Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems

Topic: Generation

Sub-Topic: Hybrid Systems

DOE 2019 Grid Modernization Lab Call

DISPATCHES

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

NETL: **David Miller**, Radhakrishna Gooty, Andrew Lee, Naresh Susarla, (Jaffer Ghouse)
SNL: **John Siirola**, Darryl Melander, Edna Rawlings, Kyle Skolfield, (Jordan Jalving)
INL: Aaron Epiney, Joshua Cogliati, (Andrea Alfonsi, Konor Frick, Jason Hansen, Cristian Rabiti)
NREL: Wes Jones, Darice Guittet, Ben Kneuven, Ignas Satkauskas, (Abinet Eseye)
LBNL: Dan Gunter, Oluwamayowa Amusat, Keith Beattie, Ludovico Bianchi
U. of Notre Dame: **Alexander Dowling**, Xinhe Chen, (Xian Gao)

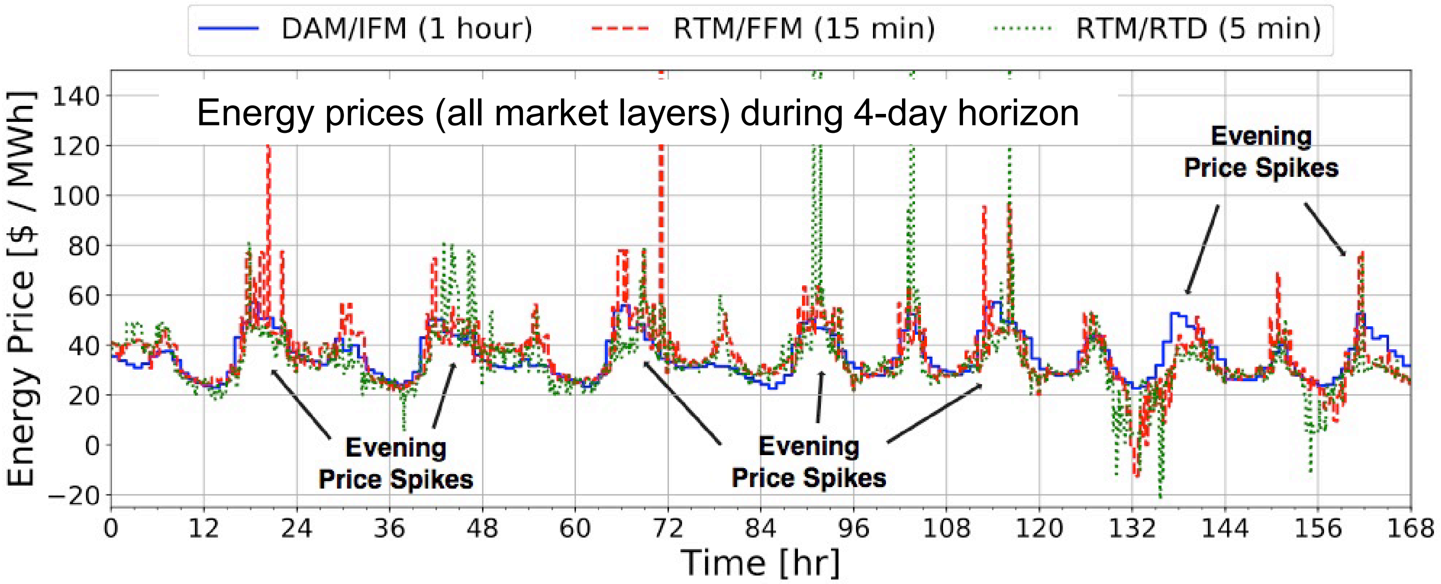
NATIONAL ENERGY TECHNOLOGY LABORATORY · Sandia National Laboratories · BERKELEY LAB · Idaho National Laboratory · NREL Transforming ENERGY · UNIVERSITY OF NOTRE DAME

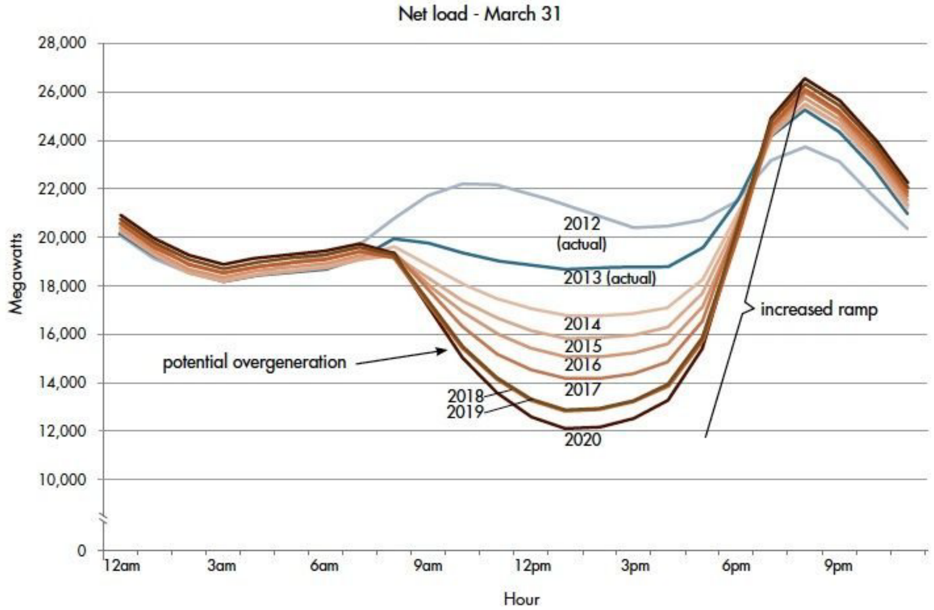
Agenda

- Overview
- Core DISPATCHES capabilities: optimization workflows, library of models
- Market surrogates capability: Power and hydrogen co-production systems
  - Generic nuclear case study
  - Generic renewable case study
- Multiscale market simulation capability: wind farm integrated with storage
- Market-informed design of thermal energy storage systems
- Industrial partnerships
  - Partner in nuclear industry
  - Arizona G&T
- Software release

Evolving Grid Increasingly Requires Flexibility

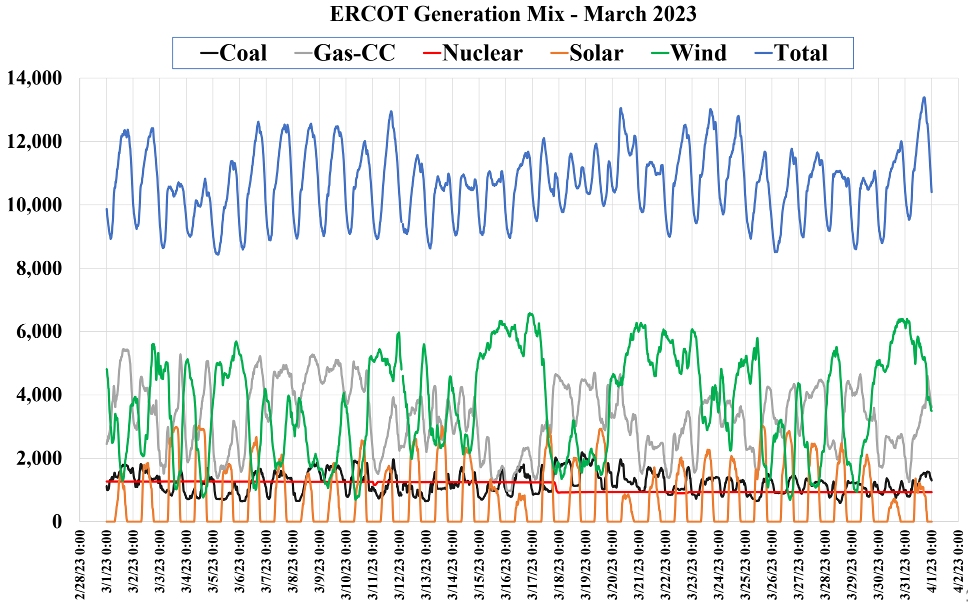
California ISO (CAISO)





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

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

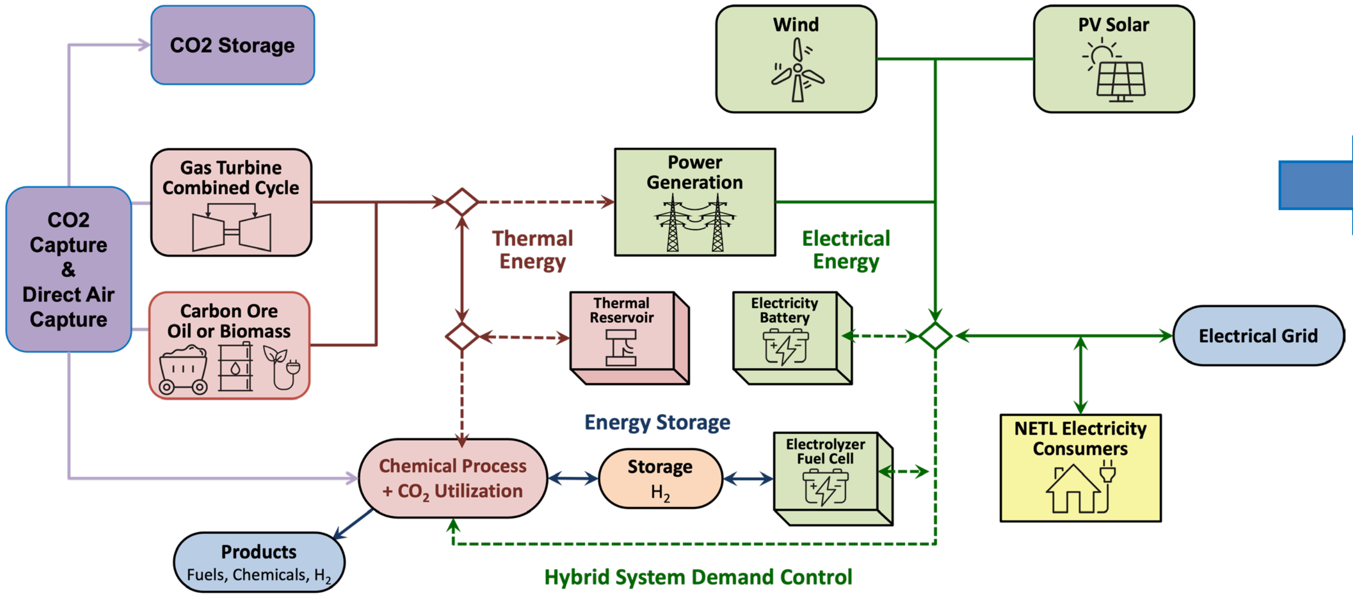
DISPATCHES
Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

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

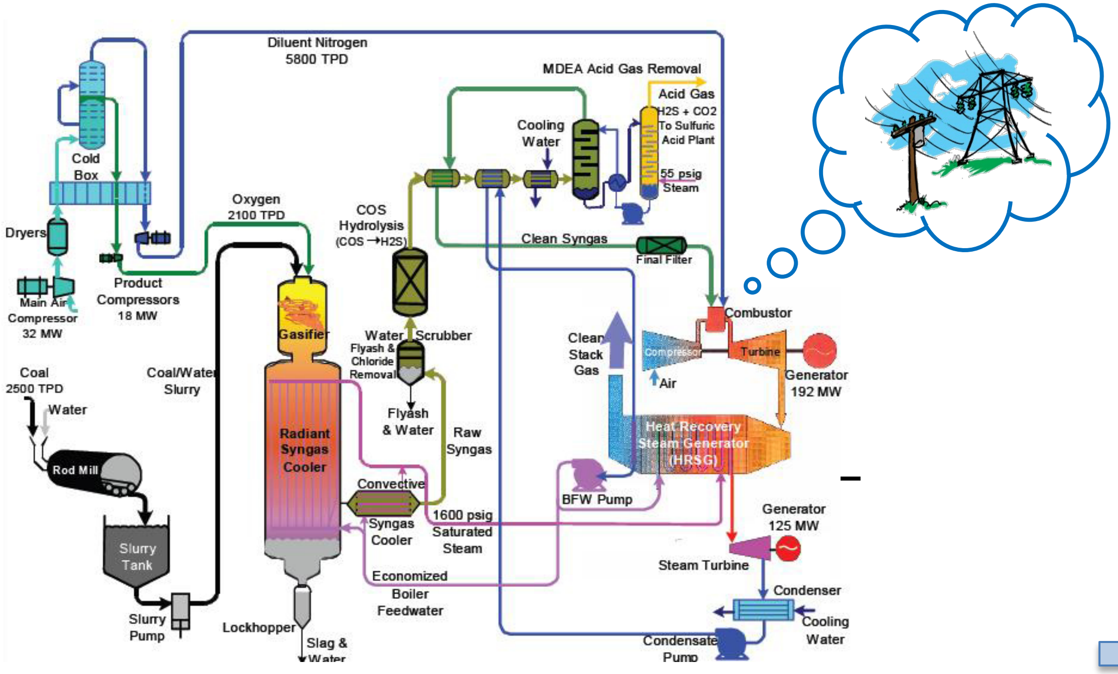
Detailed plant model assuming grid as an infinite capacity bus

Market Interactions

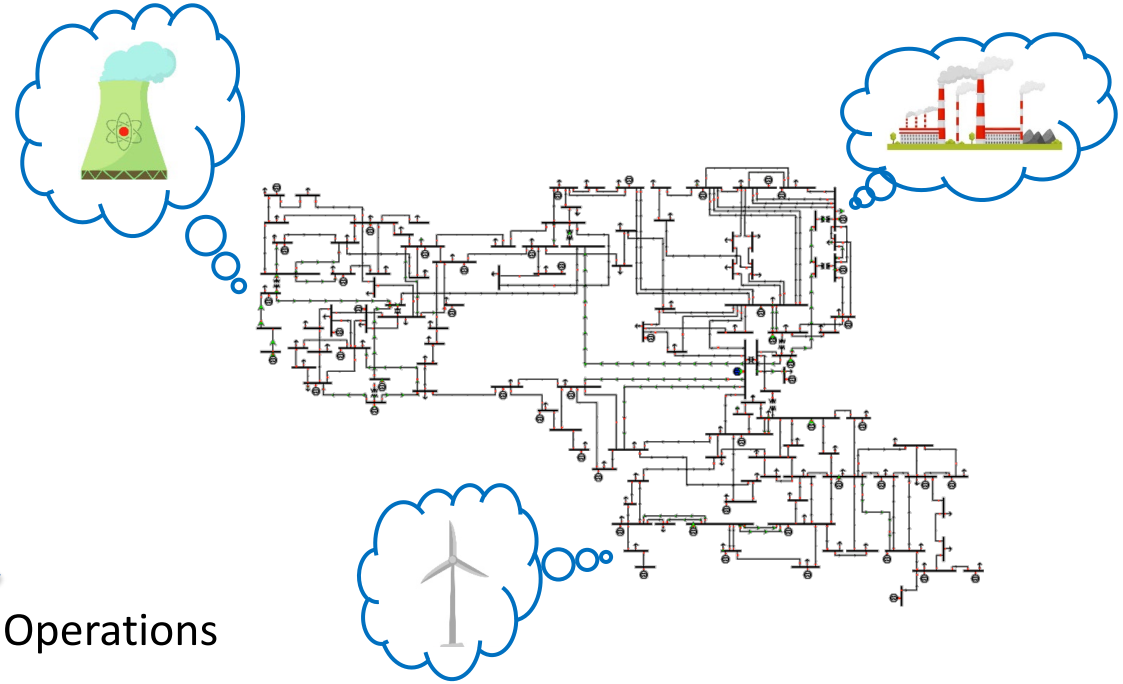
Hybrid System Operations

Grid-centric Modeling

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



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



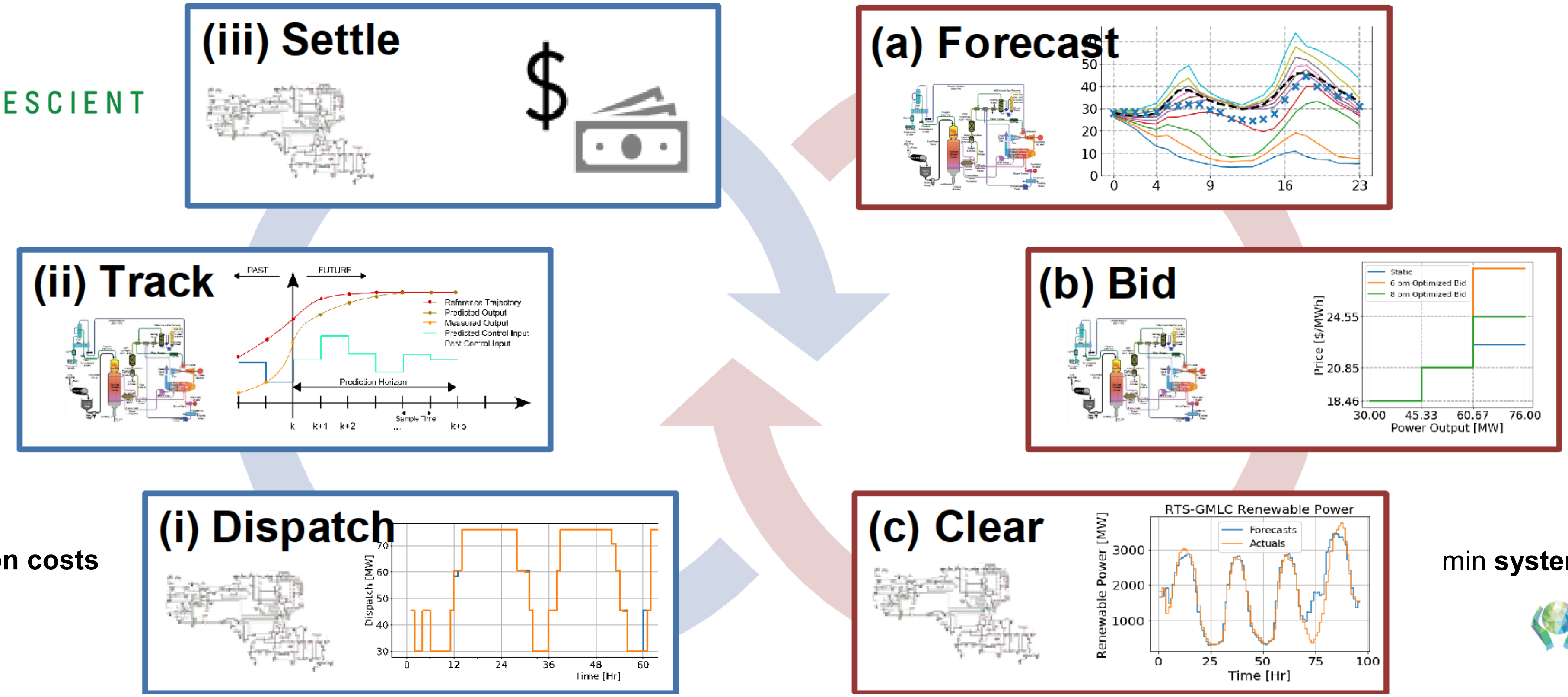
https://icseg.iti.illinois.edu/files/2013/10/IEEE118.png

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

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

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

balance:
- **cost**
- **health**
- **tracking penalty**



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

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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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UNIVERSITY OF NOTRE DAME

07/2020 to 06/2023

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

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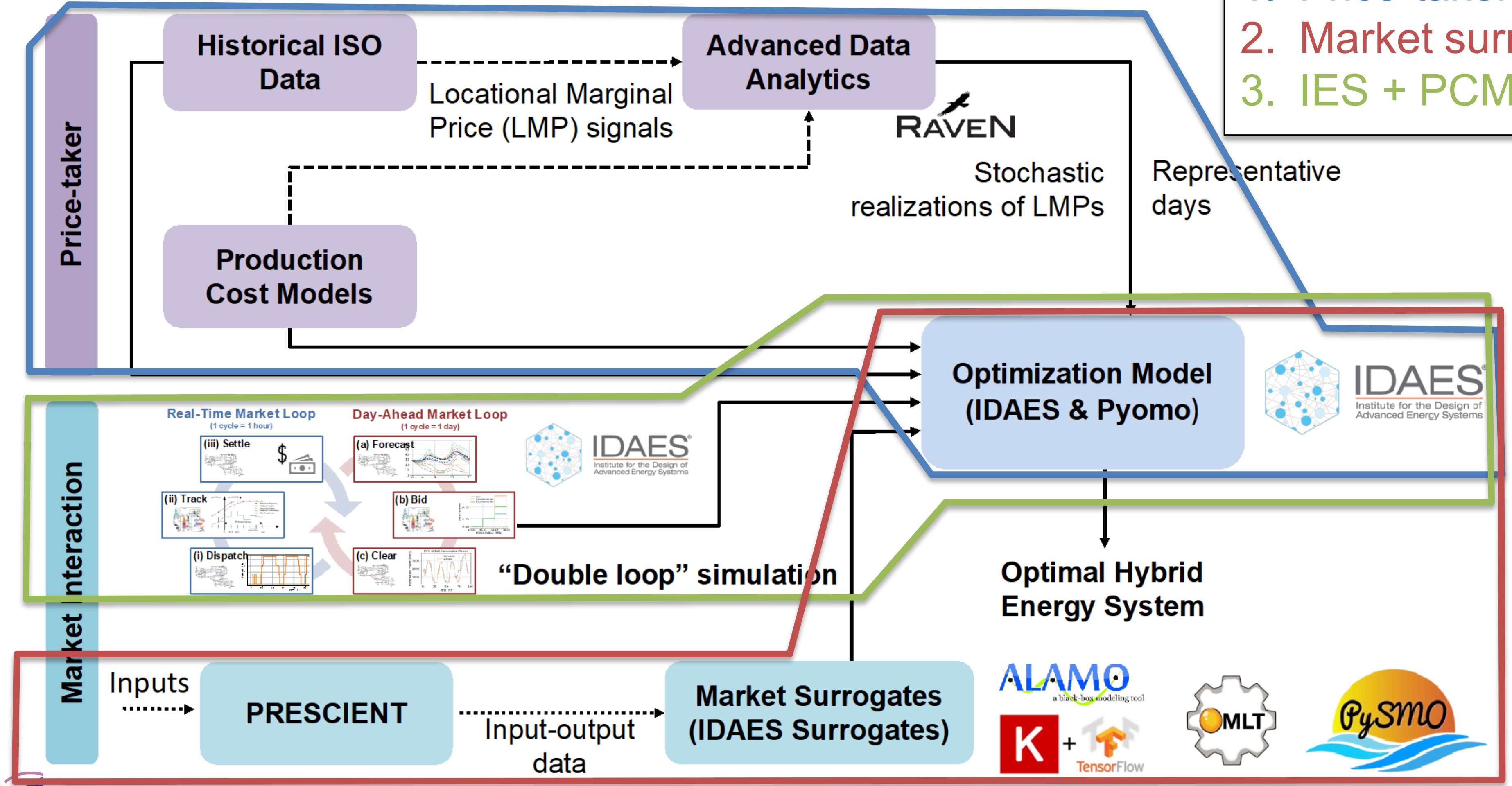
DISPATCHES Optimization Workflows

DISPATCHES

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



Three Workflows:

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

DISPATCHES Modeling Library Enables Diverse Case Studies

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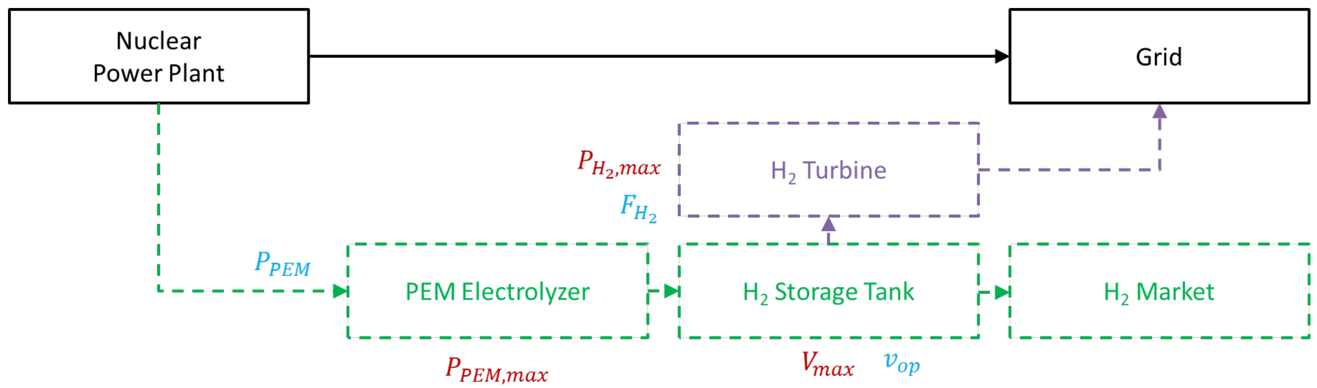
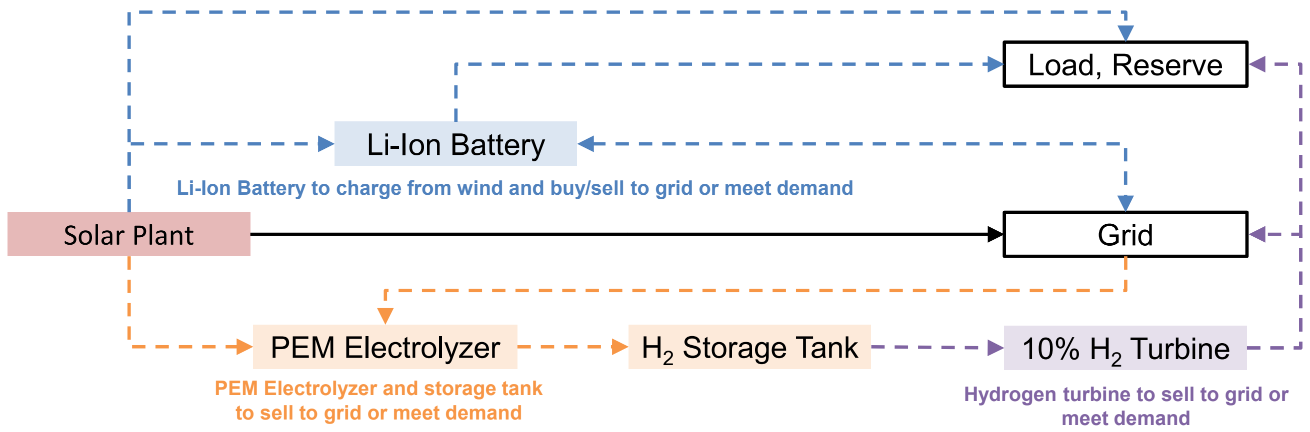
Low fidelity submodels for rapid analysis

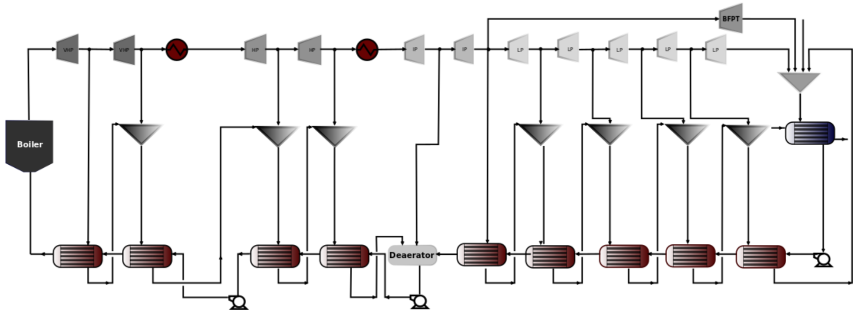
Nuclear (baseload) + PEM electrolyzer + H_2 turbine + H_2 storage



Solar or Wind + PEM electrolyzer + battery + H_2 turbine + H_2 storage

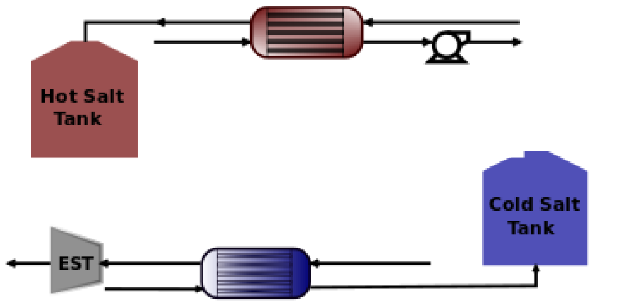


High fidelity submodels for rigorous design



Ultra-Supercritical Power Plant (USCPP)

\+



Thermal Energy Storage (TES)

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Modular modeling enables easy customization to analyze many IES configurations

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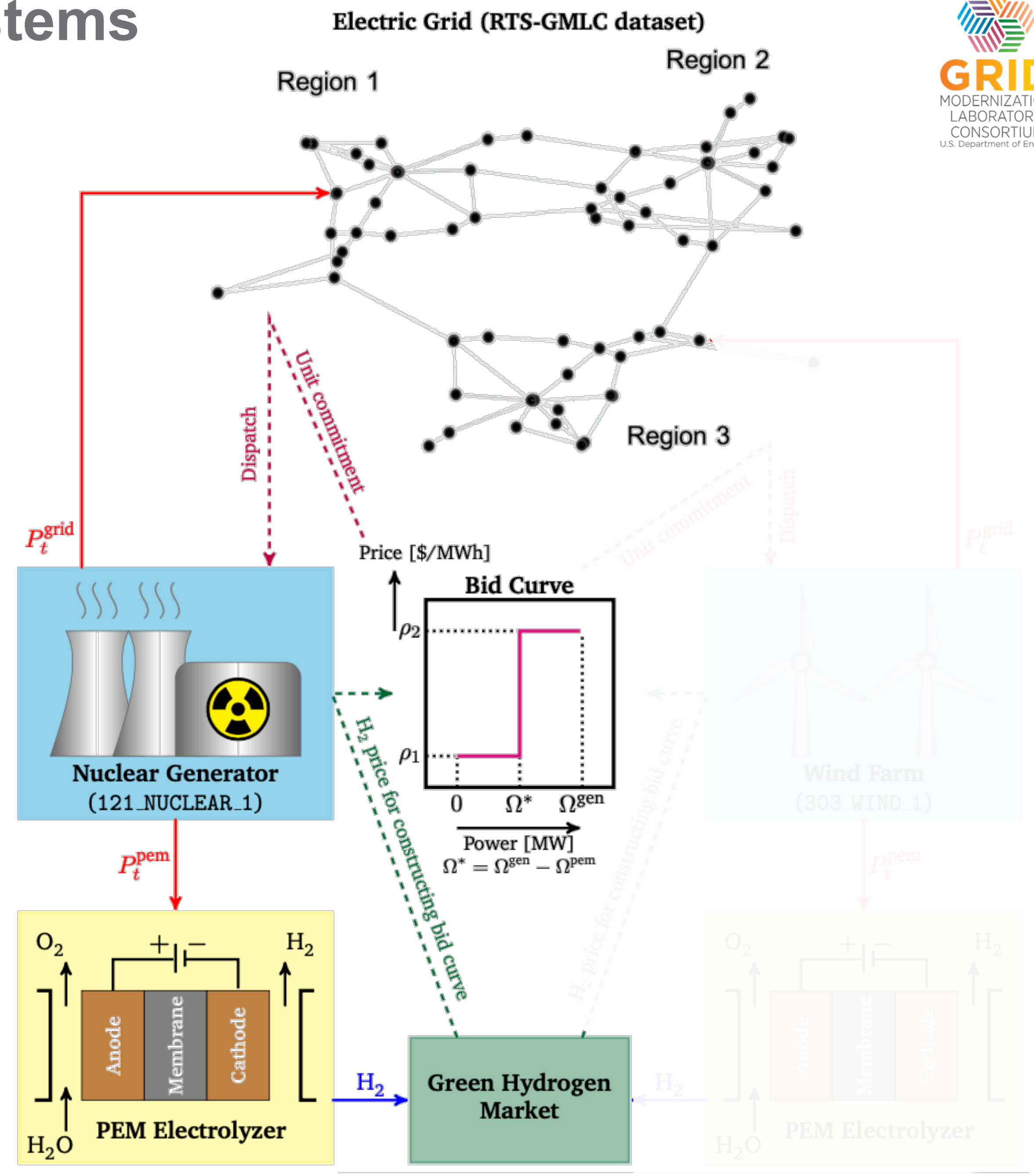
Power and Hydrogen Co-production Systems

- Increasing renewables → volatile grid conditions
  - Nuclear generators cannot respond
  - Curtailment of renewable power
- Participate in alternate markets, e.g., H_2
  - Increases profitability, efficiency, flexibility of
  - Decarbonize other sectors
- 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
- H_2 markets are in their infancy
  - Assume unconstrained H_2 demand
  - Assume time-invariant H_2 price, perform sensitivity analysis



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

Nuclear Case Study Summary (Flexibility from Co-Products)

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U.S. Department of Energy

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

Market surrogates: 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

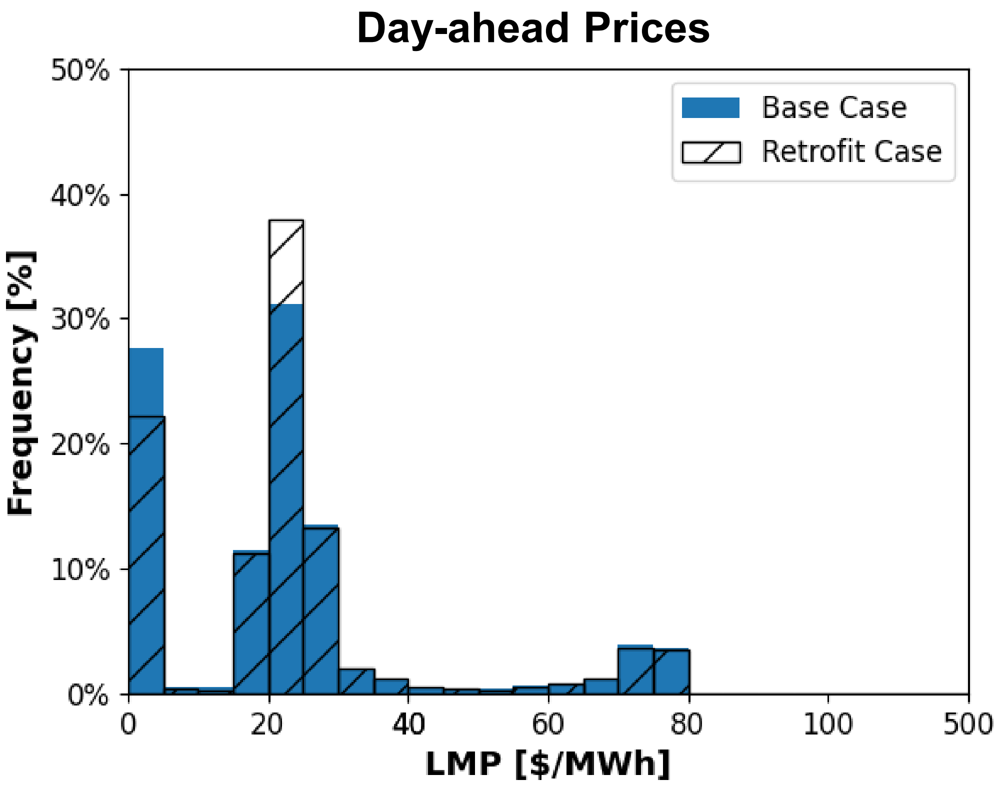
Method applies to other baseload generators, e.g., large coal or gas-fired generators with carbon capture

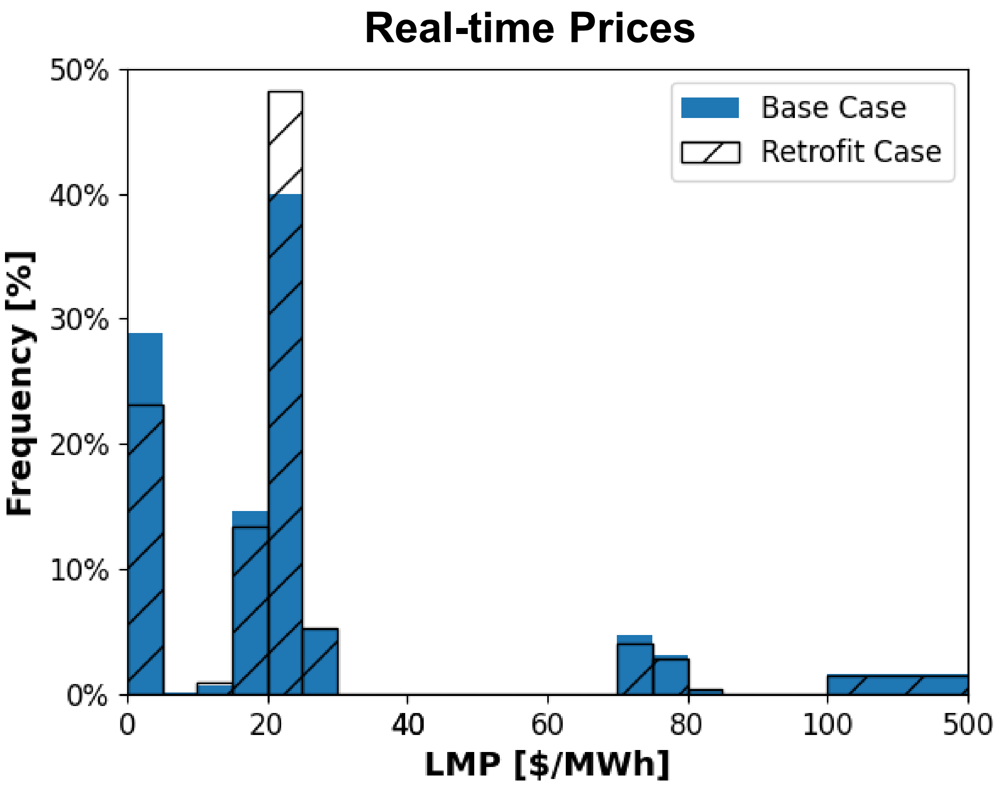
Easy to adapt to other electrolysis technologies – solid oxide electrolyzer cell (SOEC)

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

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)





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

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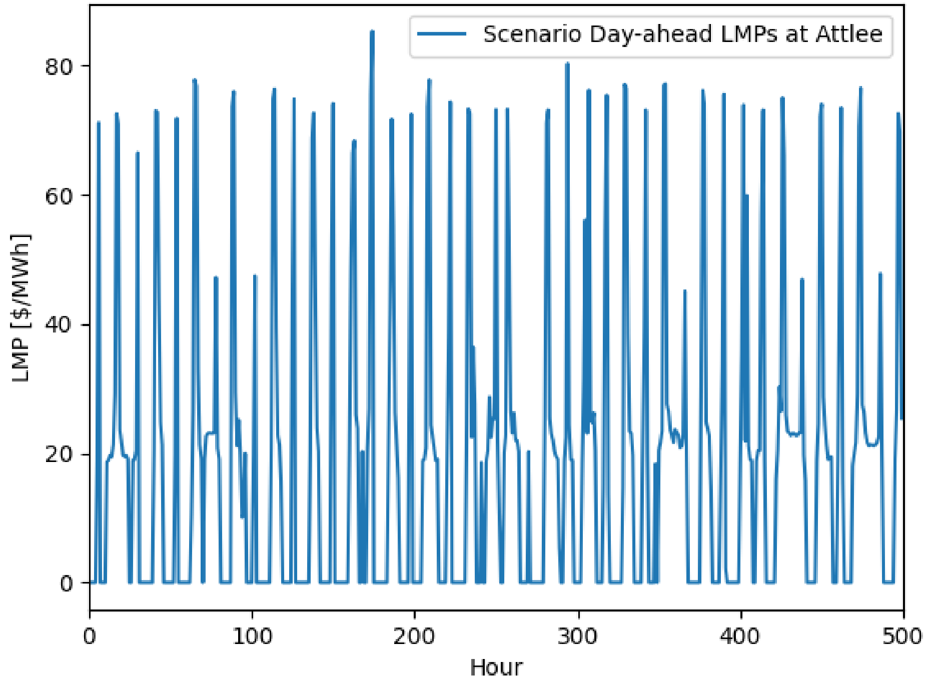
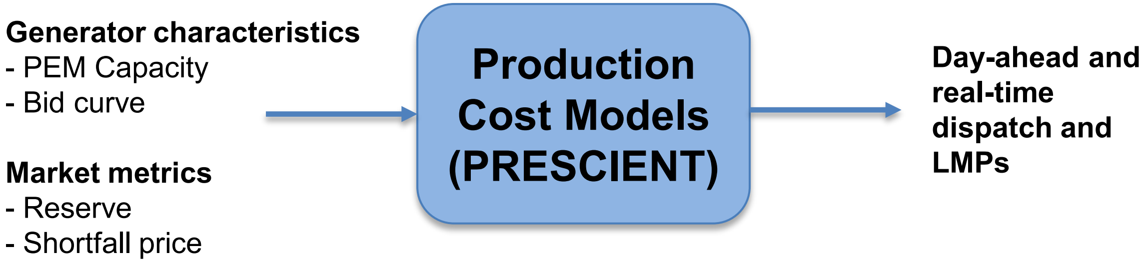
- **PT1:** Generate LMP data (PCM or historical)

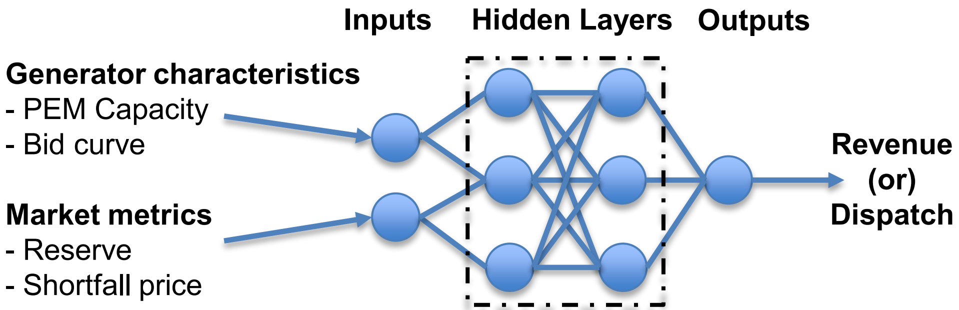


- **PT2:** Formulate and solve the price-taker problem

- **MS1:** Generate training data



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



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

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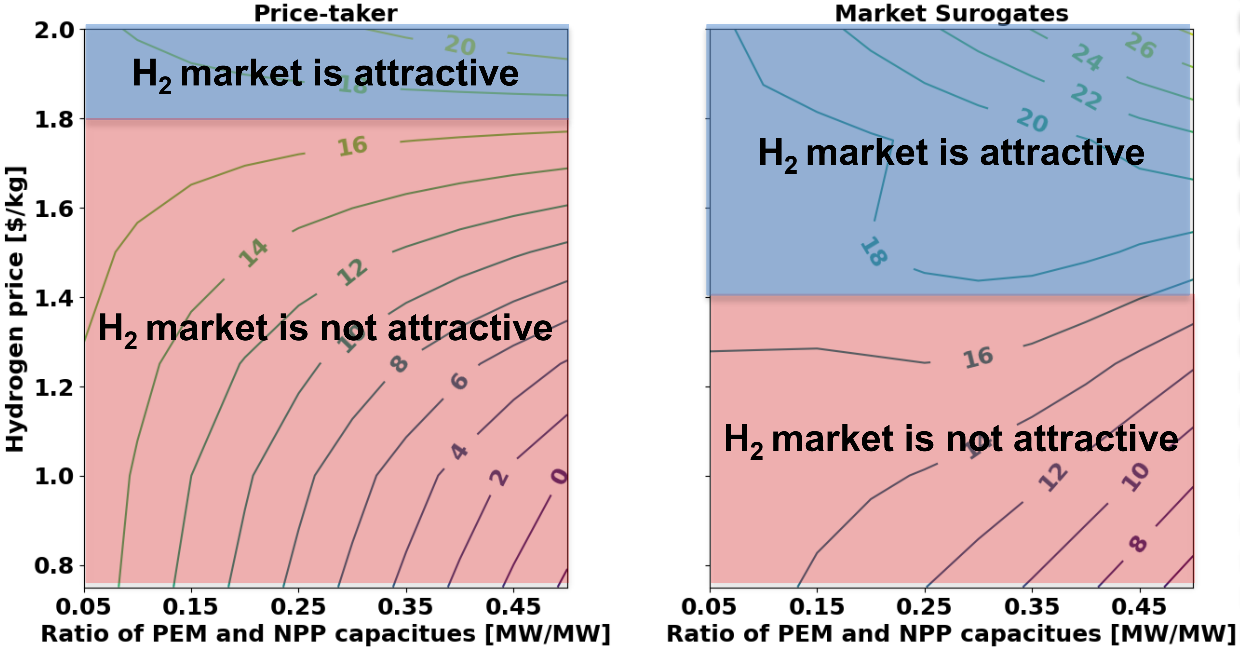
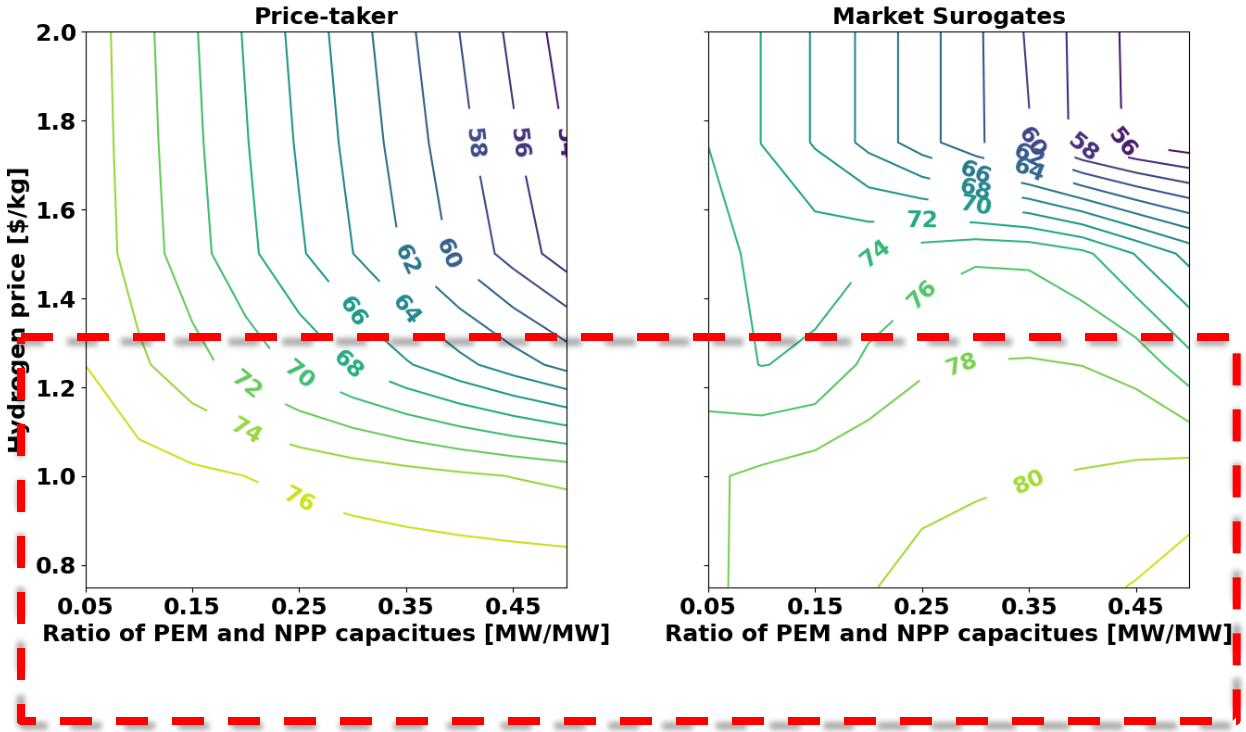
Nuclear Case Study Results: Price-taker vs Market Surrogates

- 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

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*See report for comparison of multiple price-taker variants

Optimization Results with Market Surrogates are More Accurate

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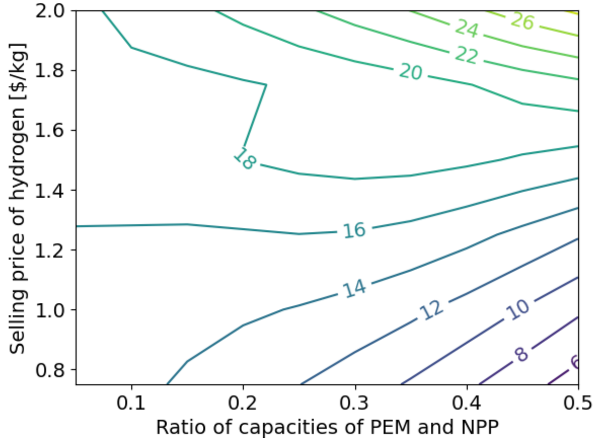
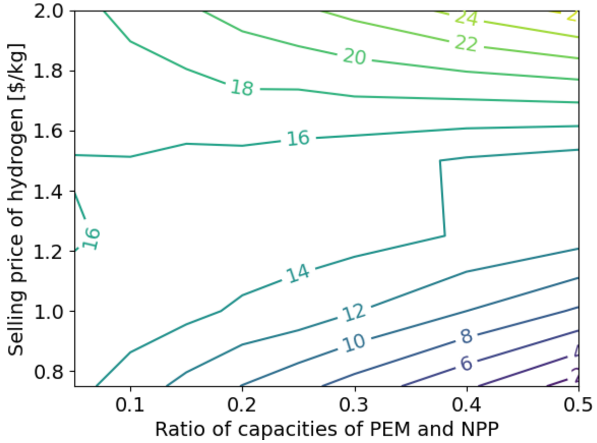
- Validation of **net present value** and breakeven hydrogen price

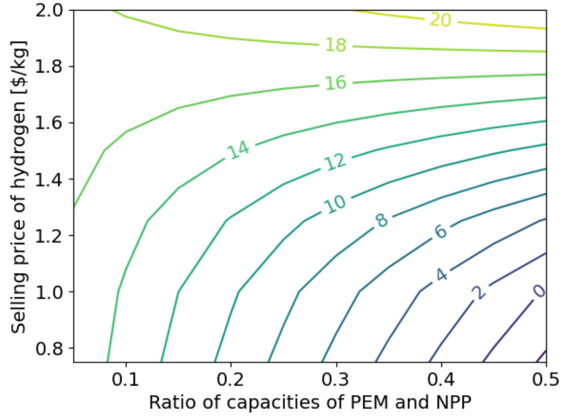
Market Surrogates



PCM Simulations

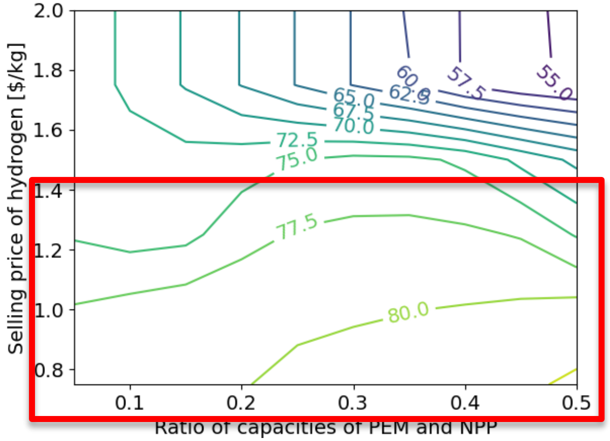


Price-taker Approach



- Validation of **electricity revenue**

Market Surrogates



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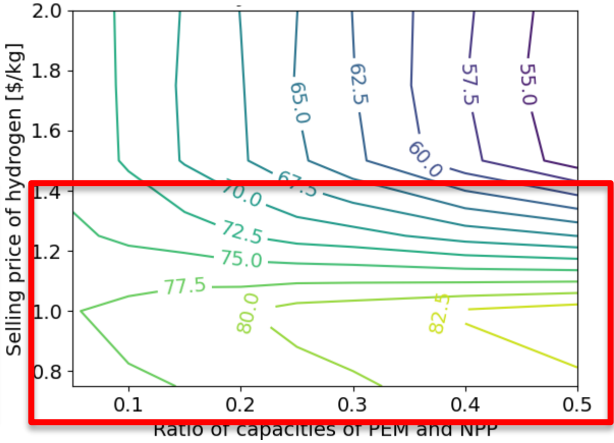
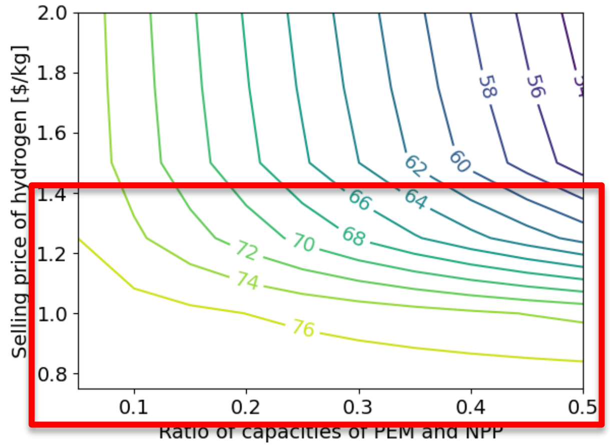


Price-taker Approach



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Nuclear Case Study Summary (Flexibility from Co-Products)

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

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Co-optimize design and operation

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Impact

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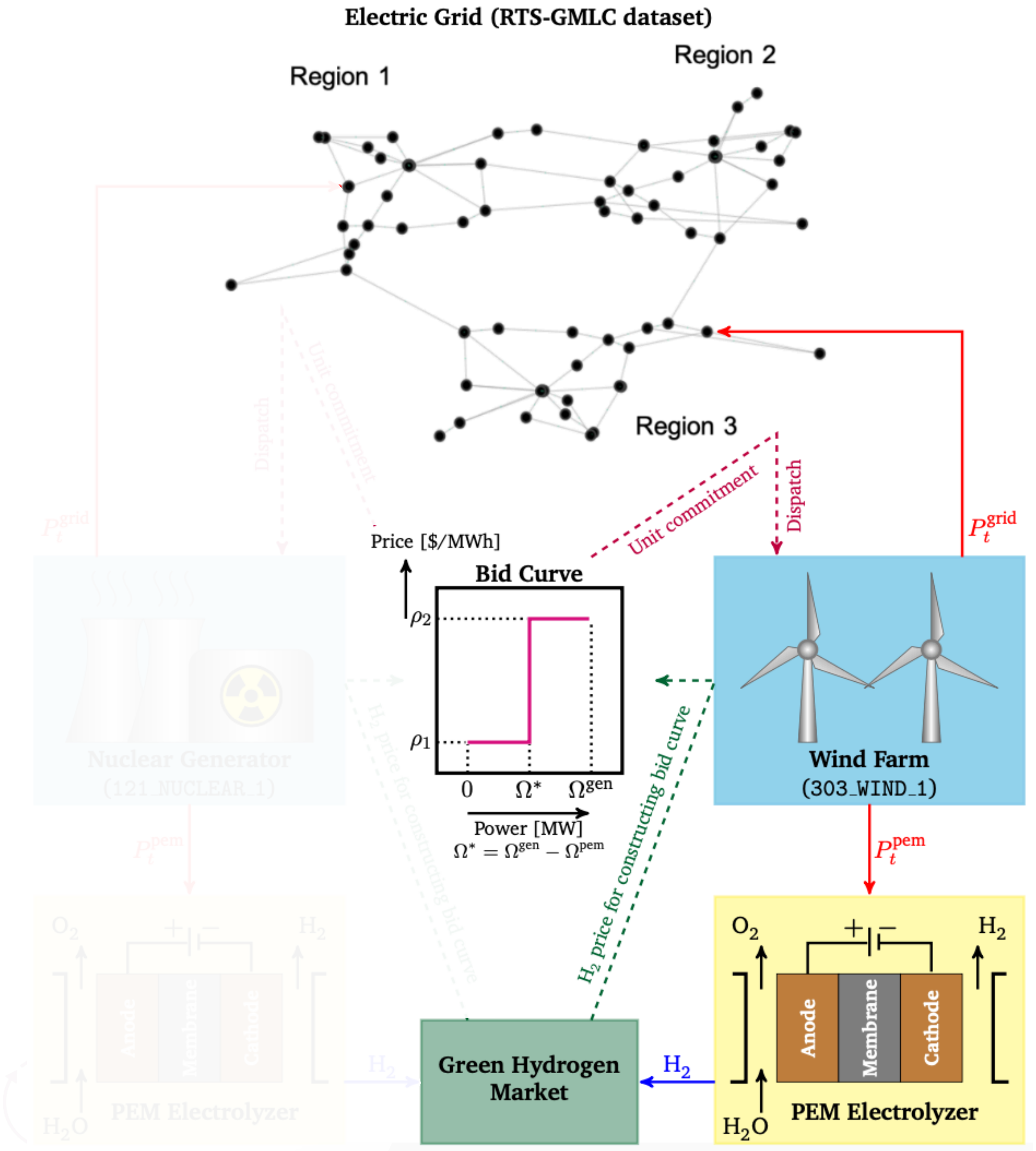
RE Case Study: Retrofit Existing Wind + PEM



Challenge for wind generation in RTS-GLMC:

- Significant curtailment in RTS-GMLC
- Revenues are inadequate to recover operating costs

How does hybridization with PEM to co-produce H_2:

- Improve economics and flexibility
- Reduce curtailment

Fundamental difference from nuclear case: renewables (wind) adds uncertainty.

<u>Different assumptions than nuclear case</u>:

- Shortfall price was \$1000/MWh (instead of \$500/MWh)
- RT market only, to avoid penalties from missed DA promises
- No depreciation nor corporate tax
- Objective value was 30-year NPV (instead of annualized)

Wind-Electrolyzer Case Study Summary (Flexibility from Co-Products)

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Problem Statement

How to hybridize an existing wind farm to produce H_2 to:

- Increase flexibility for the grid
- Increase profitability
- Decrease curtailment
- Manage uncertainty

Co-optimize design and operation

Method

Compare and validate the three DISPATCHES workflows:

- Price-taker optimization
- PCM enumeration
- Market surrogate optimization
- Validation with PCM

Key Findings

Hybridization dramatically improves wind farm economics and curtailment

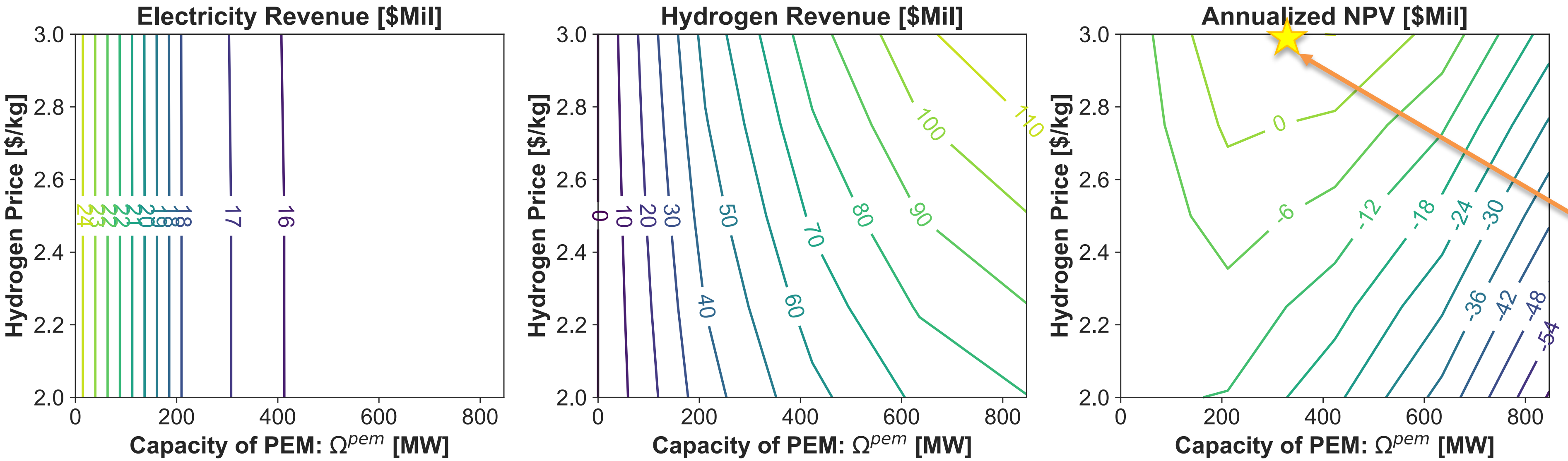
Market surrogate bridge gap between PCM enumeration and the price-taker optimization

Impact

H_2 via electrolysis provides flexibility to integrate renewables into the electric grid

Extend methods to other renewable systems (e.g., solar thermal, PV) and other hybridization pathways (e.g., chemicals such as NH_3)

RE Case Study: Optimal Design with Price-Taker



Optimum for $3/kg H_2

322 MW PEM

7 $mil NPV

Optimal PEM Designs

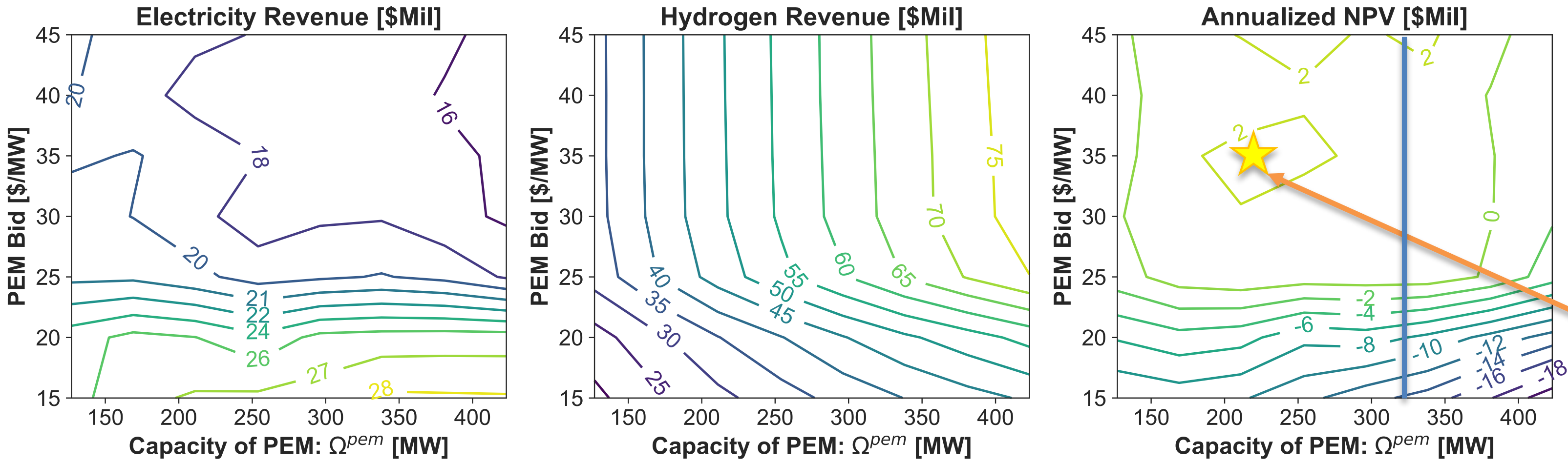
H_2 Price [$/kg]	PEM Size [MW]	Ann. NPV [$mil]
2.00	65	-10
2.25	123	-7.1
2.50	204	-3.3
2.75	262	1.4
3.00	**322**	**7.0**

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)

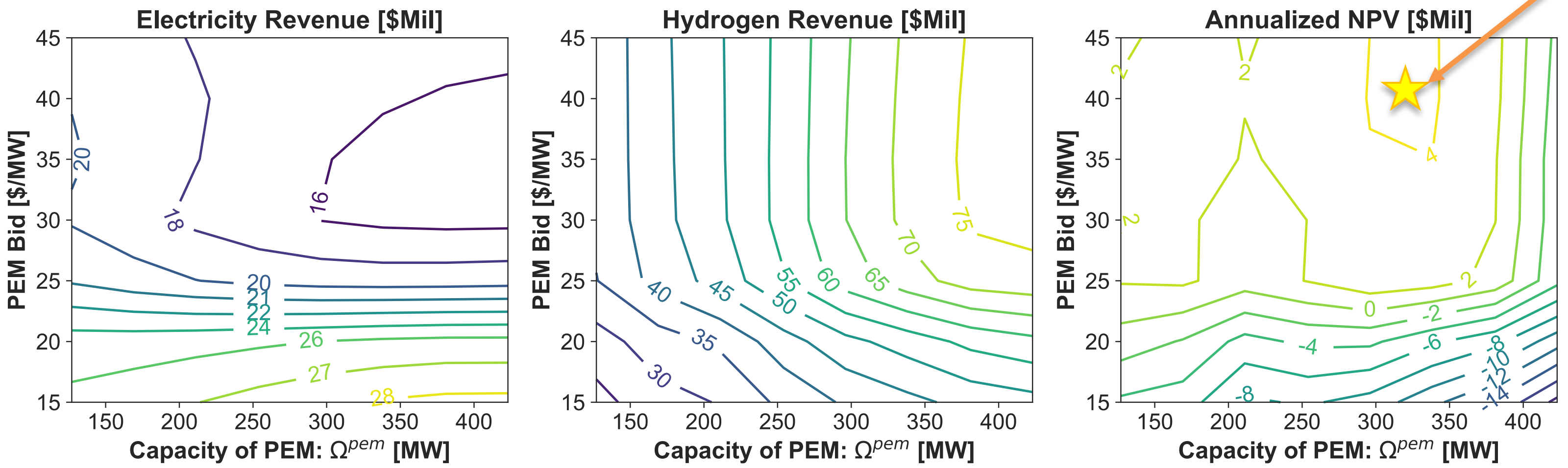
Market Surrogate Fit

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

Wind-Electrolyzer Case Study Summary (Flexibility from Co-Products)

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Wind-Battery Case Study Summary (Flexibility from Time-Shifting)

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Problem Statement

How to retrofit an existing **wind farm** with **battery energy storage** to:

- Increase flexibility for the grid
- Increase profitability
- Decrease curtailment?

Co-optimize design and operation

Methods

Compare two modeling approach:

- **Price-taker optimization**: neglect IES impact on market outcomes interaction with the market.
- **Multiscale IES-PCM simulation**: IES bids into market, quantify IES/market interaction.

Key Findings

Participating only in the electrical energy market is not profitable because of high capital and OM costs

The price-taker optimization overestimates the IES economic value.

The IES/market interaction changes the LMP.

Impact

Approach is applicable all IES including other renewable sources (e.g., solar thermal, PV) and energy storage technologies (e.g., thermal, compressed air, chemical)

Opportunity to generalize the market surrogates approach (previous case studies) to consider energy storage

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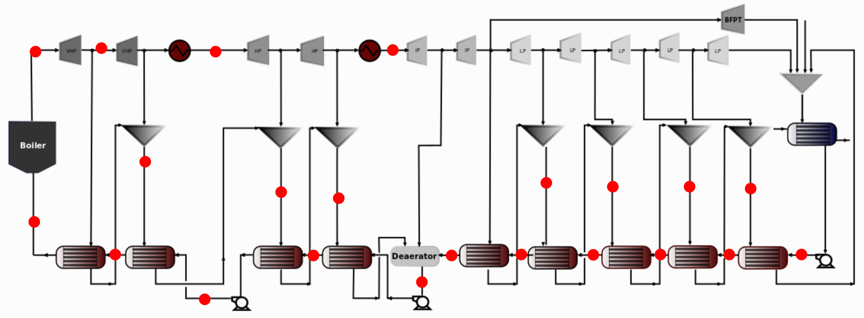
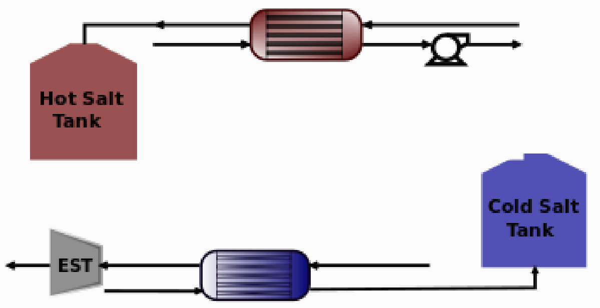
Optimal design and integration of a thermal energy storage (TES) with a fossil-based thermal power plant

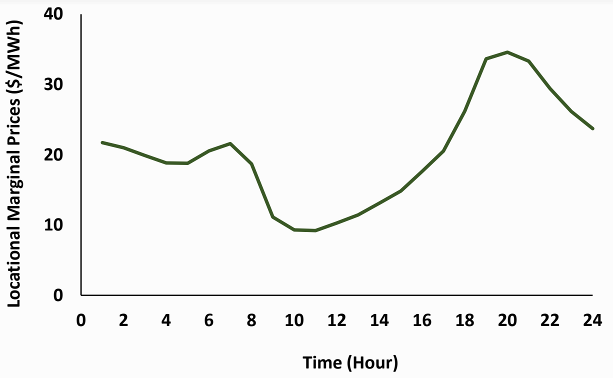
- **Motivation:**
  - Base load plants are required to operate flexibly under high variable renewable integration



Ultra-supercritical Power Plant (USCPP)



Thermal Energy Storage (TES)



Dynamic Electricity Prices

- **Determine:**
  - Optimal **integration points** considering rigorous process level models
  - Optimal **size** of energy storage considering dynamic electricity market
- **Key challenges**
  - Computational tractability when using non-linear first-principles models
  - Combinatorial complexity presented by the integral choices

Fossil + Thermal Storage Case Study (Flexibility from Time-Shifting)

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U.S. Department of Energy

Problem Statement

Optimal design and integration of thermal energy storage (TES) with ultra supercritical steam cycle while considering time-varying electricity prices and **large-scale process model**

Determine:

- **Discrete design** decisions (71 integration options!)
- **Continuous design capacity** variables

Method

Two-step approach:

- **Step 1: GDP** to determine storage material and points of integration of TES.
- **Step 2: Multi-period** to calculate optimal size and operational conditions of integrated USCPP with time-varying electricity prices.

Key Findings

Systematic evaluation of 71 multiple flowsheet configurations within one model

Designing considering time-varying electricity prices prevents under- or over-sizing storage

Impact

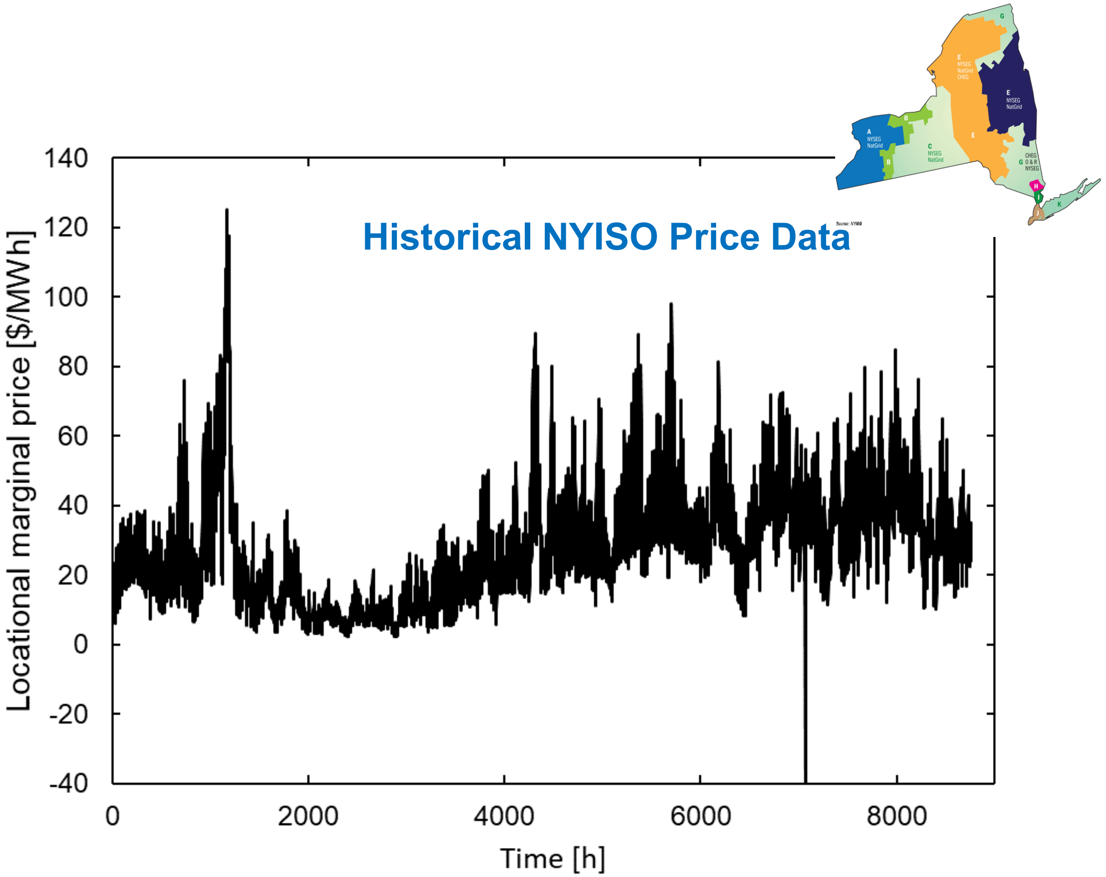
Method is applicable NGCC & biomass gasification for co-producing H_2 & electricity with CO_2 capture, and nuclear or solar generators with TES.

Analysis method supports analyzing historical electricity prices or market surrogates

Agenda

- Overview
- Core DISPATCHES capabilities: optimization workflows, library of models
- Market surrogates capability: Power and hydrogen co-production systems
  - Generic nuclear case study
  - Generic renewable case study
- Multiscale market simulation capability: wind farm integrated with storage
- Market-informed design of thermal energy storage systems
- Industrial partnerships
  - Partner in nuclear industry
  - Arizona G&T
- Software release

Nuclear + H_2 Industrial Partner Case Study: Problem Statement



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

Revenues:

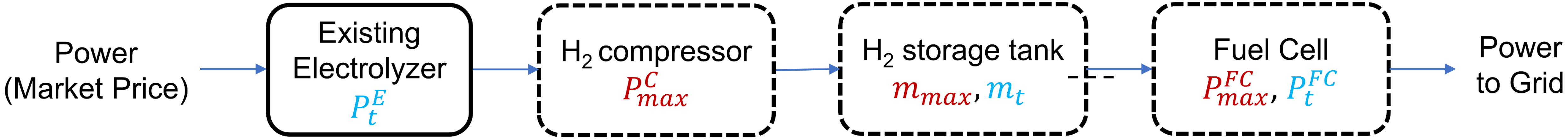
- Electricity sales (historical dynamic prices)
- H_2 sales (assume constant price)
- Hydrogen Production Tax Credit (HPTC; 45V in IRA)
- Capacity payments (CP), requires 4 hours of fuel on-site

Design Decisions:

- Storage tank size
- Fuel cell capacity

Operating Decisions:

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



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

IRA: Inflation Reduction Act

Nuclear + H_2 Industrial Partner Case Study (Flexibility from Time-Shifting)

Problem Statement

Co-optimize design and operation of a H_2 + nuclear peaking power plant with H_2 storage

Method

Price Taker Optimization: valid since the capacity of the peaker is very small

Additional revenues from hydrogen production tax credit (45V in IRA) and capacity market

Key Findings

Capacity payments need to be an order of magnitude higher (~$15) than present day (~$2.50) to reach multi-million net present value.

Hydrogen Production Tax Credit improves economics. If it is not extended after 10 years, build decision may still be marginally profitable.

Impact

Quantify necessary market conditions for carbon-neutral technologies to be economically viable

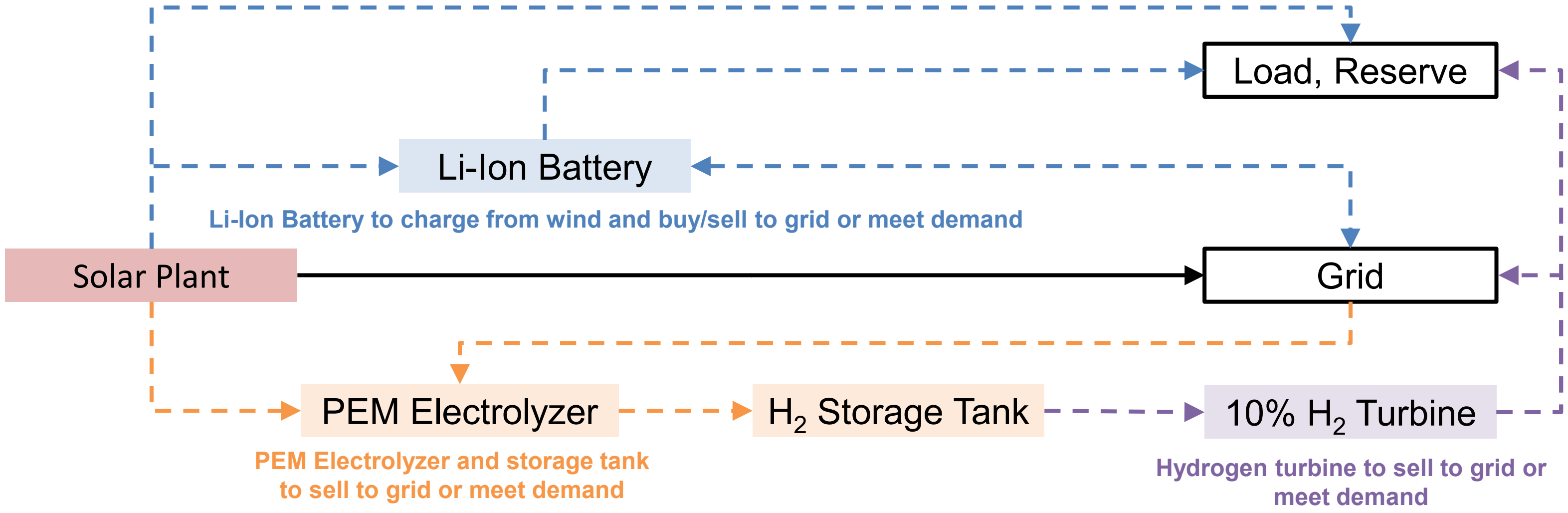
E.g.: Identified capacity payment value for which the overall economics are favorable.

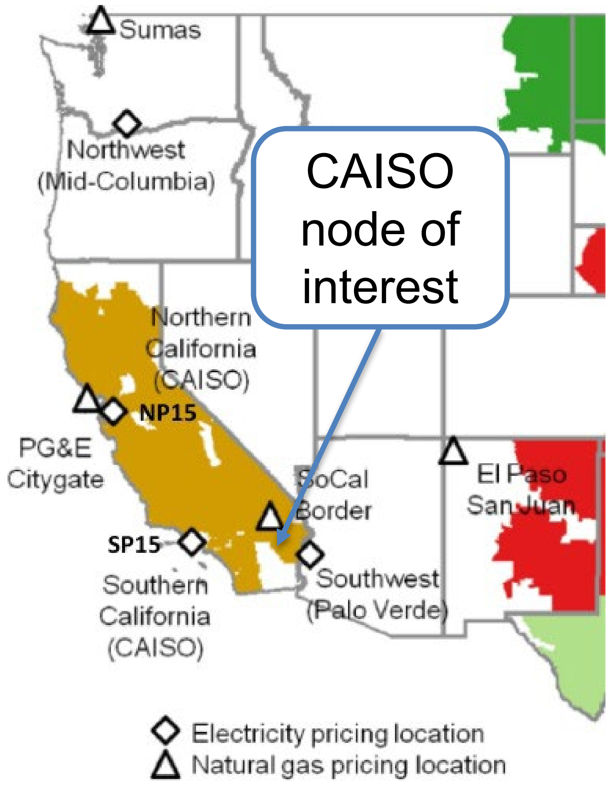
Easily extendable to other systems, utility/industry goals

Arizona G&T Case Study: Problem Statement

Goal: Co-optimize an IES with PV, PEM electrolysis, battery storage, and a flexible gas turbine that combusts H_2 and natural gas blends to:

- Meet load of existing baseload steam turbine
- Provide reserves via curtailed PV power, turbine headroom, PEM footroom, stored battery power
- Replace original 181 MW of capacity
- Benefit from exchange with CAISO
- Benefit from hydrogen market
- Reduce emissions





Major pricing locations in the Western Interconnection.
Source: C.K. Woo, et al. “Carbon trading’s impact on California’s real-time electricity market prices”

Analysis Questions:

1. What are the PV and storage sizes? Are they realistic on-site?
2. How expensive to replace steam plant with a new flexible gas turbine (up to 100% H_2)?
3. What are the impacts on carbon emissions?

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

Arizona G&T Case Study (Flexibility from Time-Shifting)

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Problem Statement

How to co-optimize design and operation of a PV plant hybridized with PEM electrolysis, battery storage, and a flexible gas turbine?

What are the impacts of minimum limits of H_2 in turbine fuel?

Method

Price-taker optimization enables analysis of historical data from CAISO

Co-optimize design and operation for different IES configuration options

Key Findings

Enforcing H_2 in turbine fuel reduces the benefits of the turbine in the winter

Building out PV + Battery alone requires a large battery capacity

Impact

Workflow is highly customizable for diverse technologies and partner analysis goals

Opportunity to extend workflow to consider other market products (e.g., ancillary services) and surrogate to go beyond price taker

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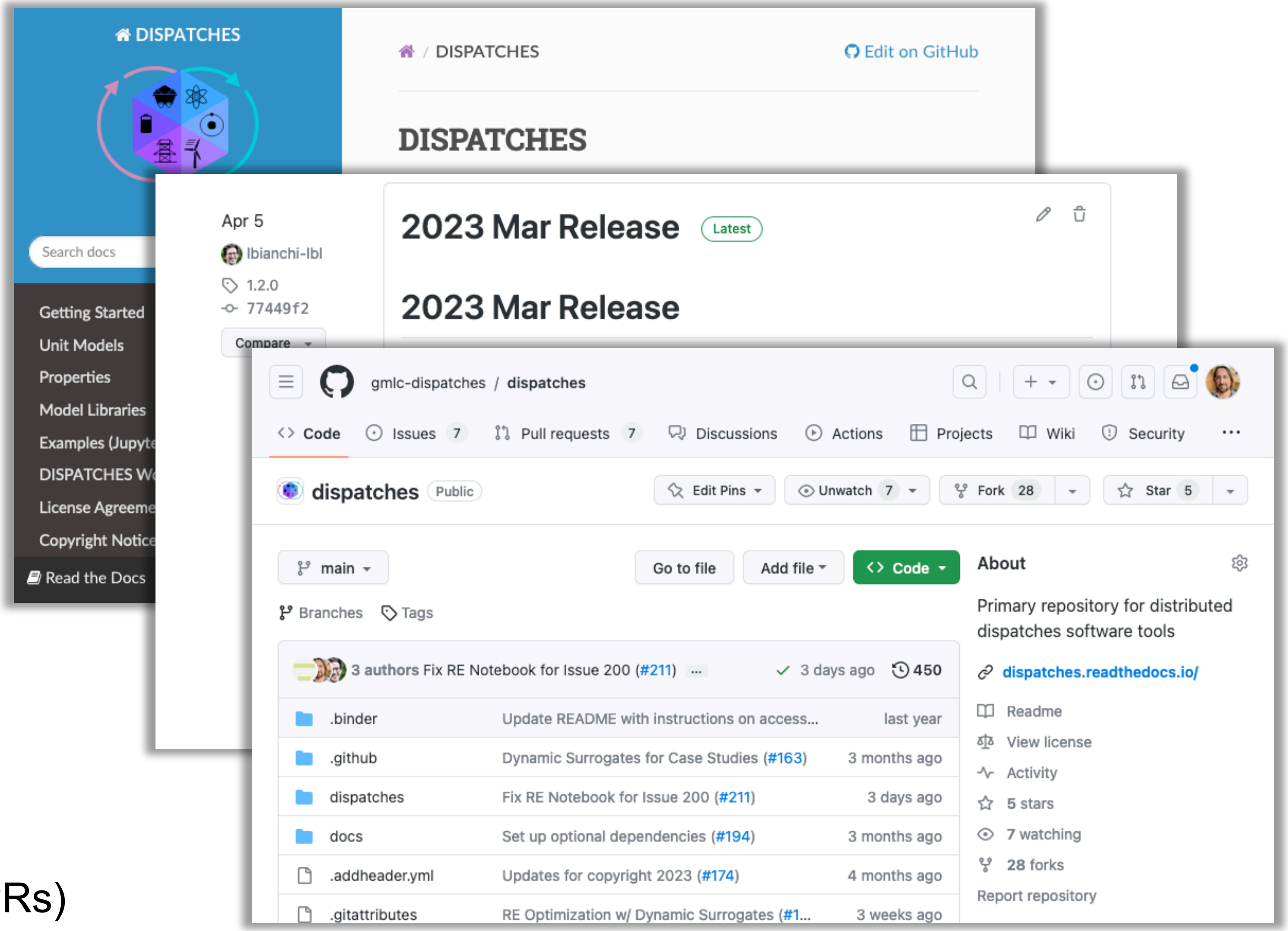
DISPATCHES: Software Documentation, Releases & Source Code

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



Open-source development statistics:
- 10+ software releases
- 100+ scheduled developer calls
- 18+ code contributors
- 140+ code contributions (Pull Requests, PRs)

Summary and Discussion

- 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
- Applied workflows to four “generic” case studies
  - Power and hydrogen co-production systems
    - Nuclear case study
    - Renewable case study
  - Multiscale market simulation capability: wind farm integrated with storage
  - Market-informed design of thermal energy storage systems
- Applying workflows to solve industry-specific problems
  - Arizona G&T: Fossil + Renewables + Storage
  - Other Industry Partner: NE + PEM + Fuel Cell
- Future opportunities

DISPATCHES

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

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