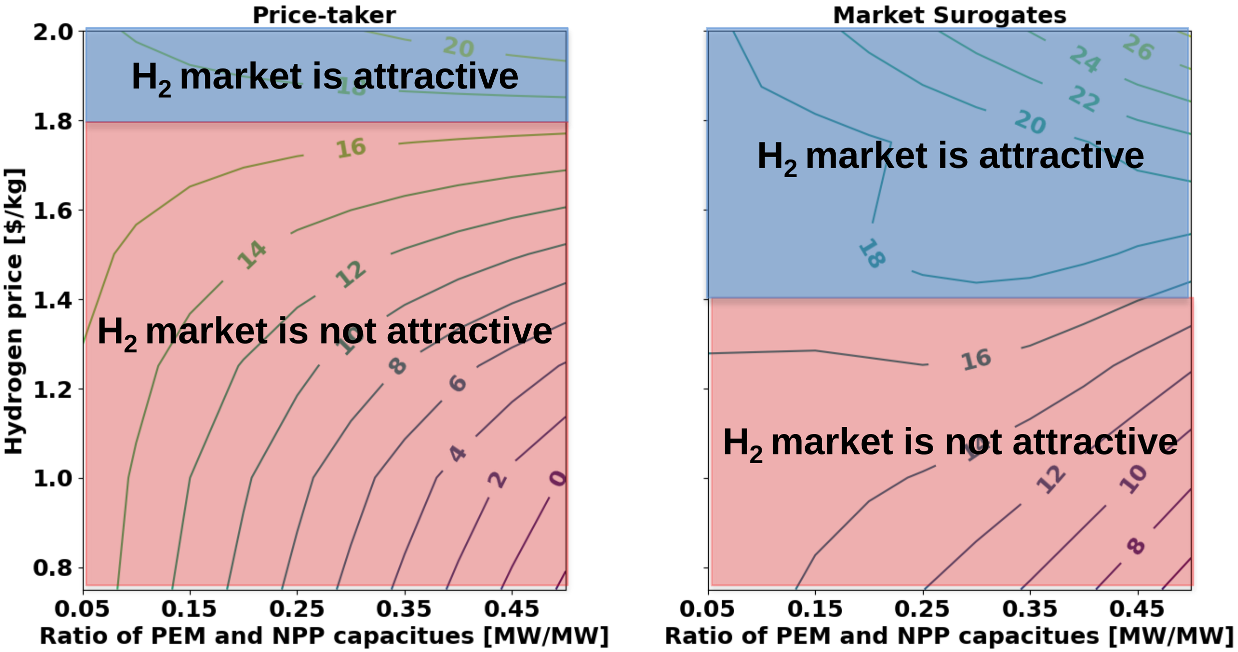
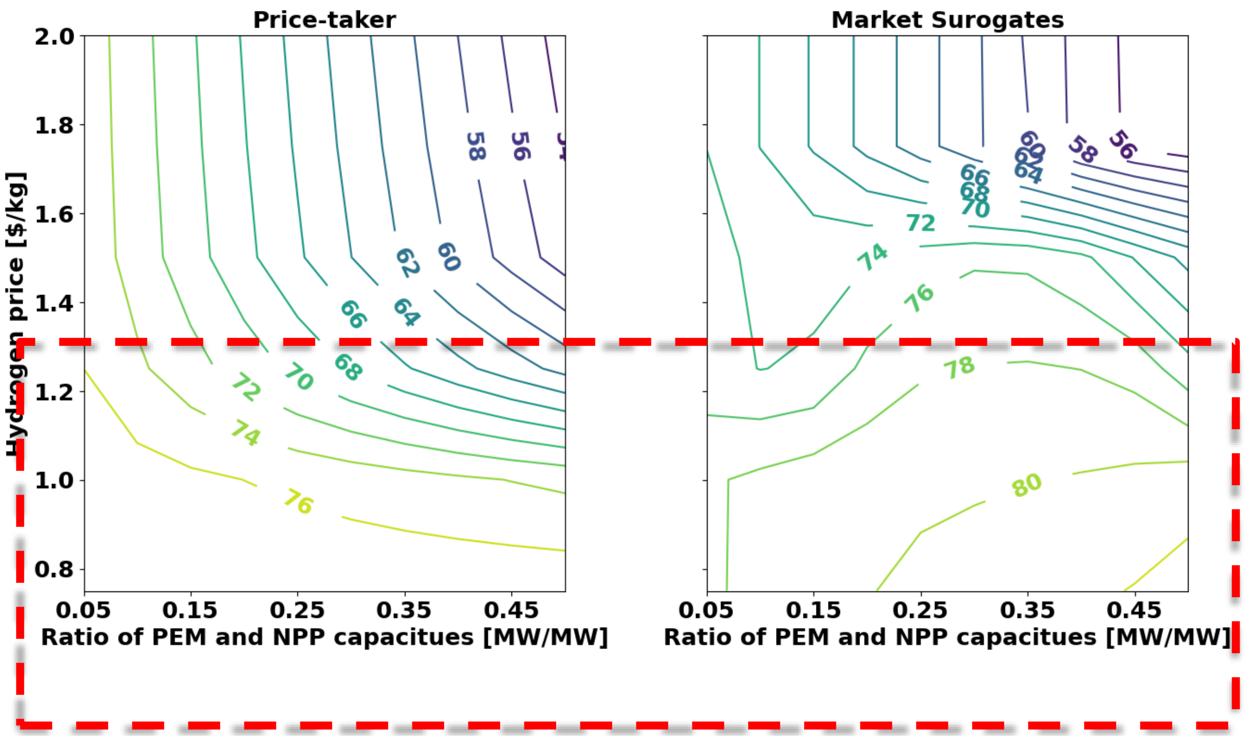
Nuclear Case Study Results: Price-taker vs Market Surrogates

- 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**

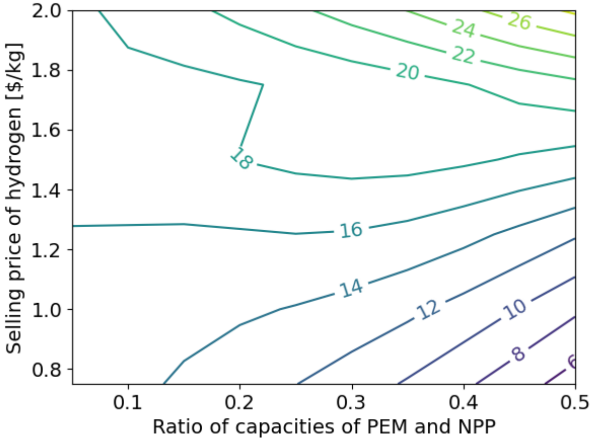


Electricity revenue depend on H_2 vs electricity production schedule – nuanced interactions

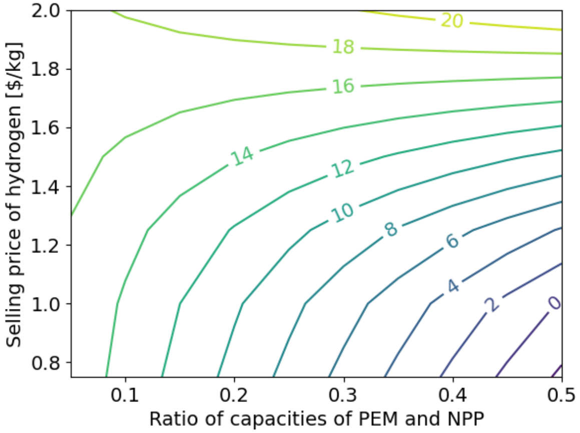
Optimization Results with Market Surrogates are More Accurate

- Validate **net present value** and breakeven hydrogen price against full PCM simulation

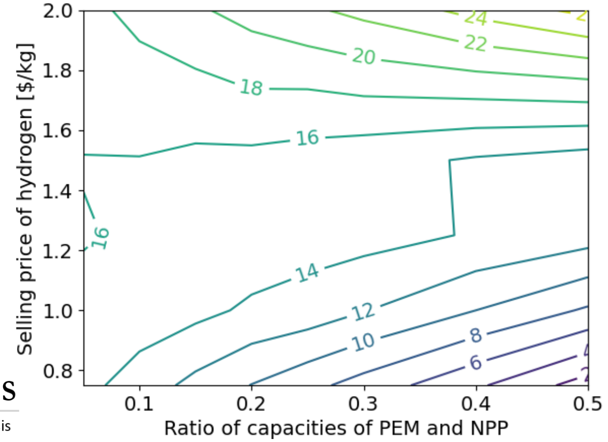
Market Surrogates



Price-taker Approach

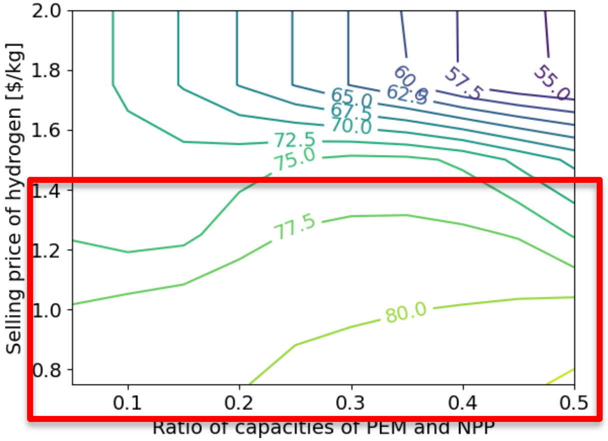


PCM Simulations

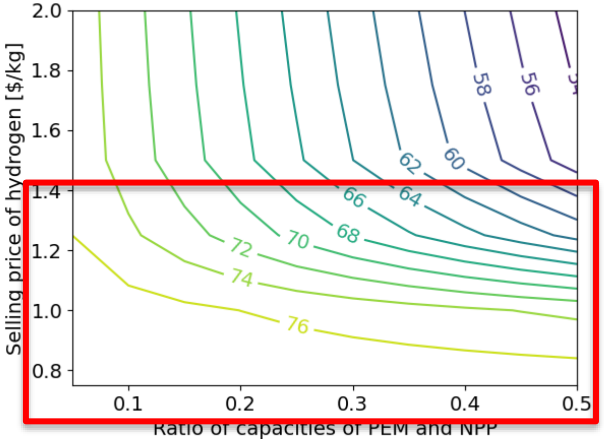


- Validate **electricity revenue** against full PCM simulation

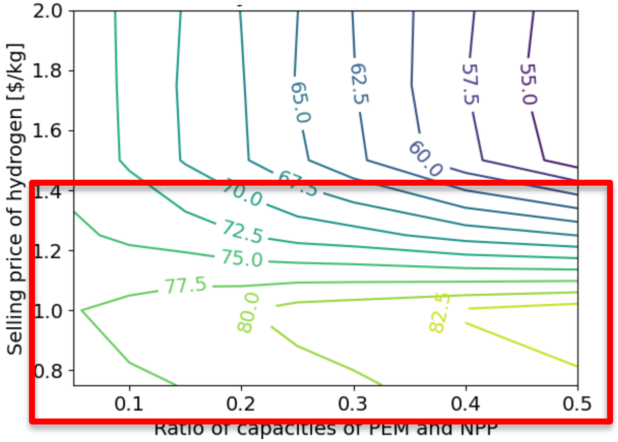
Market Surrogates



Price-taker Approach



PCM Simulations



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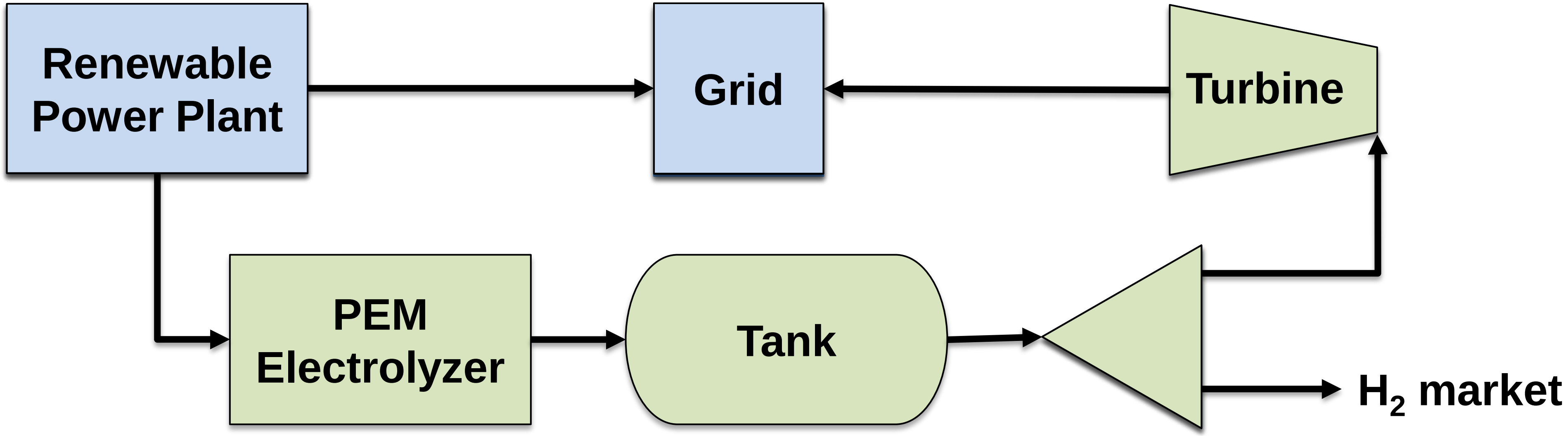
DISPATCHES Case Study:

Nondispatchable (wind/solar) Power Plant Integrated with Low-Temperature Electrolysis



Case study goals:

- Address significant curtailment of renewable generators in (synthetic) grid model
- Improve generator net revenue
- Address additional uncertainty inherent in nondispatchable generation

Relative to the nuclear case study

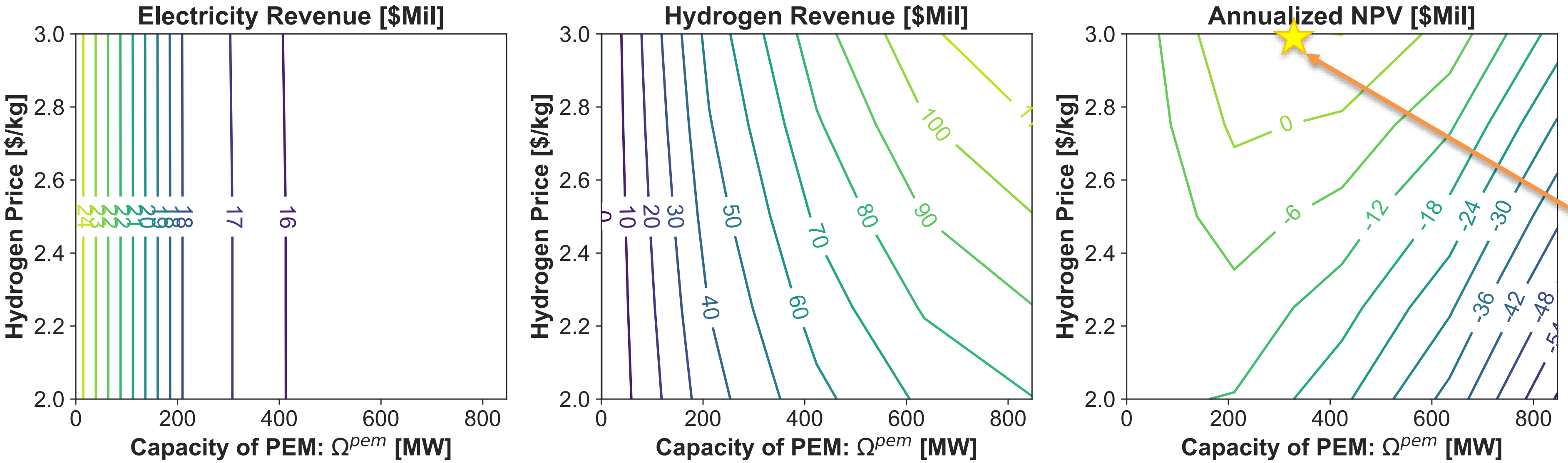
- Similar design decisions (capacities of PEM, tank, and turbine)
- Only consider real-time market (avoid penalties from missing day-ahead commitments)
- Modified market parameters (increased shortfall price, omit depreciation and corporate tax)

Key findings

Hybridization dramatically improves wind farm economics and reduces curtailment

Market surrogate bridge gap between exhaustive PCM simulation enumeration and the price-taker optimization

RE Case Study: Optimal Design with Price-Taker



Optimum for $3/kg H_2

322 MW PEM

7 $mil NPV

Optimal PEM Designs

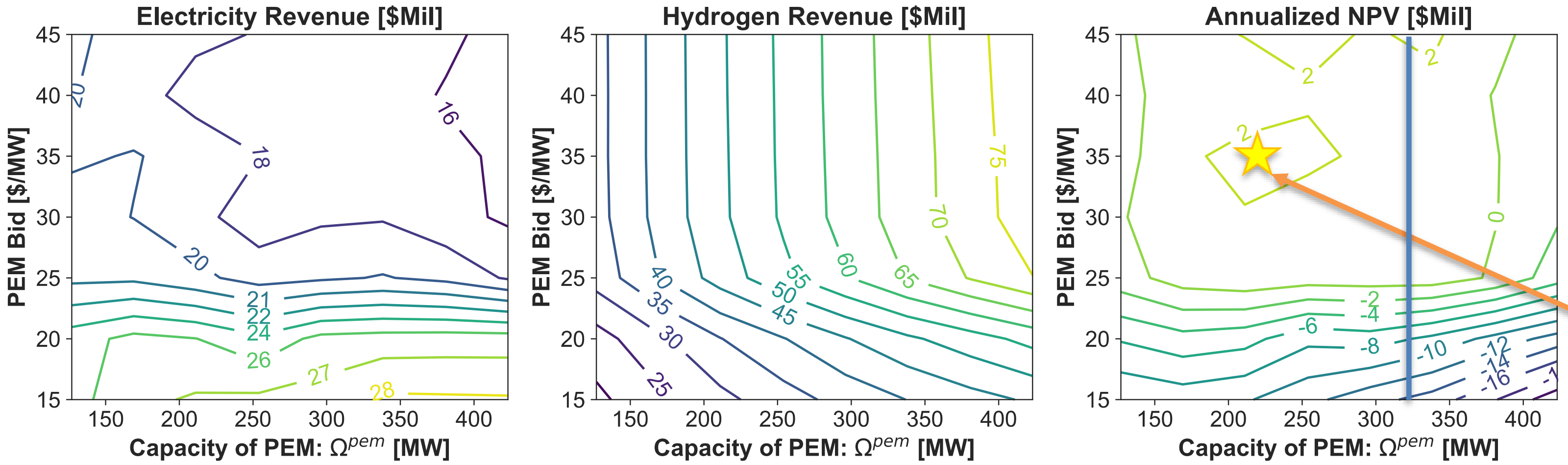
H_2 Price [$/kg]	PEM Size [MW]	Ann. NPV [$mil]
2.00	65	-10
2.25	123	-7.1
2.50	204	-3.3
2.75	262	1.4
3.00	**322**	**7.0**

The optimal NPVs are positive for $2.75/kg H_2 or higher. The revenue from this design was primarily from the hydrogen market.

$3/kg scenario was selected for comparison with the market surrogate approach (next)

RE Case Study: Market Surrogates Validation ($3/kg)

PCM Enumeration



Avg Δ -1.5%
(-9.5 to 7.3%)

Avg Δ 5.2%
(-2.5 to 2.4%)

Avg Δ 13.4%
(-1.6 to 5.4 mil)

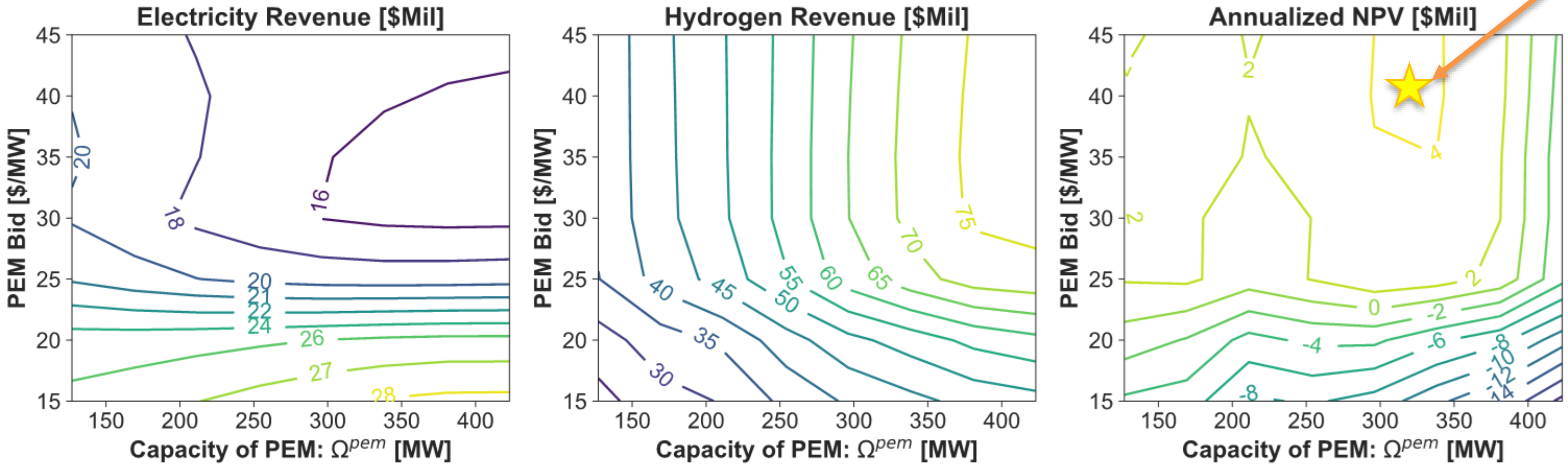
Market Surrogate Fit

Mean R^2	Max R^2	Min R^2
0.9935	0.9983	0.9774

PCM Enumeration Optimum:
212 MW, 35 $/MWh

Market Surrogate Optimum:
317 MW, 41 $/MWh

Market Surrogates



Finding: moderate differences in revenue (enumeration vs surrogates vs price taker) leads to different optimal designs

RE Case Study: Comparison and Validation of Analysis Methods

Co-Optimization	PEM Size [MW]	Bid Price [$/MWh]	Elec. Rev [Mil]	H_2 Rev [Mil]	Ann. NPV [Mil]
PCM Enumeration	212	35	19	49	2.5
Market Surrogate	317	41	17	68	4.3
Price Taker	322	-	16	79	7

Market surrogate approaches bridges gap between PCM enumeration and Price Taker co-optimization results

Validation	PEM Size [MW]	Bid Price [$/MWh]	Elec. Rev [Mil]	H_2 Rev [Mil]	Ann. NPV [Mil]
PCM Enumeration	212	35	21	54	6.7
Market Surrogates	317	41	19	68	6.6
Price Taker	322	35	20	68	7.2

Differences in co-optimization and validation results are mainly due to the how the IES is modeled in the PCM.

Representing an IES in market/PCM is nuanced!

Two Unit Strategy: Co-Optimization

As a "renewable" (wind) and "virtual" (PEM) units:

- Does not provide reserves
- Always "on”
- Easy to generate surrogate training data

vs.

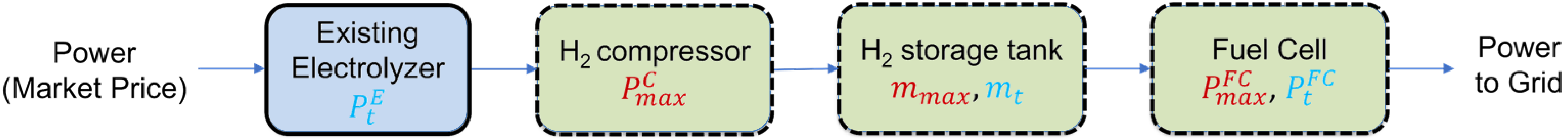
One Unit Strategy: Validation

As a thermal generator:

- Participates in some reserve markets
- Fixed to be always "on”
- More rigorous, uses “double loop”

DISPATCHES Case Study:

Industrial application: small-scale integration H_2 peaker with nuclear power plant in NYISO



Power (Market Price)

Existing Electrolyzer P_t^E

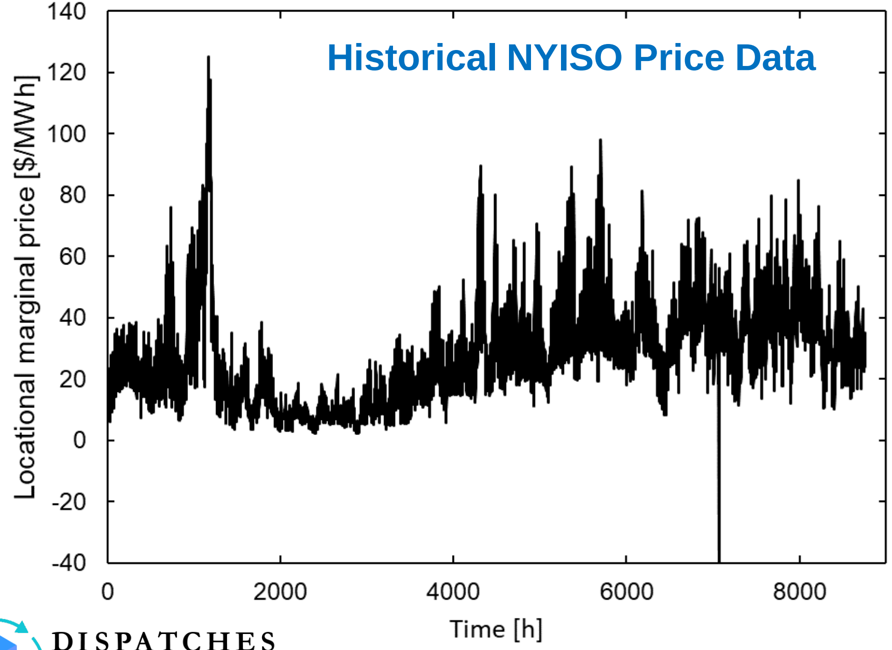
H_2 compressor P_{max}^C

H_2 storage tank m_{max}, m_t

Fuel Cell P_{max}^{FC}, P_t^{FC}

Power to Grid

Is a nuclear + small H_2 peaker with storage economically viable in the NYISO market?



Revenues:

- Electricity sales (historical dynamic prices)
- H_2 sales (assume constant price)
- Hydrogen Production Tax Credit (HPTC; 45V in IRA)
- Capacity payments (CP), requires 4 hours of fuel on-site

Design Decisions:

- Storage tank size
- Fuel cell capacity

Operating Decisions:

- H_2 production schedule
- H_2 consumption schedule
- H_2 Storage level (bounded)

Key findings

Capacity payments need to be an order of magnitude higher (~$15) than present day (~$2.50) to reach significant positive NPV

Hydrogen Production Tax Credit improves economics.

IRA: Inflation Reduction Act

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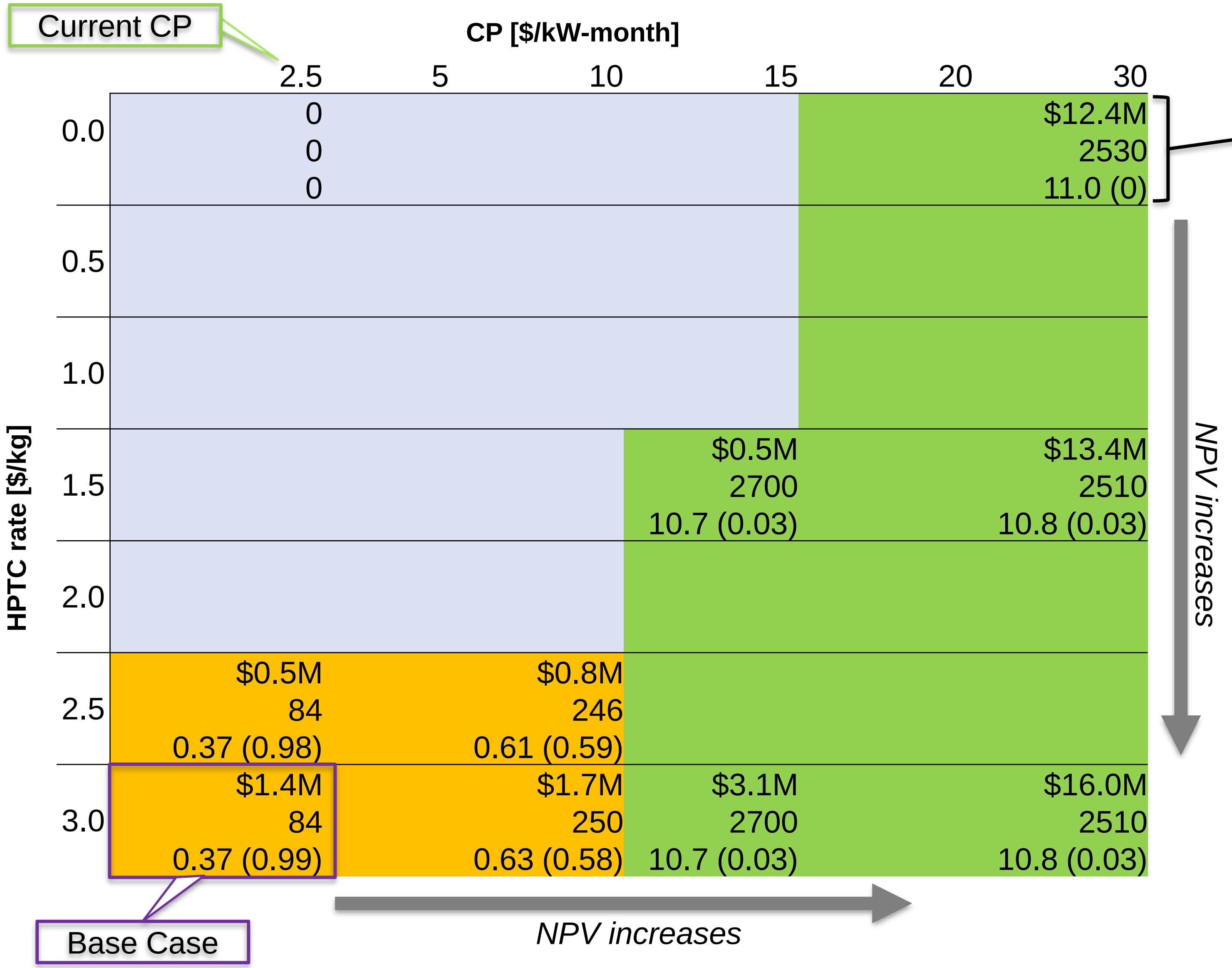
Sensitivity Analysis: What Drives H_2 Peaker Revenue?



Current CP

CP [$/kW-month]

HPTC rate [$/kg]	2.5	5	10	15	20	30
0.0	🟦 0 0 0	🟦	🟦	🟦	🟩	🟩 $12.4M 2530 11.0 (0)
0.5	🟦	🟦	🟦	🟦	🟩	🟩
1.0	🟦	🟦	🟦	🟦	🟩	🟩
1.5	🟦	🟦	🟦	🟩 $0.5M 2700 10.7 (0.03)	🟩	🟩 $13.4M 2510 10.8 (0.03)
2.0	🟦	🟦	🟦	🟩	🟩	🟩
2.5	🟨 $0.5M 84 0.37 (0.98)	🟨	🟨 $0.8M 246 0.61 (0.59)	🟩	🟩	🟩
3.0	🟨 $1.4M 84 0.37 (0.99)	🟨	🟨 $1.7M 250 0.63 (0.58)	🟩 $3.1M 2700 10.7 (0.03)	🟩	🟩 $16.0M 2510 10.8 (0.03)

Base Case

NPV increases

NPV increases

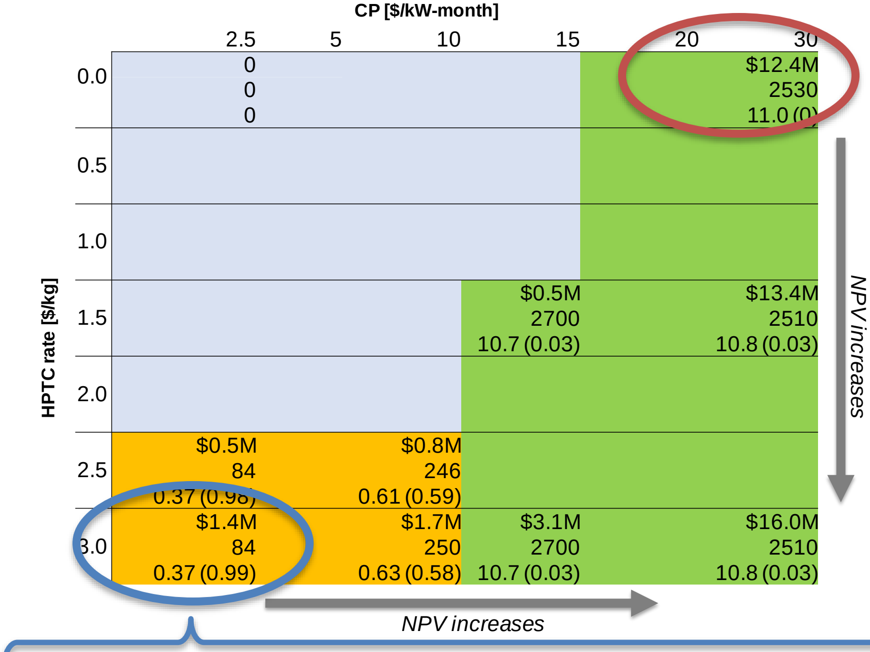
NPV [$M]
Tank [kg]
Fuel Cell [MW] (capacity factor)

- 🟨 Hydrogen Production Tax Credit (HPTC) dominant
- 🟩 Capacity payment (CP) dominant
- 🟦 No-build (NPV = 0)

Key Takeaways:

- Price-taker-based analysis valid given the small electrolyzer size
- CP ≥ $20/kW-month is required without HPTC
- For sufficiently high HPTC, CP ≥ $15/kW-month is sufficient
- At present-day CP, revenue is primarily through the HPTC

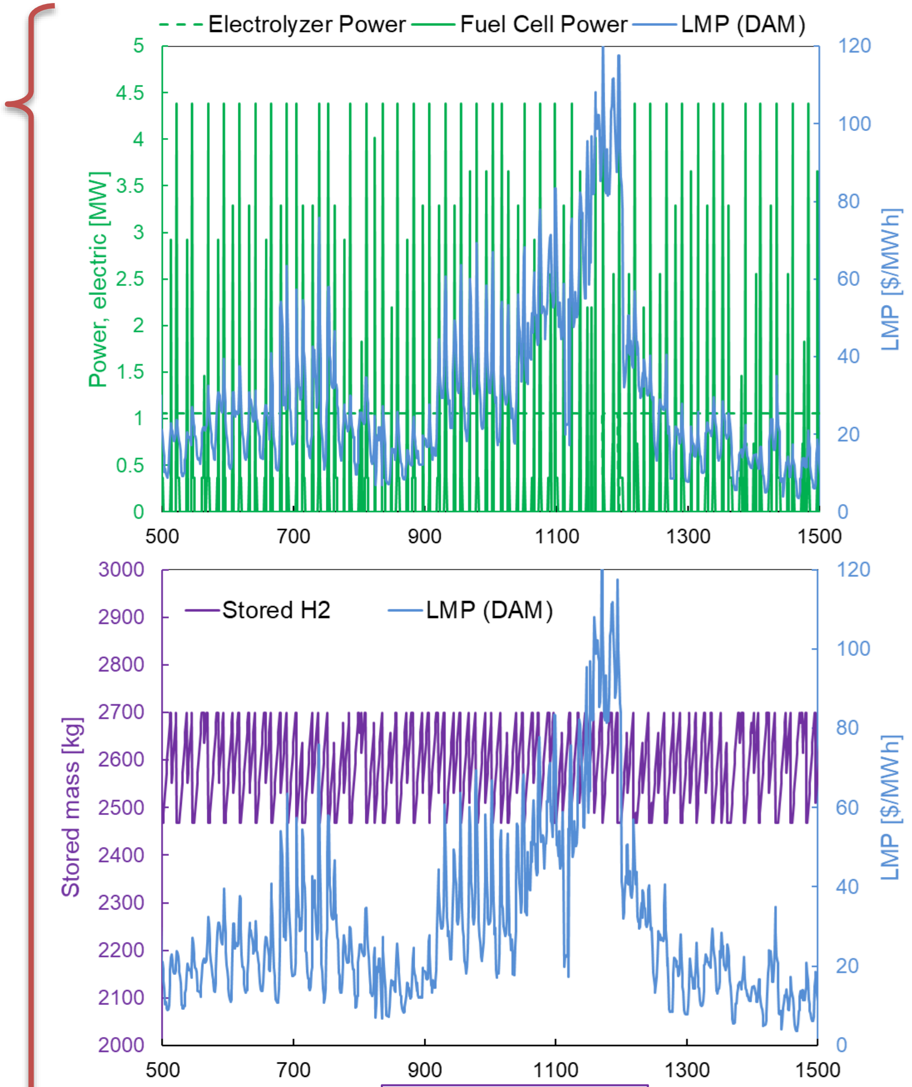
Operating profiles change significantly in different environments



HPTC rate [$/kg] \ CP [$/kW-month]	2.5	5	10	15	20	30
0.0	0 0 0					$12.4M 2530 11.0 (0)
0.5						
1.0						
1.5				$0.5M 2700 10.7 (0.03)		$13.4M 2510 10.8 (0.03)
2.0						
2.5	$0.5M 84 0.37 (0.98)		$0.8M 246 0.61 (0.59)			
3.0	$1.4M 84 0.37 (0.99)		$1.7M 250 0.63 (0.58)	$3.1M 2700 10.7 (0.03)		$16.0M 2510 10.8 (0.03)

At high CP,

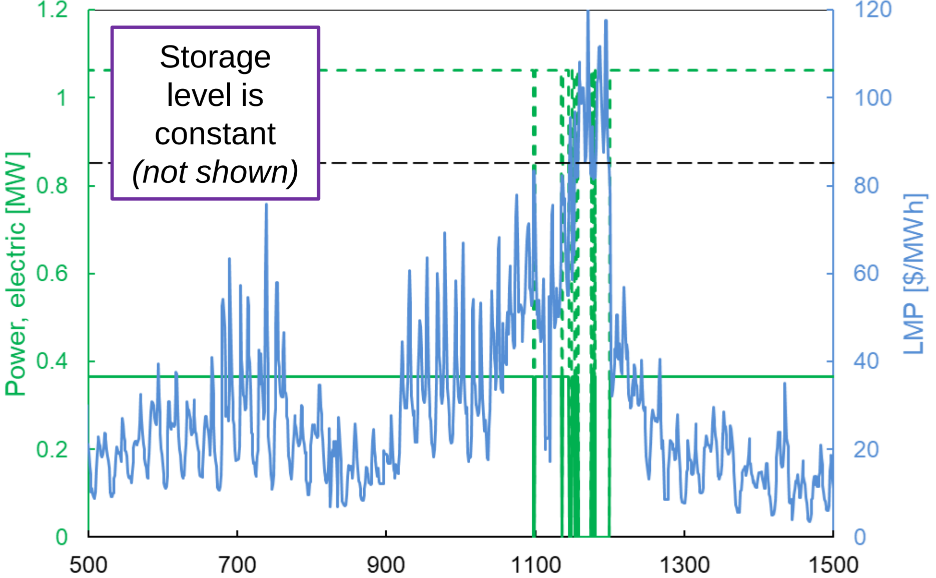
- Large fuel cell (~30x electrolyzer)
- Low capacity factor, cyclic production
  - ➢ Behaves as peaker



Storage level oscillates from min. required (91%) to 100%

At low CP, high HPTC

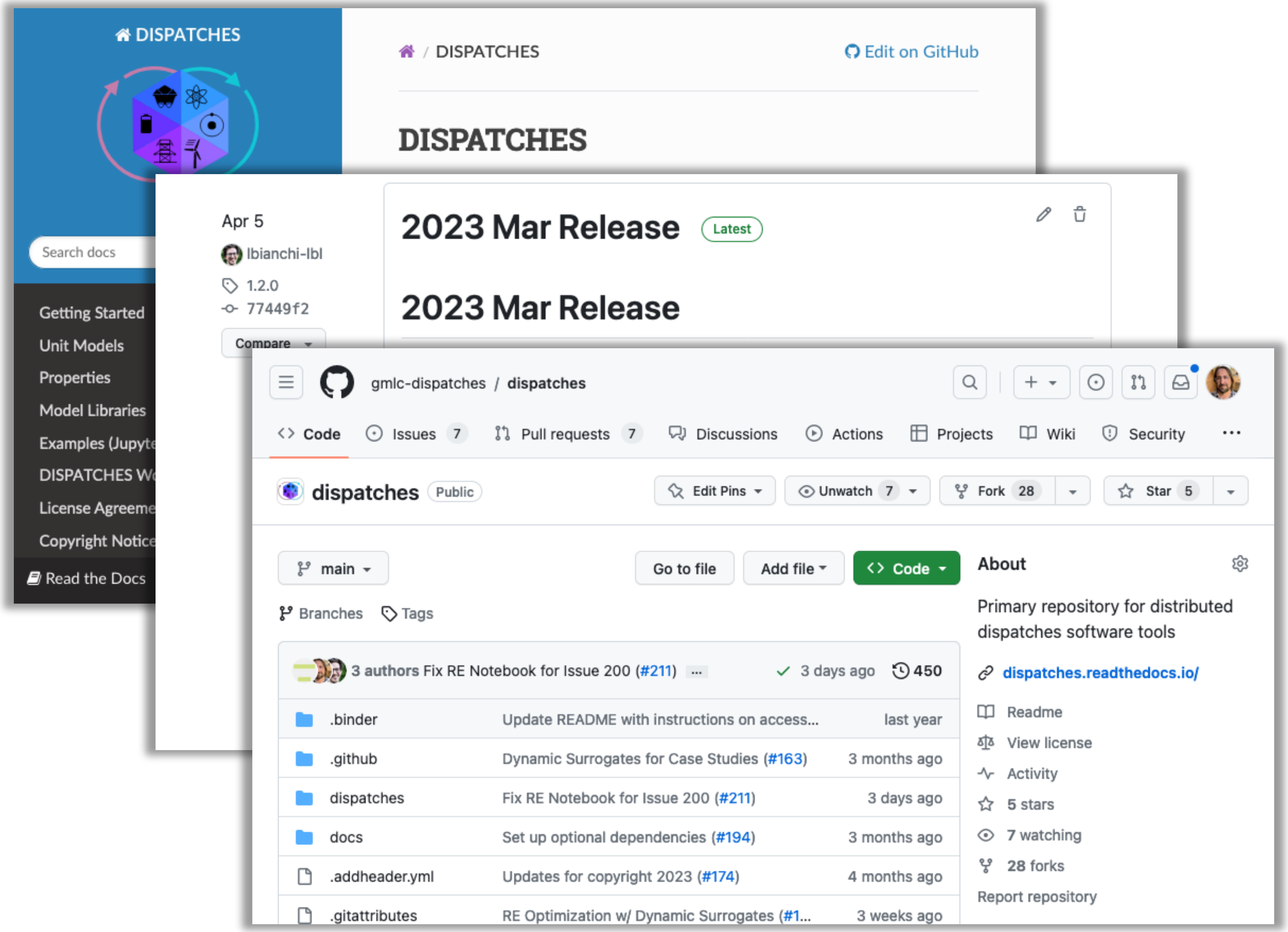
- Small fuel cell (matched to electrolyzer)
- High capacity factor, constant production
  - ➢ Base load generator (not peaker)



Storage level is constant *(not shown)*

DISPATCHES: Software Documentation, Releases & Source Code

- Documentation (starting point):
  https://dispatches.readthedocs.io
- Software Releases:
  https://github.com/gmlc-dispatches/dispatches/releases
- Source code:
  https://github.com/gmlc-dispatches/dispatches/



Primary repository for distributed dispatches software tools

dispatches.readthedocs.io/

Readme
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3 authors Fix RE Notebook for Issue 200 (#211) ... ✓ 3 days ago 450

.binder	Update README with instructions on access...	last year
.github	Dynamic Surrogates for Case Studies (#163)	3 months ago
dispatches	Fix RE Notebook for Issue 200 (#211)	3 days ago
docs	Set up optional dependencies (#194)	3 months ago
.addheader.yml	Updates for copyright 2023 (#174)	4 months ago
.gitattributes	RE Optimization w/ Dynamic Surrogates (#1...	3 weeks ago

Summary

- DISPATCHES developed
  - Models and workflows supporting the conceptual design of novel hybrid systems in a way that enables rigorous exploration of the design space
  - Design optimization techniques that explicitly value the output of the hybrid system within the context of the grid and region it is deployed
- Key findings
  - The standard “Price Taker” assumption commonly adopted to aid system analysis can over-predict revenues for flexible systems (e.g., participating in arbitrage)
  - Machine learning / surrogate models are an effective approach for integrating process design with market participation
- DISPATCHES demonstrated standard workflows to “generic” and industry-specific case studies
  - Power and hydrogen co-production systems
    - Nuclear case study
    - Renewable case study
    - Nuclear generation and H_2 Peaker
  - Other case studies (not covered in this poster)
    - Multiscale market simulation capability: wind farm integrated with storage
    - Market-informed design of thermal energy storage systems
    - Integrated fossil, renewables, storage and power purchasing