INL/MIS-24-78858-Revision-0

Integrated Energy Systems Modeling and Simulation

June 2024

Changing the World's Energy Future

Elizabeth Kirkpatrick Worsham

Idaho National Laboratory

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Integrated Energy Systems Modeling and Simulation

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DOE-NE Integrated Energy Systems

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Overview

- Posing the Problem: **Energy Demand and Supply**
- A Possible Solution: **Integrated Nuclear-Renewable Energy Systems**
- How to Make Predictions: **Modeling Tools**
- Nuclear Cogeneration and Integrated Systems: **Examples in Action**

Energy Demand and Supply

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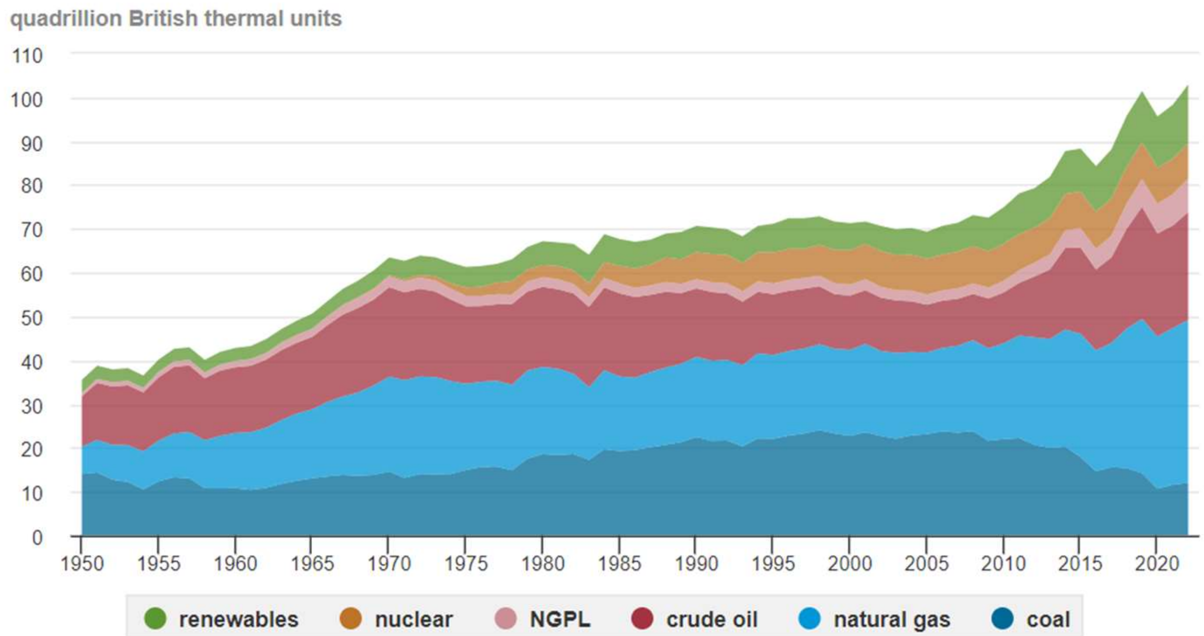
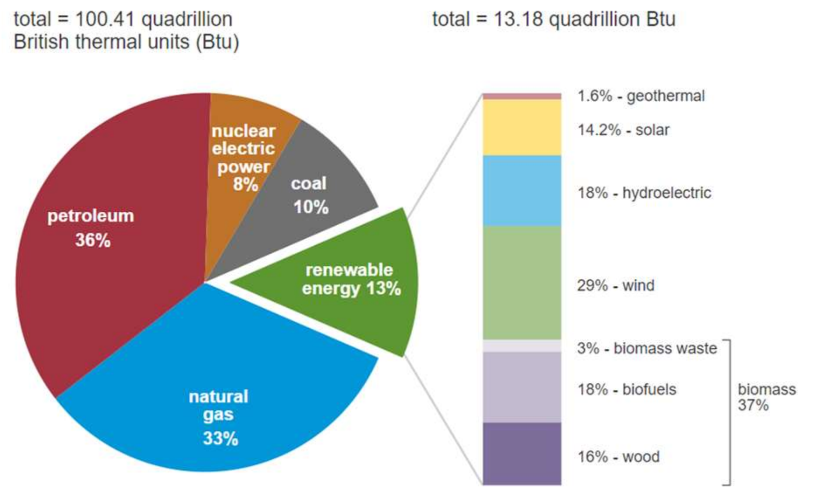
The Bottom Line Up Front — Today's Reality

U.S. primary energy production by major sources, 1950-2022



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.2, April 2023, preliminary data for 2022
Note: NGPL is natural gas plant liquids.

U.S. primary energy consumption by energy source, 2022



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2023, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

Variable Renewable Generators in Electricity Markets

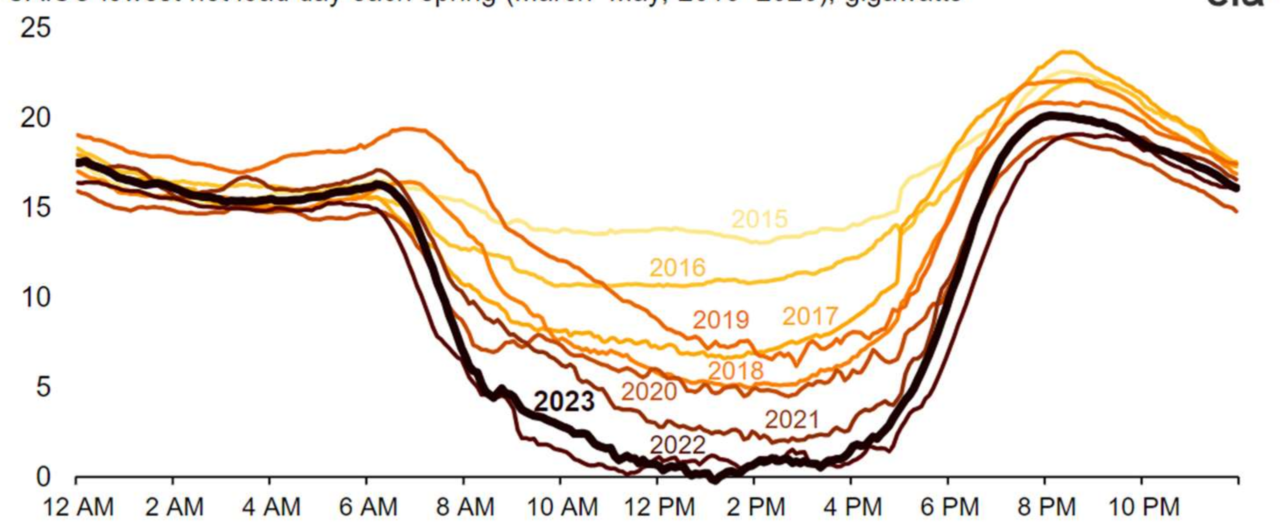
Need for Grid Stability and Reliability

Example: Impact on demand of solar generation assets

- Peak generation ≠ peak demand
- Requires additional components and approaches to maintain stable, reliable grid
  - Energy storage
    - Within day, but also seasonal
  - Curtailment
- Deepening belly puts financial pressure on baseload generators

California's duck curve is getting deeper

CAISO lowest net load day each spring (March–May, 2015–2023), gigawatts



Data source: California Independent System Operator (CAISO)

Integrated Nuclear-Renewable Energy Systems

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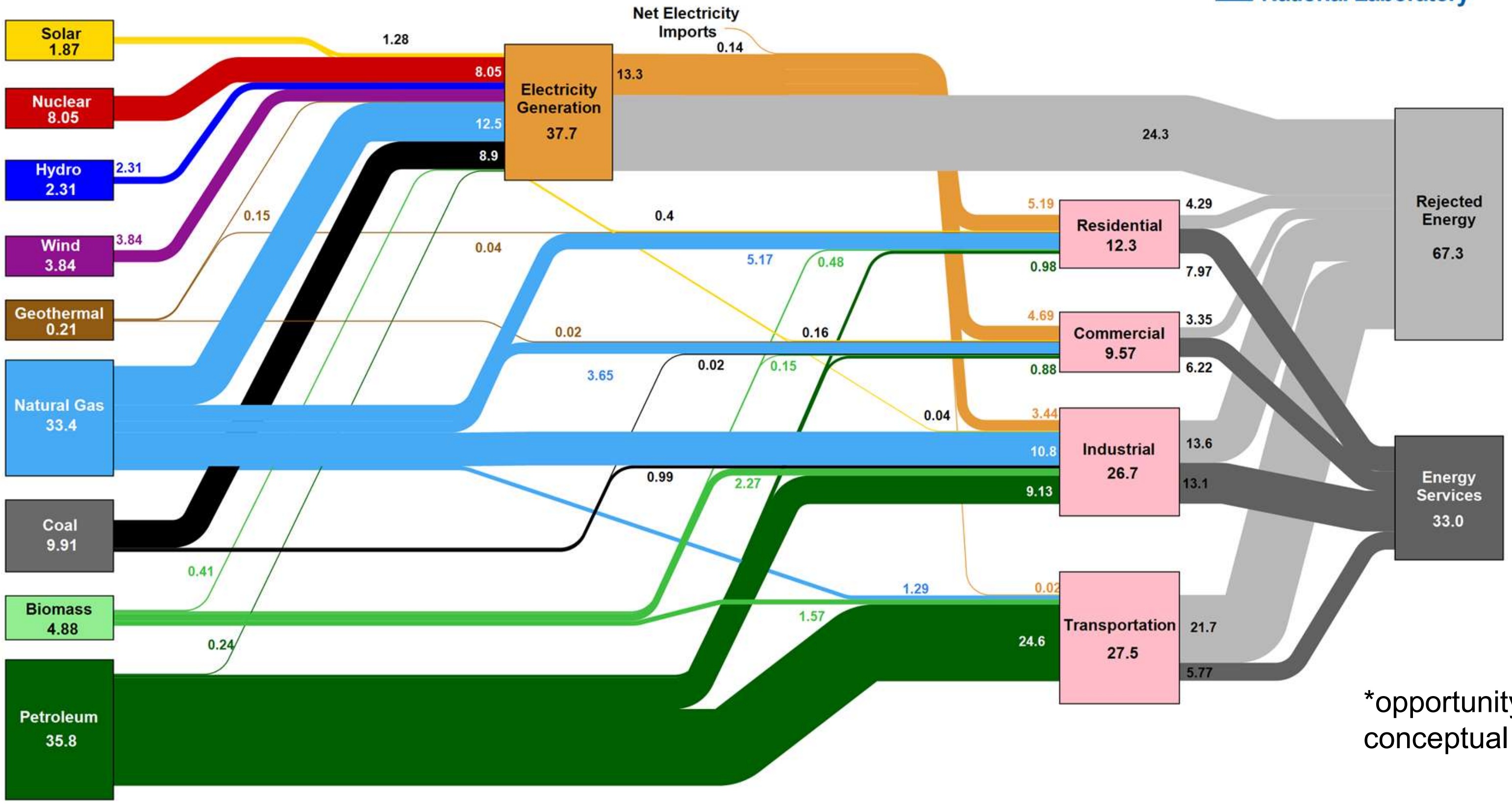
Significant Opportunities for Nuclear Energy Expansion:

Estimated U.S. Energy Consumption in 2022: 100.3 Quads

Lawrence Livermore National Laboratory



Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Future Opportunities for Nuclear Energy in the United States

- ✓ Heat for residential, commercial, and industry use
- ✓ Flexible electricity
- ✓ Electricity for transportation
- ✓ Fuels for industry
- ✓ Fuels for transportation
- ✓ Fuels for commercial
- ✓ Fuels for residential

*opportunity energy flows are conceptual and not to scale

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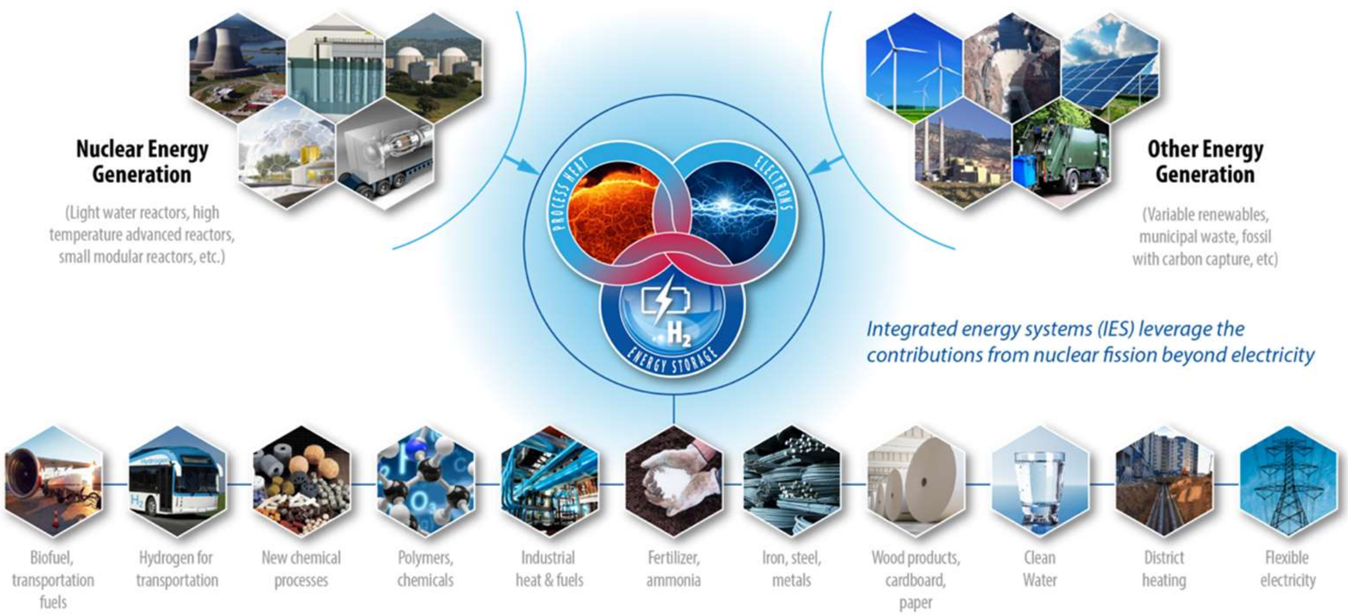
Shifting the Energy Paradigm through Research, Development, and Demonstration



The primary energy currencies for IES are:
Heat, Electricity, Hydrogen and Carbon

Heat:

Demonstrate high efficiency thermal energy use

Electricity:

Enable a sustainable, resilient, and reliable clean energy grid

Hydrogen and Carbon:

Develop novel chemical and industrial processes using low-emission energy

Integration:

Enhance tools and approaches to optimize IES operations

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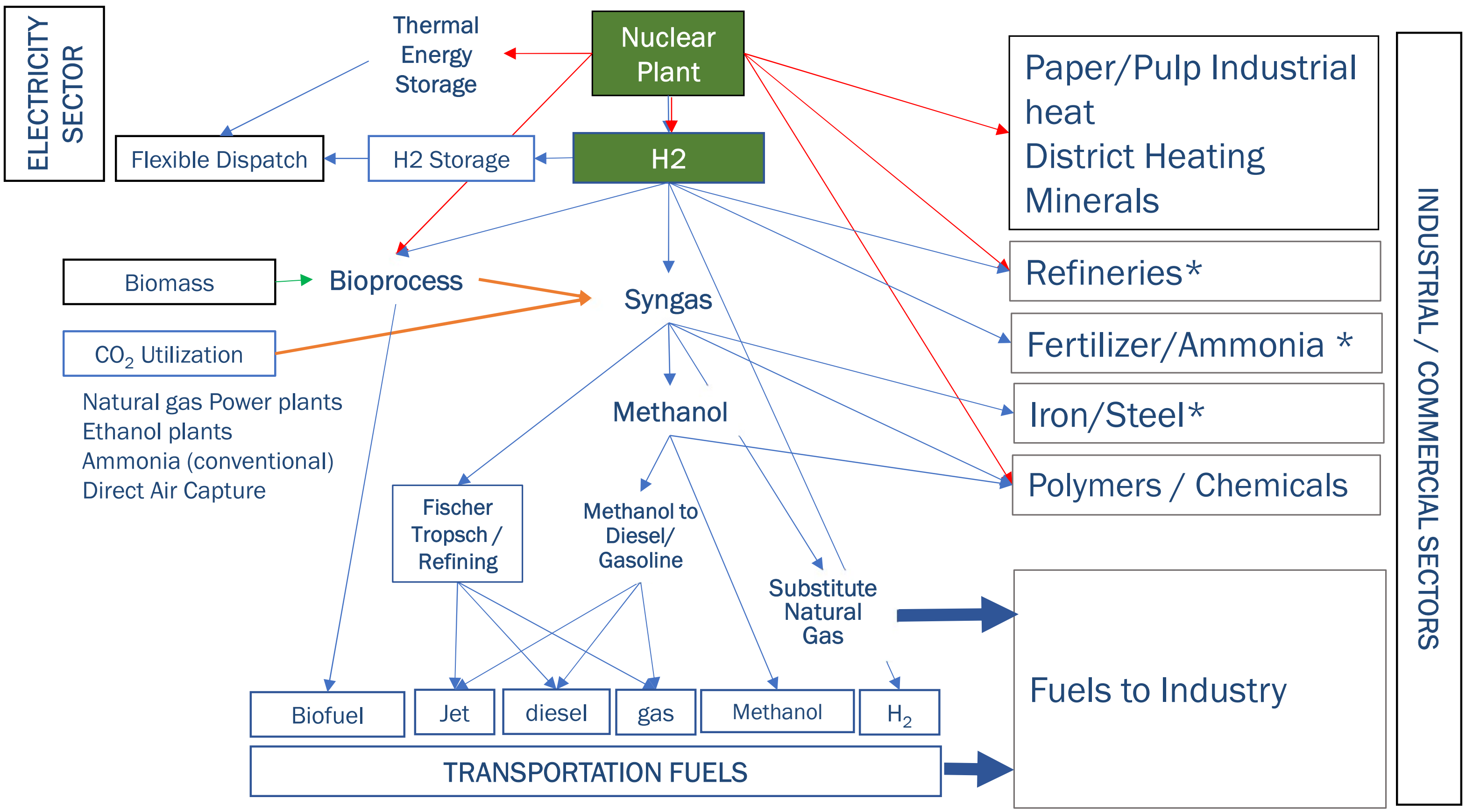
Advanced Nuclear Energy Pathways by Sector



* *Significant additional electricity use not shown to simplify diagram*

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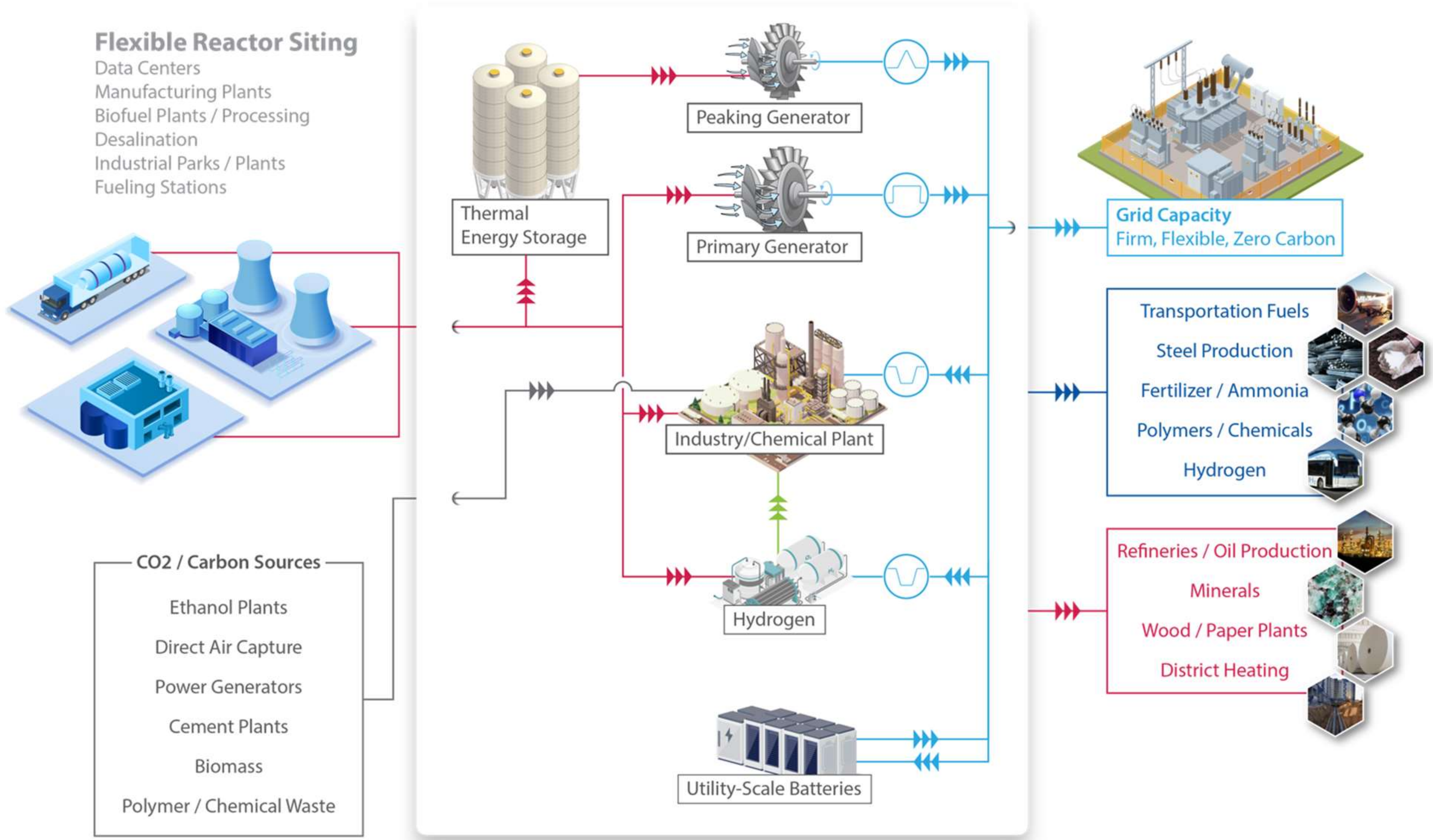

Flexible Reactor Siting
Data Centers
Manufacturing Plants
Biofuel Plants / Processing
Desalination
Industrial Parks / Plants
Fueling Stations
Thermal Energy Storage
Peaking Generator
Primary Generator
Industry/Chemical Plant
Hydrogen
Utility-Scale Batteries
Grid Capacity
Firm, Flexible, Zero Carbon
Transportation Fuels
Steel Production
Fertilizer / Ammonia
Polymers / Chemicals
Hydrogen
Refineries / Oil Production
Minerals
Wood / Paper Plants
District Heating
CO2 / Carbon Sources
Ethanol Plants
Direct Air Capture
Power Generators
Cement Plants
Biomass
Polymer / Chemical Waste

Modeling Tools

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IES Guiding Questions

- What are economically and technically viable options for integrated energy system (IES) coupling to nuclear power plants?
- What is the statistically ideal mix for Nuclear-IES within various markets?
- What are driving economic factors that nuclear technology can leverage though IES coupling?
- What are optimal and safe coupling strategies between IES technologies and nuclear power plants?
- What is the governing control scheme for IES?

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What does FORCE Solve?

- Complete package of open-source tools for technoeconomic analysis of IES
  - Technical
    - Steady-state equipment sizing (HYBRID.ASPEN, etc.)
    - Second-by-second transient analysis (HYBRID.Modelica, etc.)
  - Real-time operation
    - Real-time optimal decision making (ORCA)
    - State space model development and update (FARM)
  - Economics
    - Long-term system-informed statistical economics (HERON)
    - Uncertainties and sensitivities (RAVEN)
    - Informed by physics

FORCE

Framework for the Optimization of Resources and Economics

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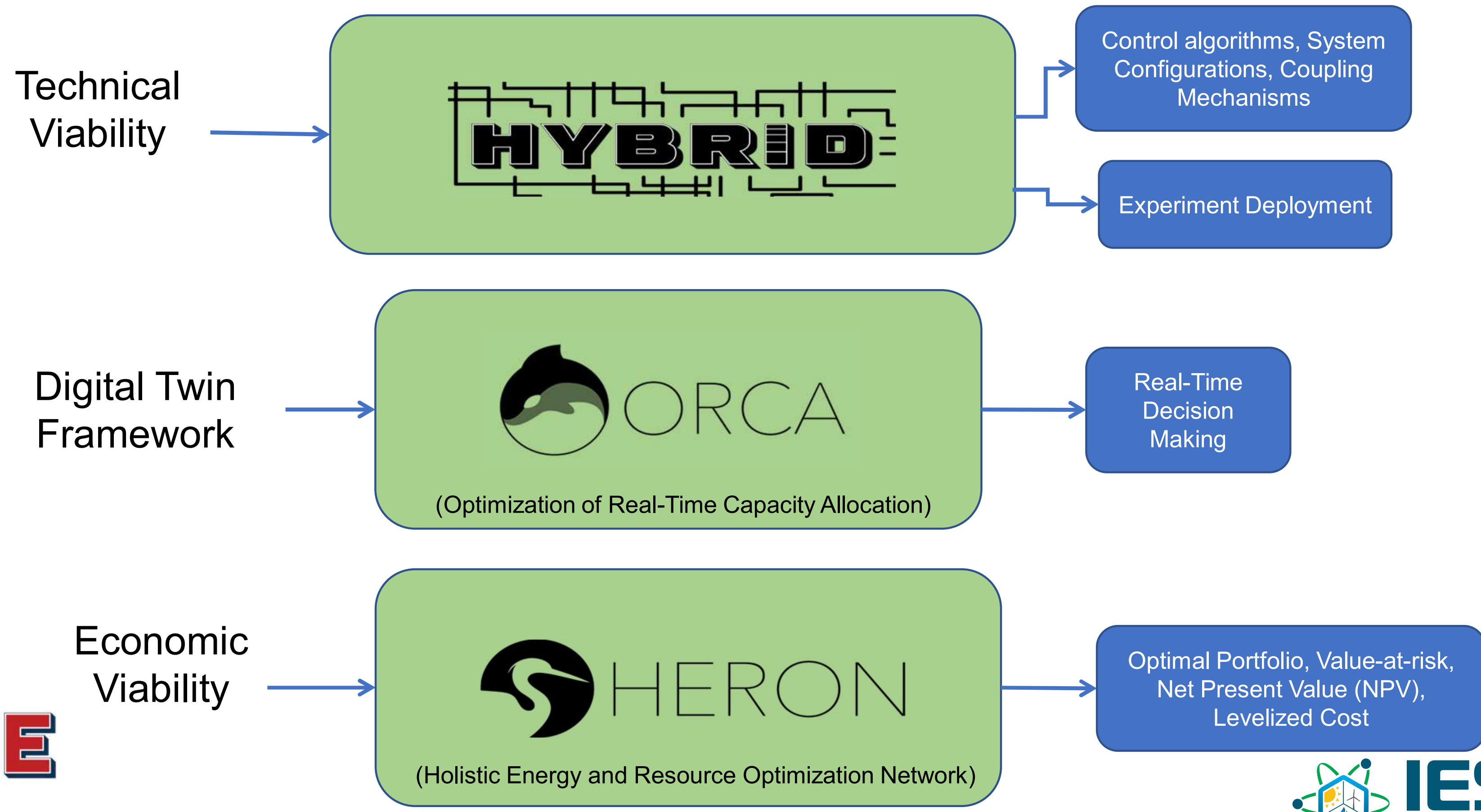
Three Workflows, Three Codes



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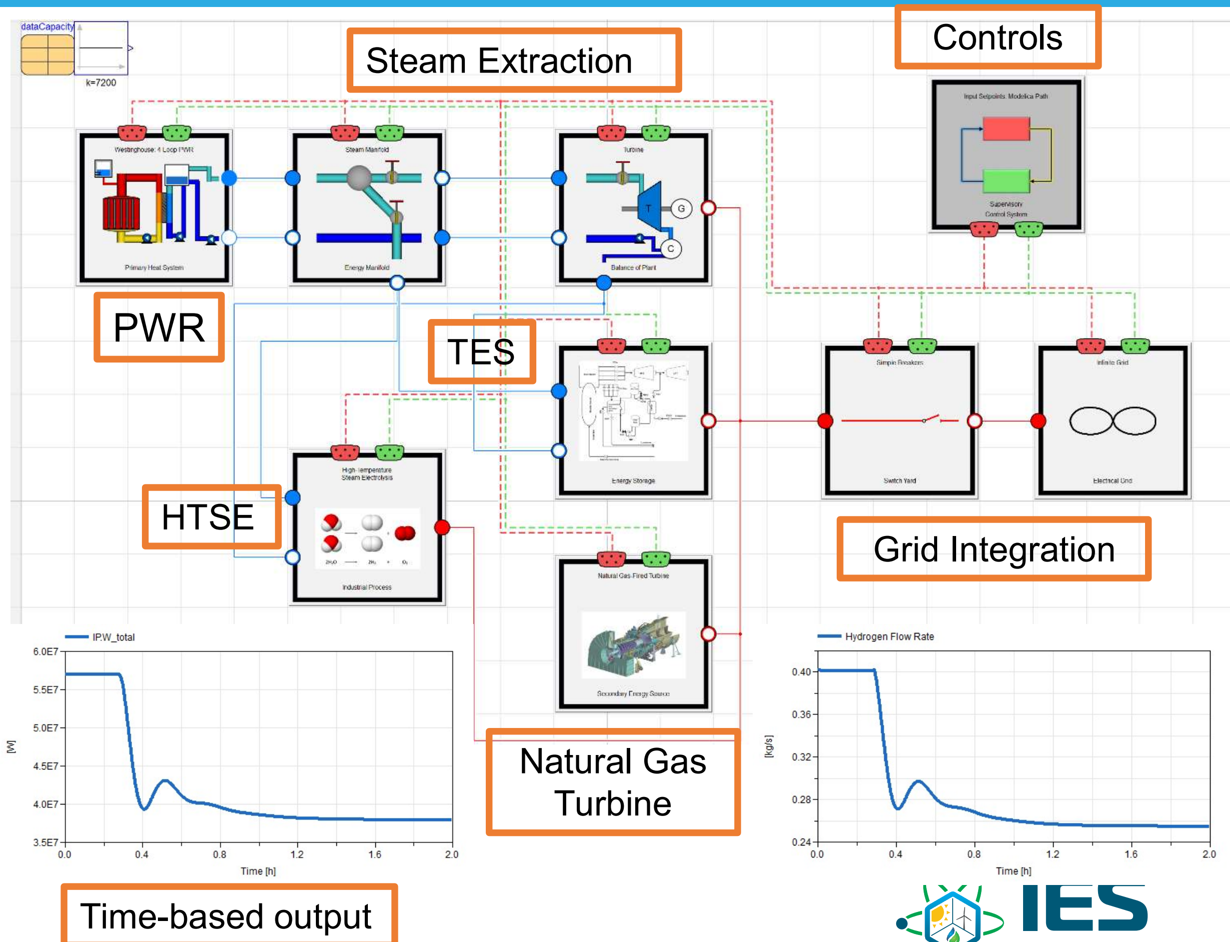
HYBRID: Process Model Simulation

- Collection of physical models
  - Industrial processes, chemical reactors, thermal energy storage (TES), steam systems, controls, etc.
- **Dynamic** models developed in the Modelica language using the commercial platform Dymola from Dassault Systems.
  - Figures of Merit: Ramp speeds, demand Missed, system stability, control strategy
- **Steady-State** models developed in Aspen Plus and Aspen HYSYS
  - Figures of merit: Energy and mass balance, component sizing, process validation

- Available: https://github.com/idaholab/HYBRID



ORCA: Real-Time Optimal Control

Real-Time Network

Components Techs:
- Ramp rates
- Transfer funcs
- Commodity I/O
- State space model

Optimization Targets
- Economics
- Reliability
- Performance

Digital Twin Systems
- Physical facilities
- Virtual facilities

ORCA

State Space Models

Dispatch Optimization

Real-Time Signals

Data Warehouse Communication

Optimal Control

FORCE

Available:
https://github.com/idaholab/ORCA

- Python library
- Accelerates building workflows
- Integrates with network pipelines
- Digital twin infrastructure
- Real-time decisions

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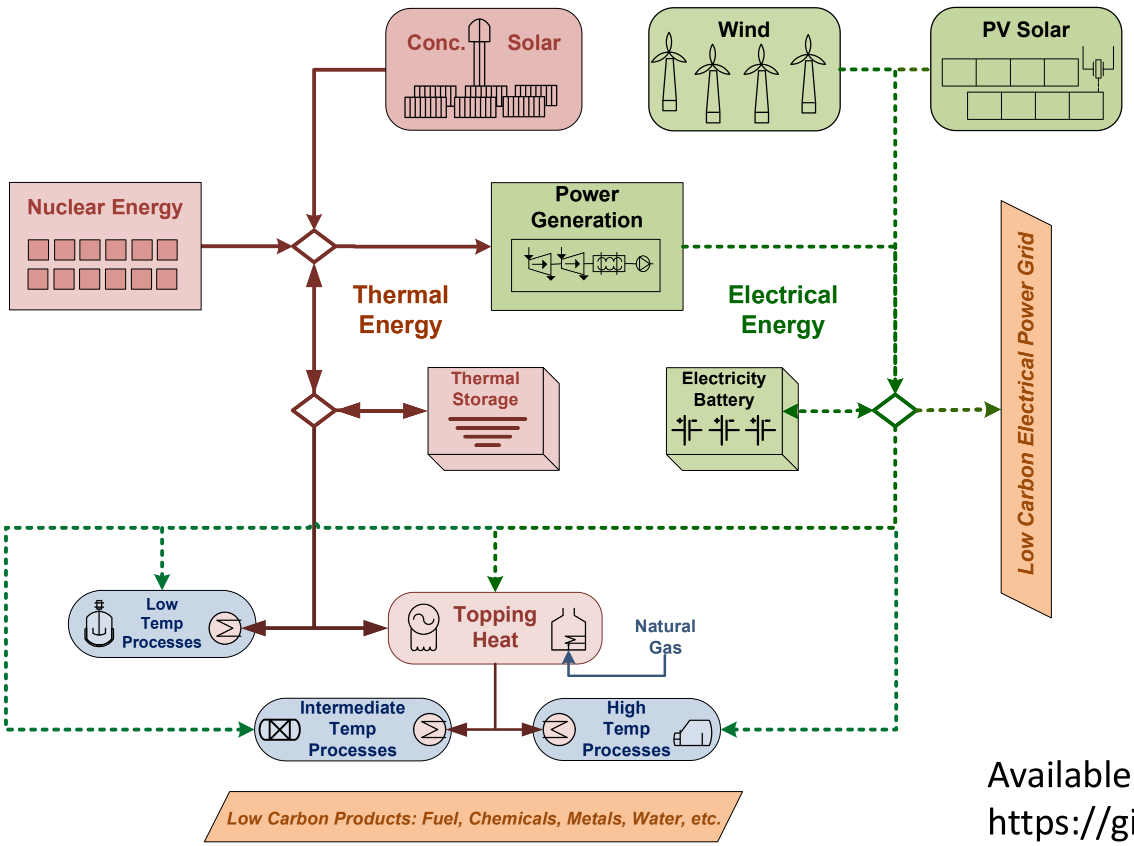
HERON: Economic Viability



- Mixed Commodity Systems
  - Technology agnostic
  - Connects networks of resources like heat, electricity, hydrogen, fuel
- Time-continuous Dispatch
  - Component ramping limitations
  - Storage charge, discharge, level
- Uncertainty Built In
  - Statistical analysis
  - Distributed economic metrics

Available:
https://github.com/idaholab/HERON

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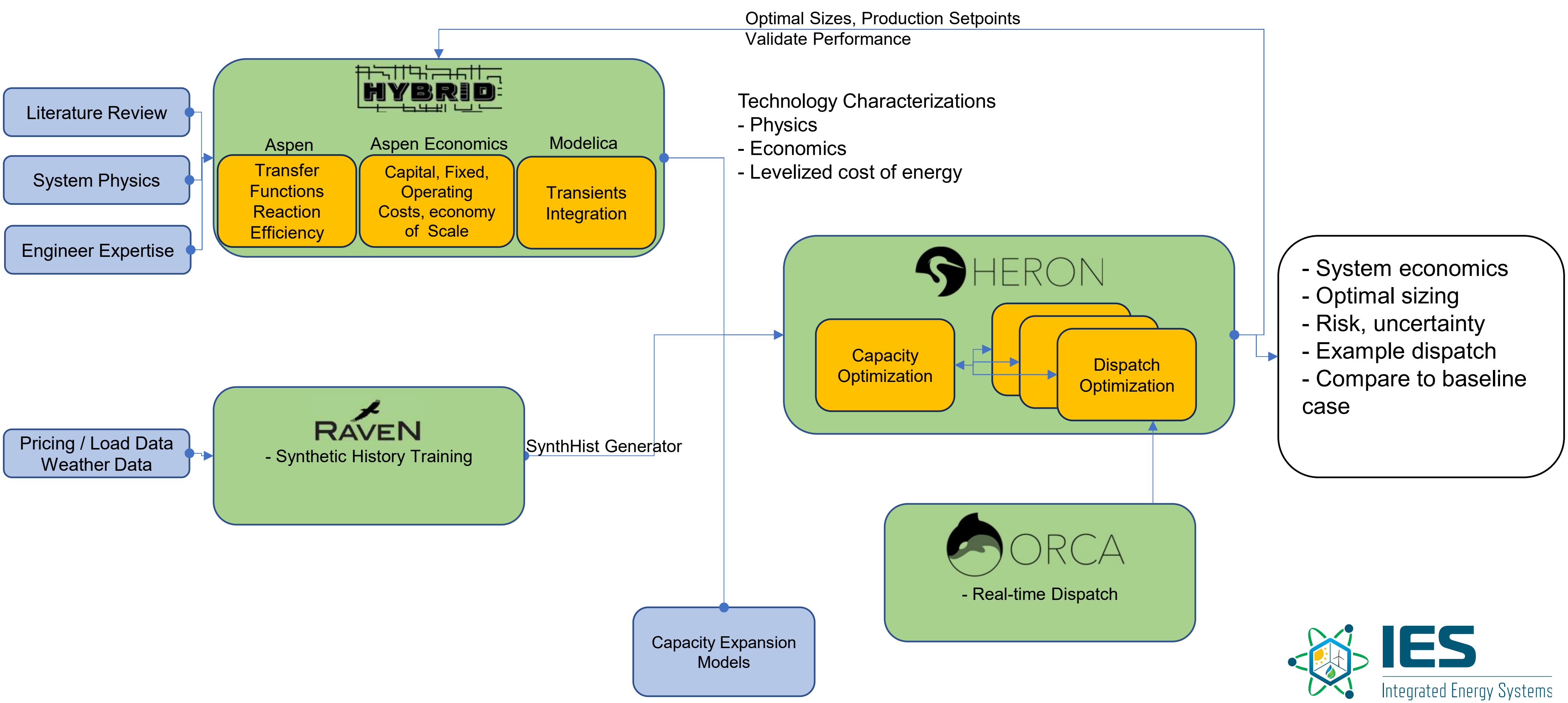
Modeling Process: IES TEA Workflow



Nuclear Cogeneration & Integrated Systems—Examples in action

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Thermal Energy Storage Systems

Motivating problem: I want to build a nuclear power plant and add thermal energy storage. Which one makes the most sense? How do we choose? How does it work?

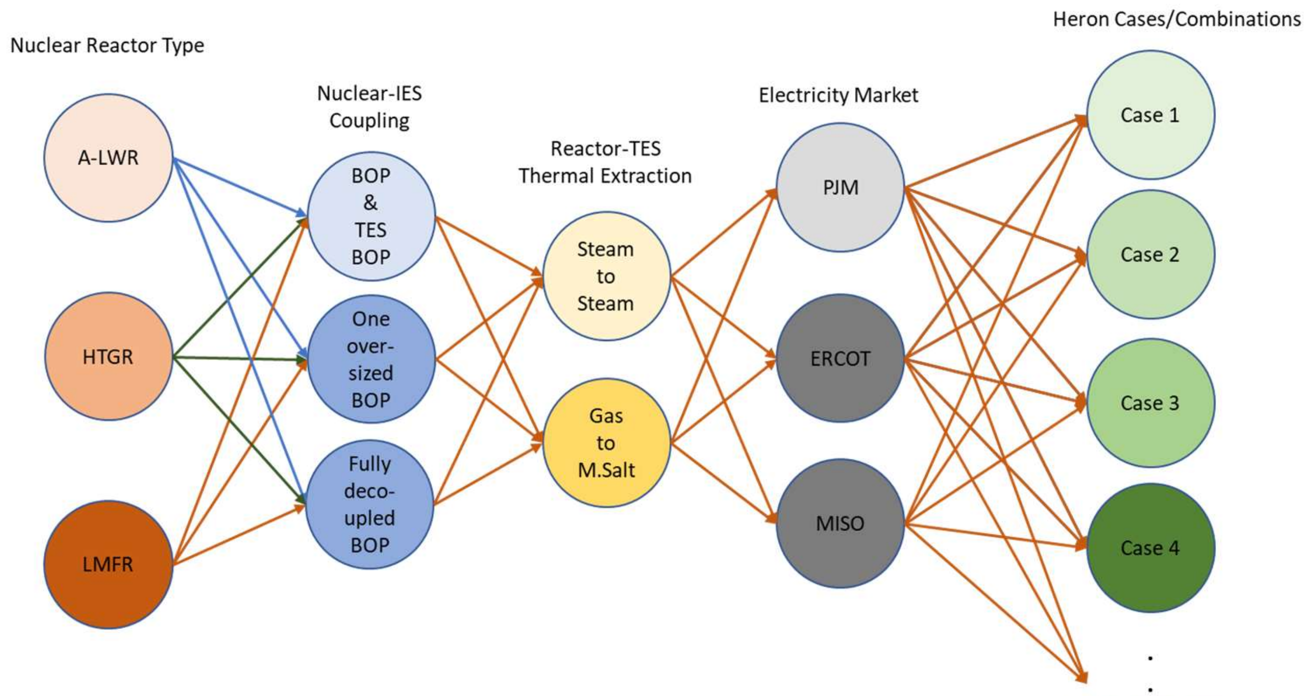
Why TES?

- Enables NPPs to respond to market variability
- Store nuclear energy in its original form (heat), enabling flexible use of electricity or heat on the back end

Step 1: Steady-state physical models (HYBRID/Aspen)

Step 2: System design cost analysis and optimization (HERON)

Step 3: Transient modeling and grid-wide economics (HYBRID/Dymola)



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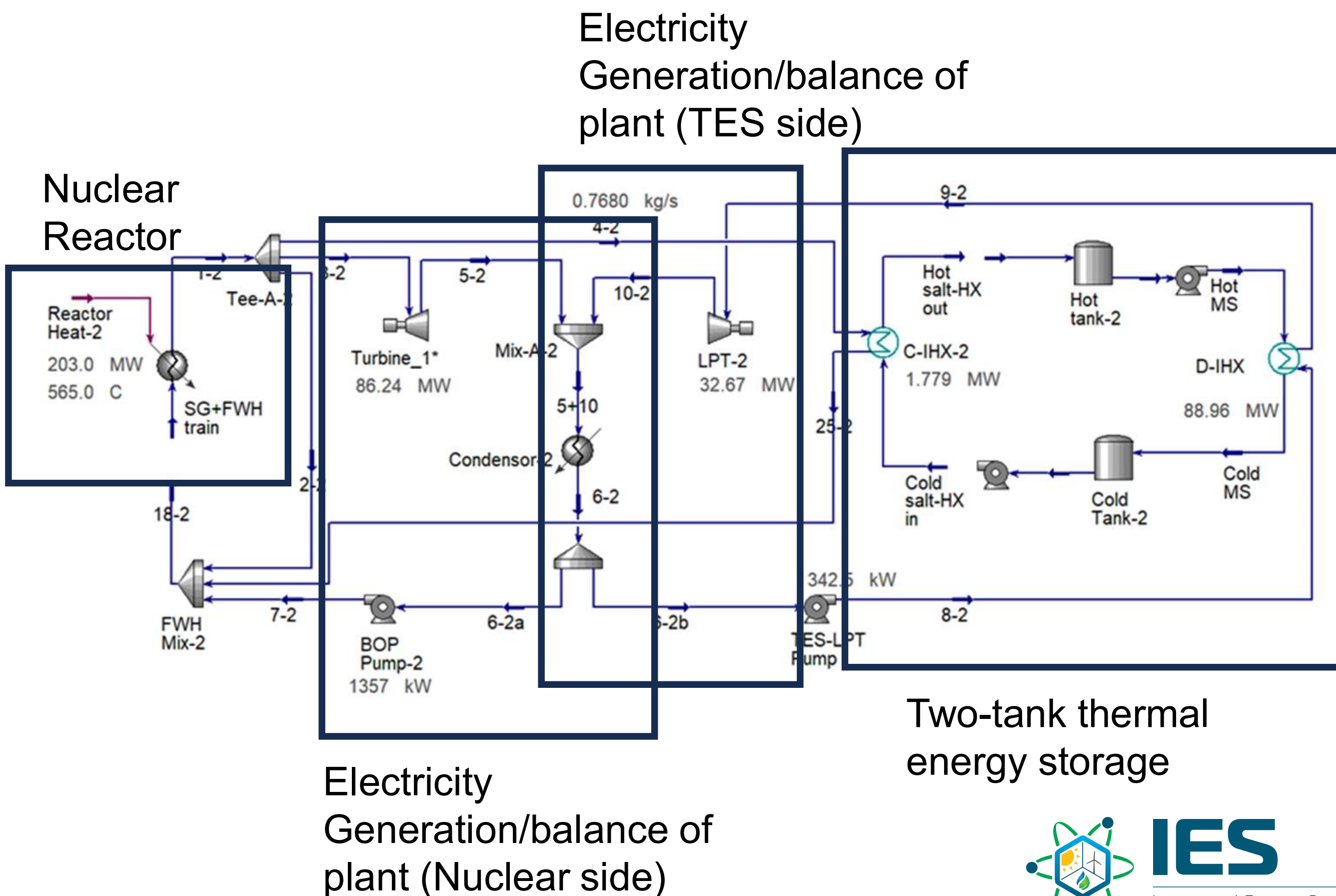
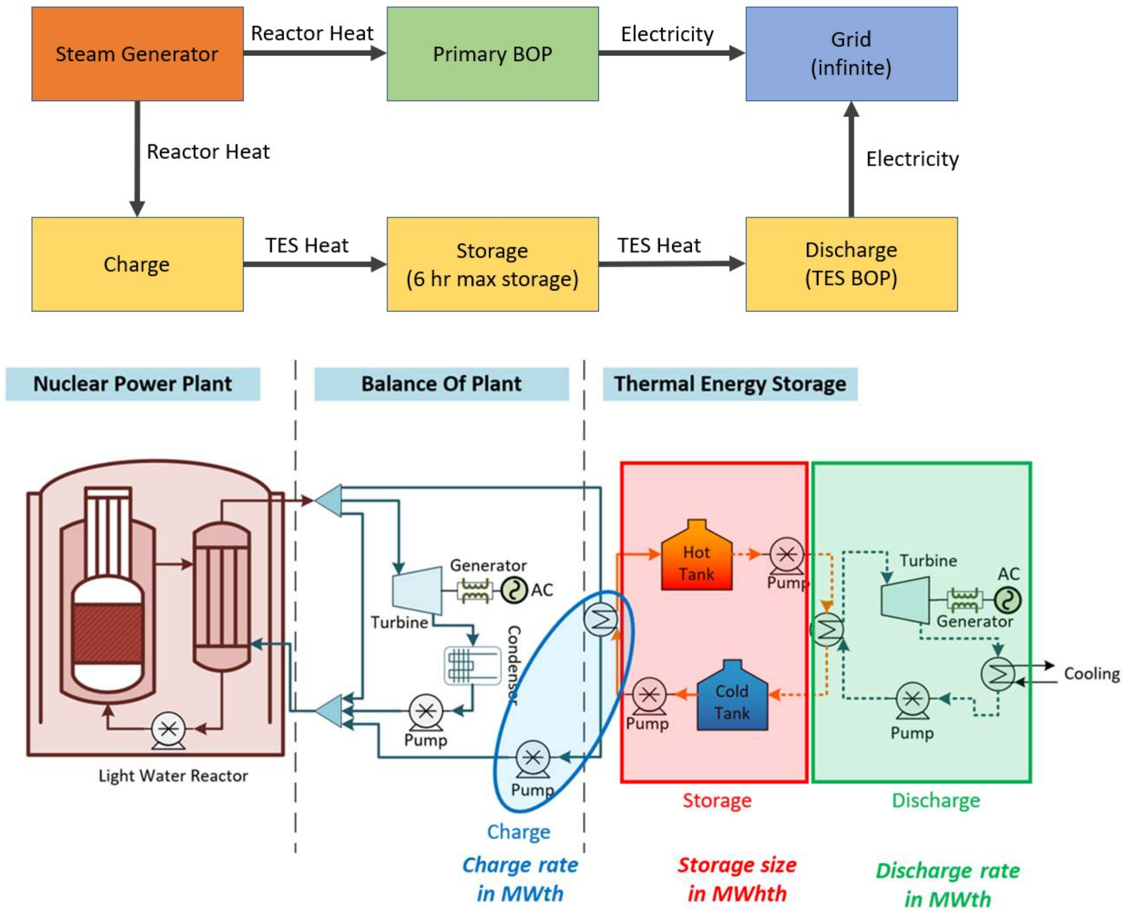
Step 1: Steady-State Physical Model

- **Is this technically feasible?**
  - Thermodynamic analysis of proposed systems
- **What is the optimal coupling approach?**
  - Develop fully-coupled TES-nuclear steady-state models
  - Component-level analysis (heat exchange (HX) technology, geometries, sizes, etc.)
- **How much will components cost?**
  - Cost analysis and cost functions for discrete system sizes



Step 2: Stochastic Optimization



- **How does the electricity price fluctuate?**
  - Analyze and reproduce price signals from various markets
- **What is the optimum system size to reduce costs?**
  - Maximize net-present-value (NPV) over the system lifetime
- **How does my system behave?**
  - View TES dispatch profiles of the IES system

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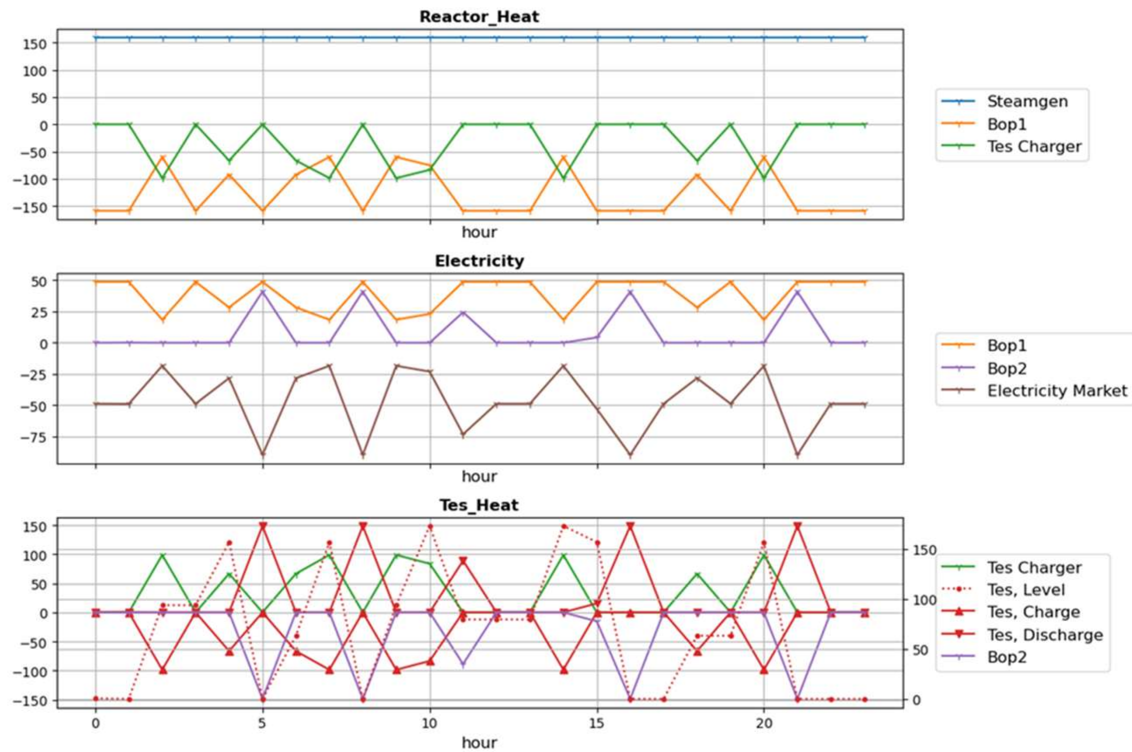
Step 2: Optimization Results

- Optimization Variables: Reactor type, markets, component capacities
- Used historical real-time market data for price and demand
- Optimal component capacities found for each combination

Selected example for Advanced LWR (A-LWR) in ERCOT



Optimization result for maximum NPV

Reactor Type	Initial Capacities	Step Size	Segment Length (hours)	Electricity Market	ΔNPV (USD)	Capacity of Charge, Storage, Discharge (MW_{th}, MWh_{th}, MW_{th})
A-LWR	50%	0.5	24	ERCOT	$1,953,313	-98.7, 173, 148.7
A-LWR	100%	0.2	120	ERCOT	$8,202,725	-155.6, 548.2, -157.5
HTGR	100%	0.5	24	ERCOT	$48,052,228	-188.4, 762, -202
HTGR	100%	0.5	120	ERCOT	$71,811,691	-200.8, 1203.6, -202.9
LMFR	100%	0.5	24	PJM	$51,298,323	-1675.2, 4719.9, -1665.8
LMFR	50%	0.5	120	PJM	$103,620,323	-1677.5, 4533.8, -1679.5
LMFR	100%	0.5	24	ERCOT	$501,653,124	-1595.2, 9515.8, -1628
LMFR	100%	0.2	120	ERCOT	$822,998,821	-1611.5, 10080, -1679

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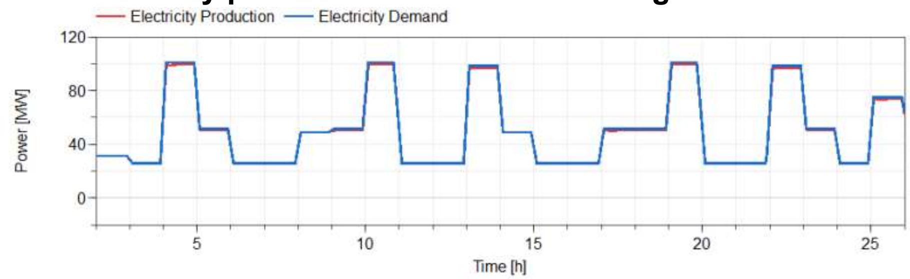
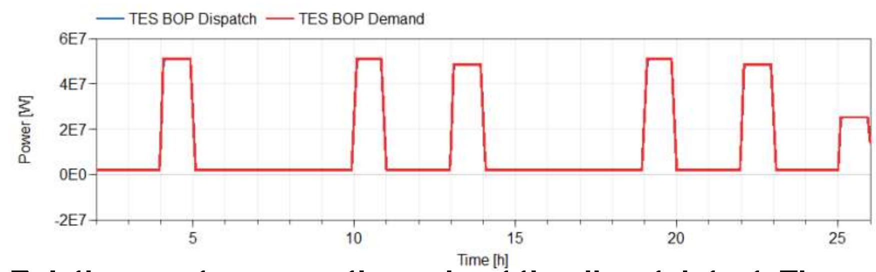
Step 3: Transient Modeling

- **How does my system behave?**
  - Understand dynamic behavior of IES
  - Investigate how changes in demand affect reactor flow and power
- **Can my integration strategy be improved?**
  - Evaluate integration techniques in transient conditions
  - Evaluate system control strategies

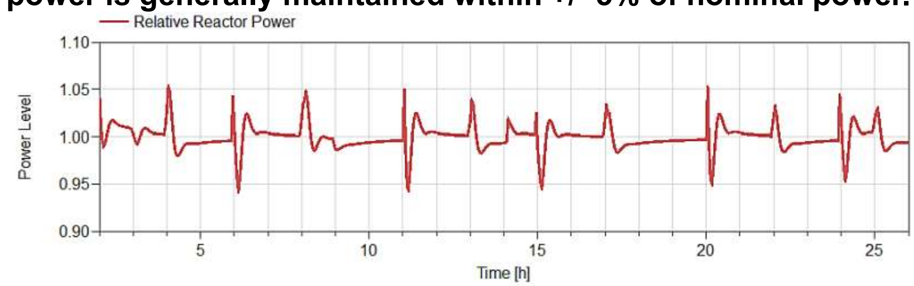
Electricity production vs. demand throughout a 24-hour



TES BOP dispatch throughout a 24-hour dispatch test



Relative reactor power throughout the dispatch test. The power is generally maintained within +/- 5% of nominal power.



Multilevel Analysis, Design, and Modeling of Coupling Advanced Nuclear Reactors and Thermal Energy Storage in an Integrated Energy System, 2022, https://www.osti.gov/biblio/1890160.

Other Applications: Nuclear Synthetic Fuels Production

- Synthetic fuels production linked to nuclear plant capacity
- Fischer-Tropsch TEA
  - LWRs
  - Different locations
  - Different CO_2 sources
- Incorporate advanced reactor designs (HTGR, SMR)
- Develop models, use cases, and dynamically evaluate the Methanol-to-Diesel (MTD) process.
- The optimized system increased NPV by $14M–1.3B compared to baseload power only scenario.

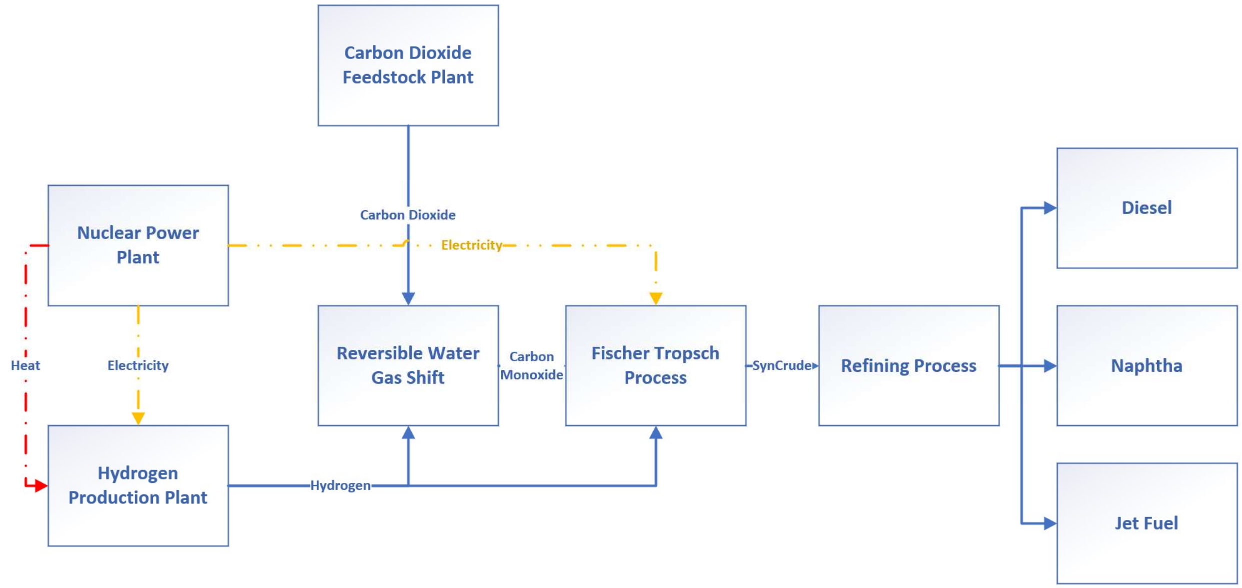


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process using Fischer-Tropsch

Grid-Integrated Production of Fischer-Tropsch Synfuels from Nuclear Power, *2023, https://www.osti.gov/biblio/1984196*

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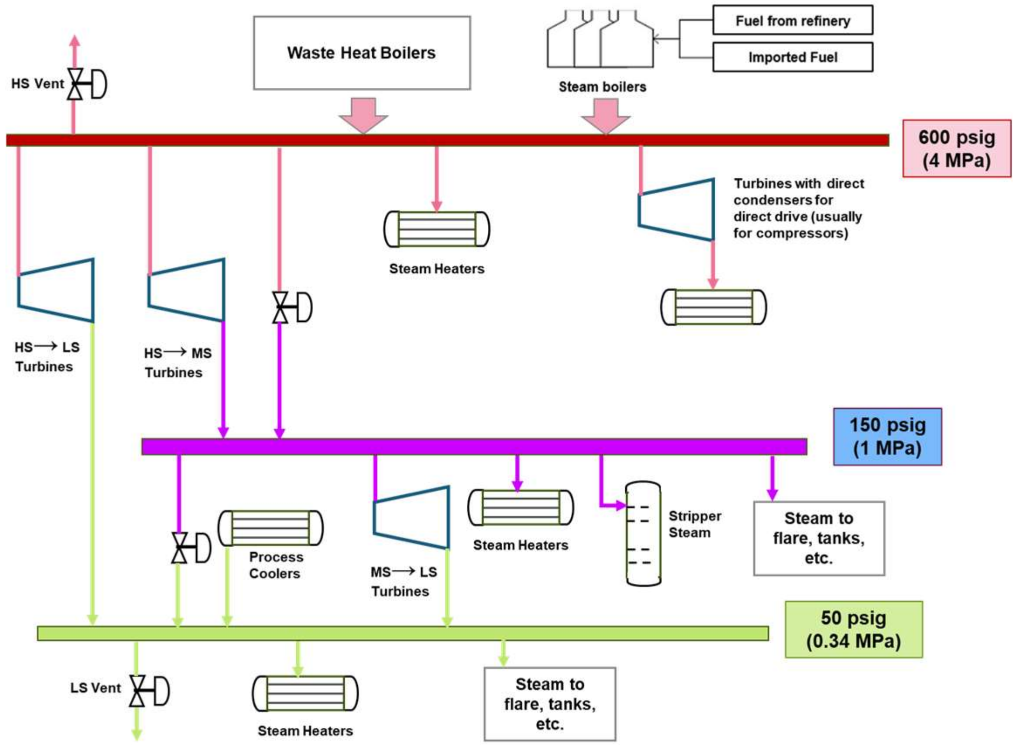
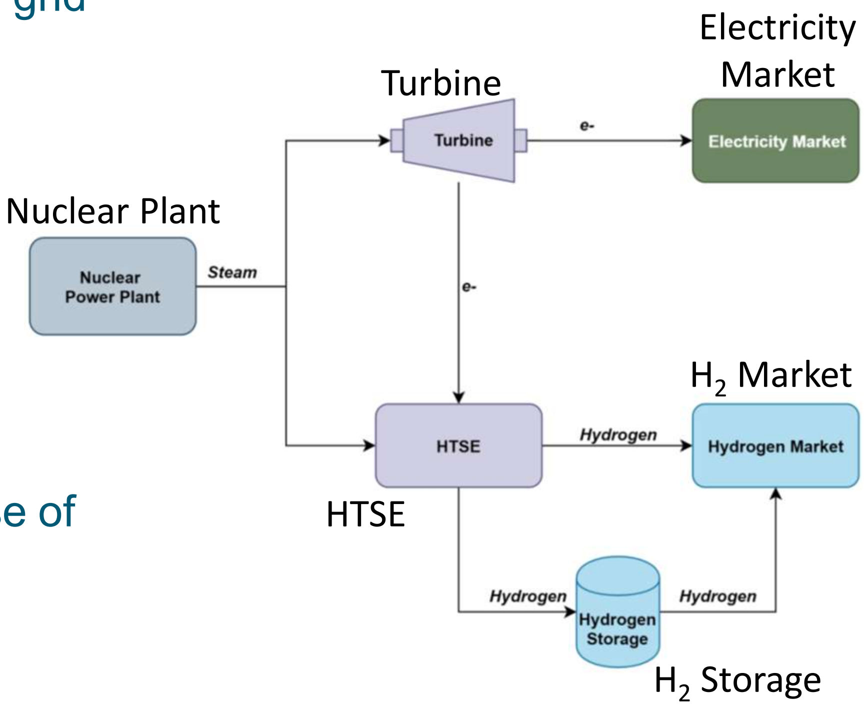
Other Applications: Industrial Decarbonization

- Created physical process models to determine plant energy balance
- Evaluate pathways for decarbonization in TEA for each application
  - Pulp and paper
  - Methanol production
  - Oil refineries
- Potential Pathways:
  - Nuclear heat integration
  - Hydrogen production
  - Carbon capture



Other Applications: Flexible Hydrogen Production

- Collaboration between national labs and industry partners
- Modeled existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid pricing → grid is more profitable
  - H_2 storage provides flexibility in plant operations, ensures that all demands are met
  - H_2 can be used for steel manufacturing, ammonia and fertilizer production, fuel cells for transportation
- Analysis results suggest a possible revenue increase of $**1.2 billion (in 2019 dollars)** over a 17-year span



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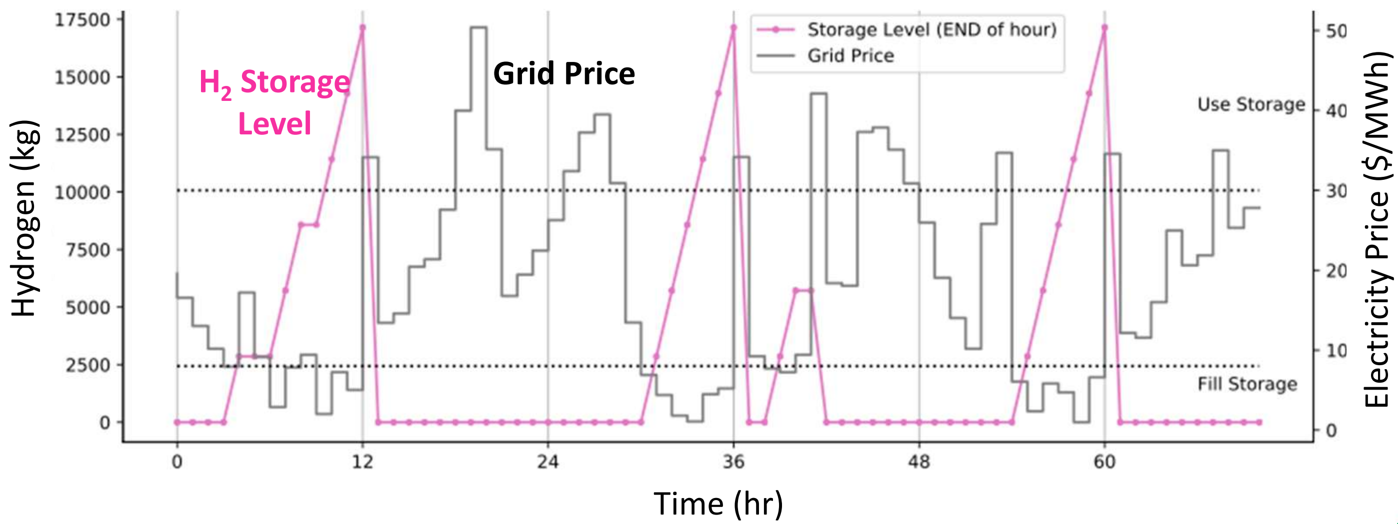
Other Applications: Flexible Hydrogen Production

- Outcome: Award from the Department of Energy for follow-on work and demonstration at Constellation Nine-Mile Point plant
- Full report: Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest (INL/EXT-19-55395)



Pilot Plant Hydrogen Production Demonstration Projects

Constellation: Nine-Mile Point Plant

- H_2 production began March 2023
- NEL Hydrogen Proton Electrolyte Membrane electrolysis module

Energy Harbor: Davis-Besse Plant

- H_2 production beginning in 2024
- 2 MW_{eDC} Cummins Proton Electrolyte Membrane electrolysis module

Xcel Energy: Prairie Island Plant

- H_2 production beginning in 2024
- Bloom Energy high temperature solid-oxide electrolysis module

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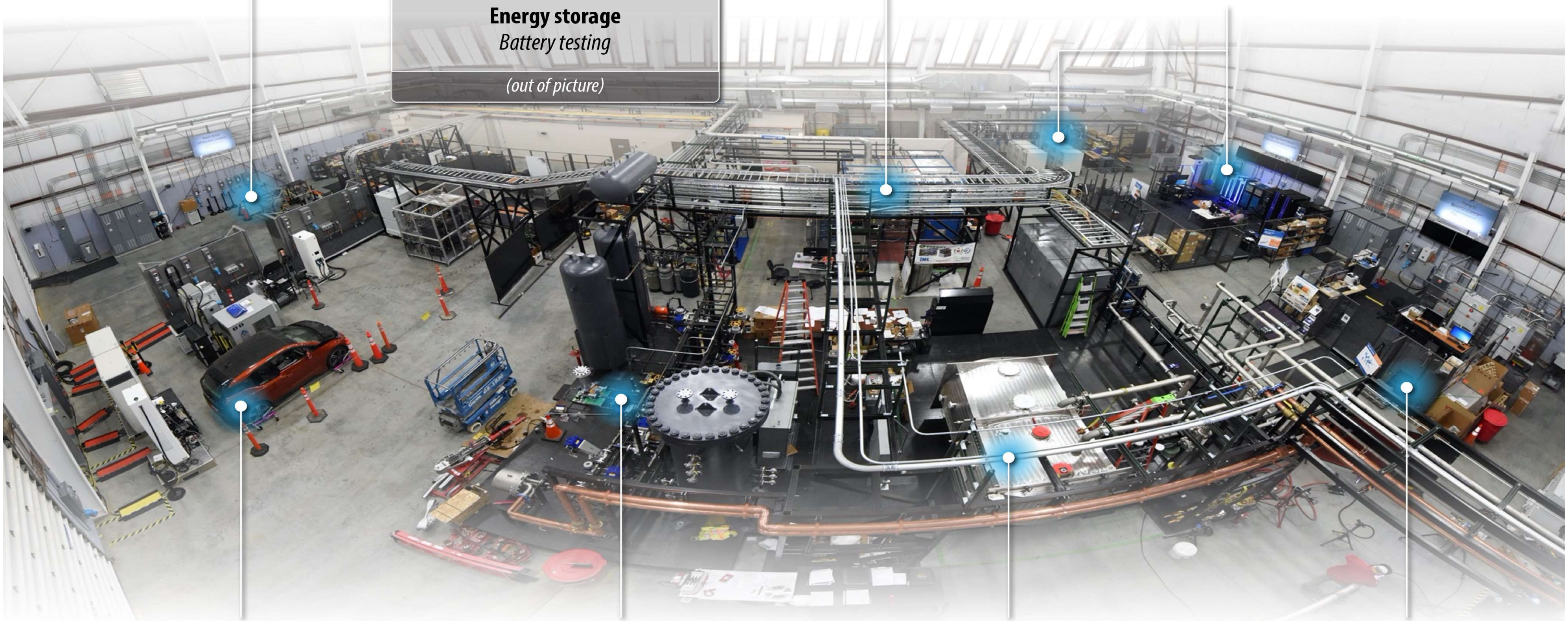
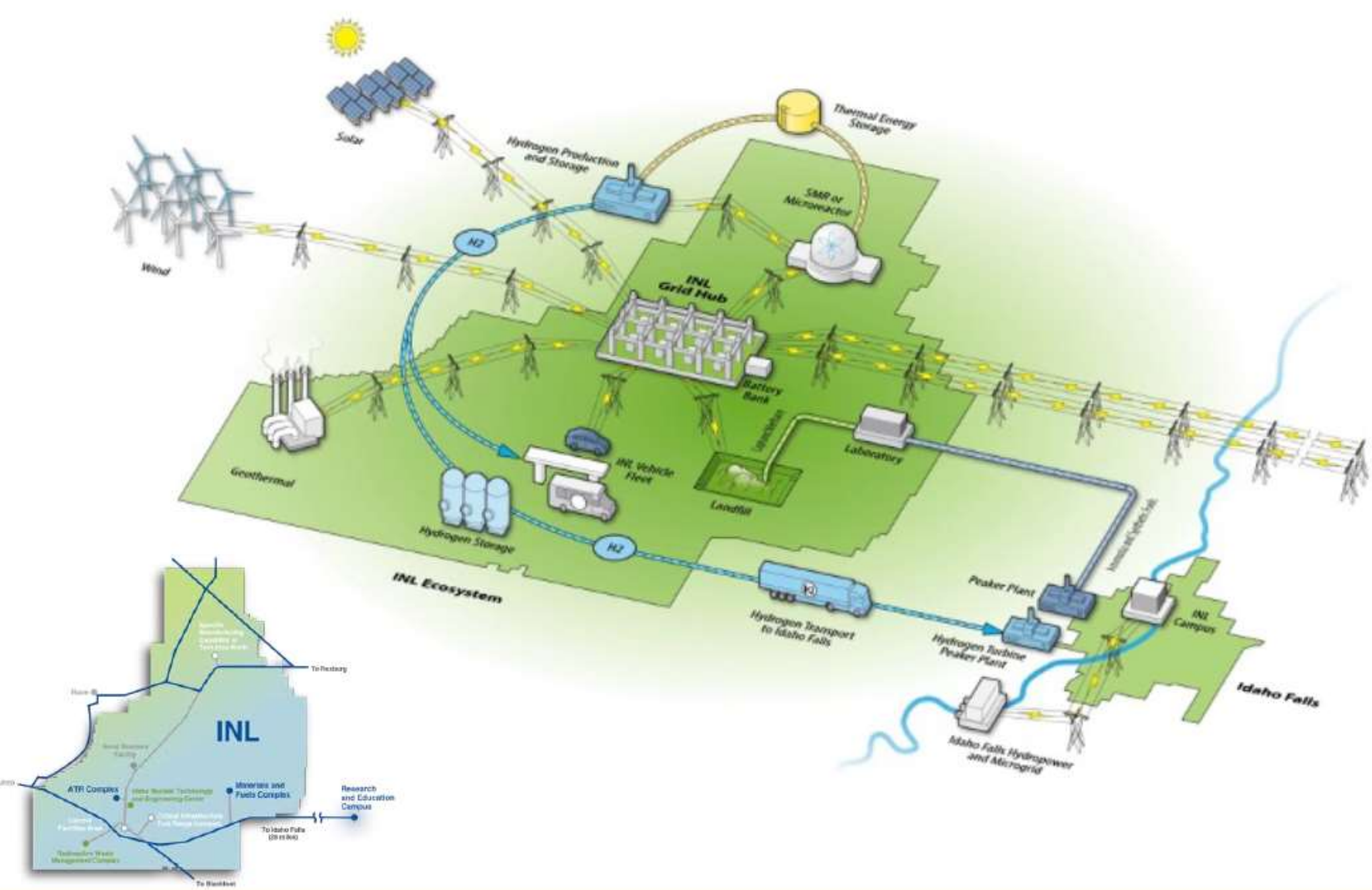
Dynamic Energy Transport and Integration Laboratory (DETAIL)



INL's commitment to net-zero will be a leading demonstration ushering in a secure, resilient net-zero energy future



- INL has committed to becoming a net-zero campus by 2031
- Attributes of a small city or county
- 890 sq mi
- >5400 employees
- >50 MWe purchased in FY2020
- >300 DOE-owned buildings
- Existing microgrid
- 3 fire stations, 1 museum, medical facilities, …
- >40 miles primary roads

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Summary

- The “Duck Curve” illustrates the reliability and cost challenges of a decarbonized energy grid.
- Nuclear can provide baseload power to the grid, and help decarbonize other sectors.
- The FORCE Tool Suite aims to solve technical, operation, and economics problems through modeling.
  - HYBRID: Physical models
  - HERON: Mixed-commodity system optimization
  - ORCA: Digital twin interface for real-time optimization
- Applications for FORCE include thermal energy storage modeling, hydrogen production, nuclear synfuels production, and industrial decarbonization, etc.

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