INL/CON-22-67675-Revision-0

Advancing Nuclear Energy to Support Economy-wide Net-zero Solutions: Challenges and Opportunities

June 2022

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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IES
Integrated Energy Systems

Advancing Nuclear Energy to Support Economy-wide Net-zero Solutions: Challenges and Opportunities

2022 American Nuclear Society Annual Meeting
Advances in Thermal Hydraulics (ATH 2022), Embedded Topical

June 13, 2022

INL/CON-22-67675

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Presentation overview

- Energy systems status quo
- New nuclear paradigm: A vision for the future
  - New market opportunities beyond electricity
- Integrated energy systems
  - Concept
  - Design/analysis
  - Opportunity for new markets
- Advancing nuclear and integrated energy systems through demonstration

IES Integrated Energy Systems

Today's energy systems

- Individual generators contribute to meeting grid demand, managed by an independent grid operator
- Individual thermal energy resources typically support industrial demand
- Transportation mostly relies on fossil fuels (with growing, yet limited, electrification)

Achieving net-zero emissions will require us to consider the role(s) of all clean energy generation options—
and we must look to non-emitting sources of heat in addition to electricity.

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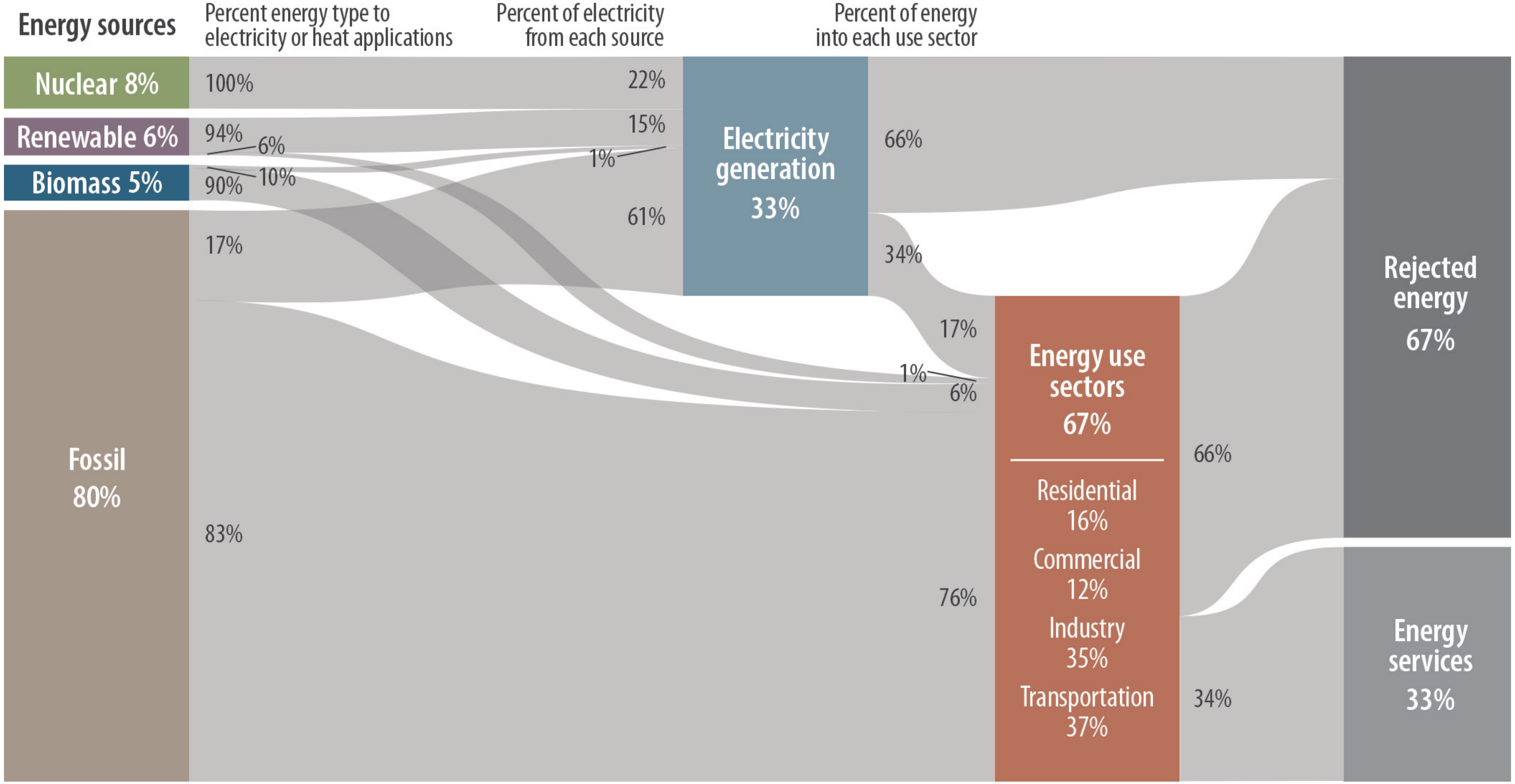
2018 energy sources and consumers, U.S.



Decarbonizing electricity is only part of the challenge

Electricity accounts for only 17% of total energy use in the U.S. across all "Energy use sectors," with the remaining 83% used in the form of heat.

Adapted from LLNL (2020), https://flowcharts.llnl.gov/

Forsberg and Bragg-Sitton, Maximizing Clean Energy Use: Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat and Hydrogen Demand, *The Bridge*, National Academy of Engineering, 50(3), p. 24-31, 2020. Available at https://www.nae.edu/239120/Fall-Issue-of-The-Bridge-on-Nuclear-Energy-Revisited.

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Motivation and challenges

- Evolution in the electric power sector
  - Advent of variable renewables → increased variation in net load
  - Transition away from traditional baseload resources
  - Increased need for generator flexibility while ensuring grid resilience, reliability
- Ambitious goals for deep decarbonization (“net-zero”)
  U.S. targets:
  - Zero emissions from electricity sector by 2035
  - Economy-wide net-zero emissions by 2050 → industry, transportation
- Traditional energy planning tools are often limited in applicability to new scenarios, technologies, opportunities
  - Cross-sectoral energy utilization from a single generator not represented

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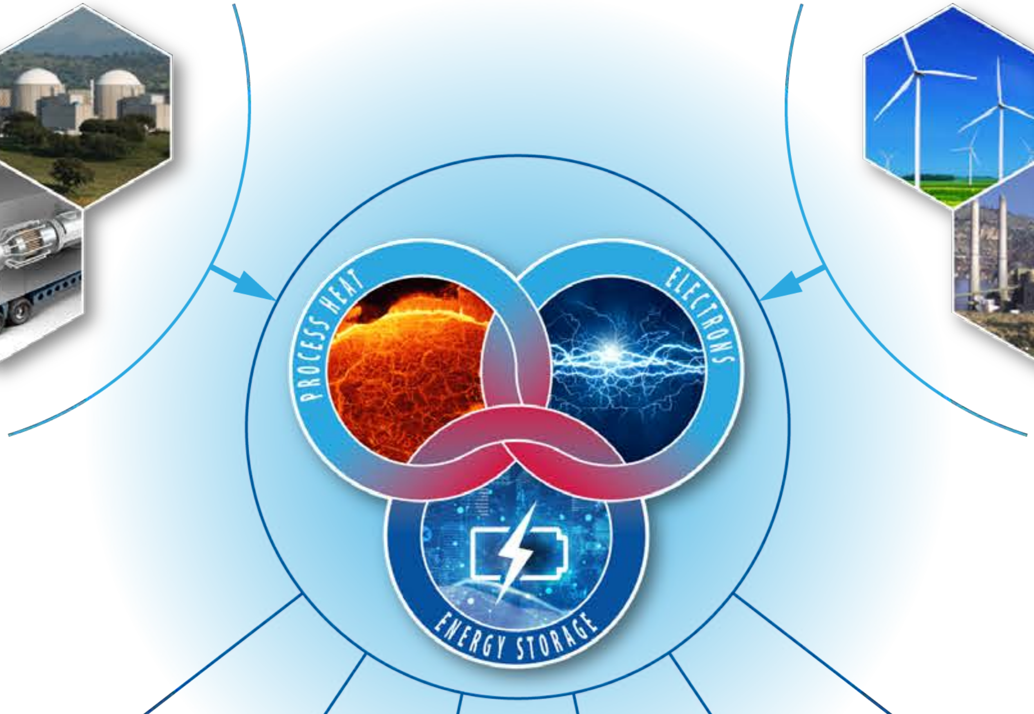
Future clean energy systems – transforming the energy paradigm

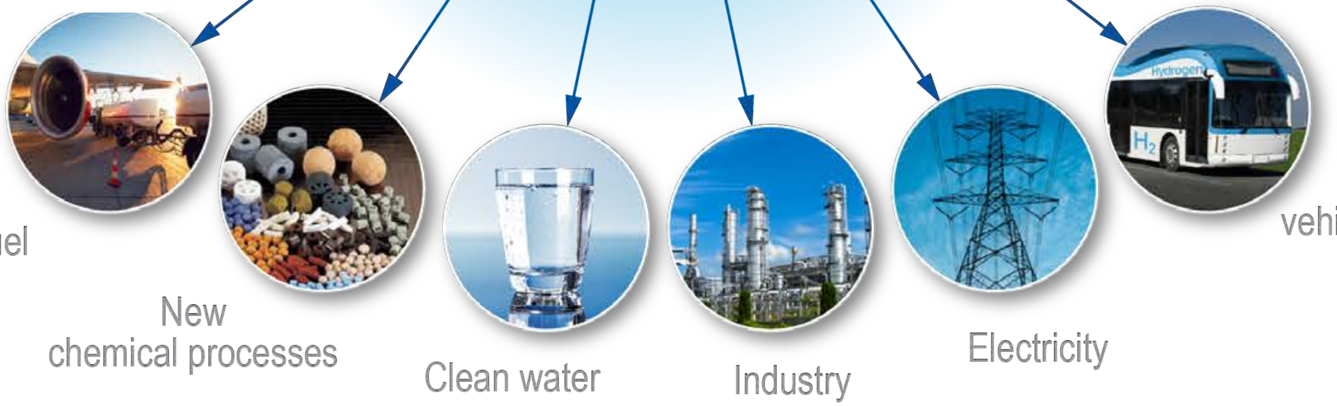
Nuclear Energy Generation

Light water reactors, high temperature advanced reactors, small modular reactors,

Other Energy Generation

Variable renewables, municipal waste, fossil with carbon capture, etc.





Integrated energy systems (IES) leverage the contributions from nuclear fission beyond electricity

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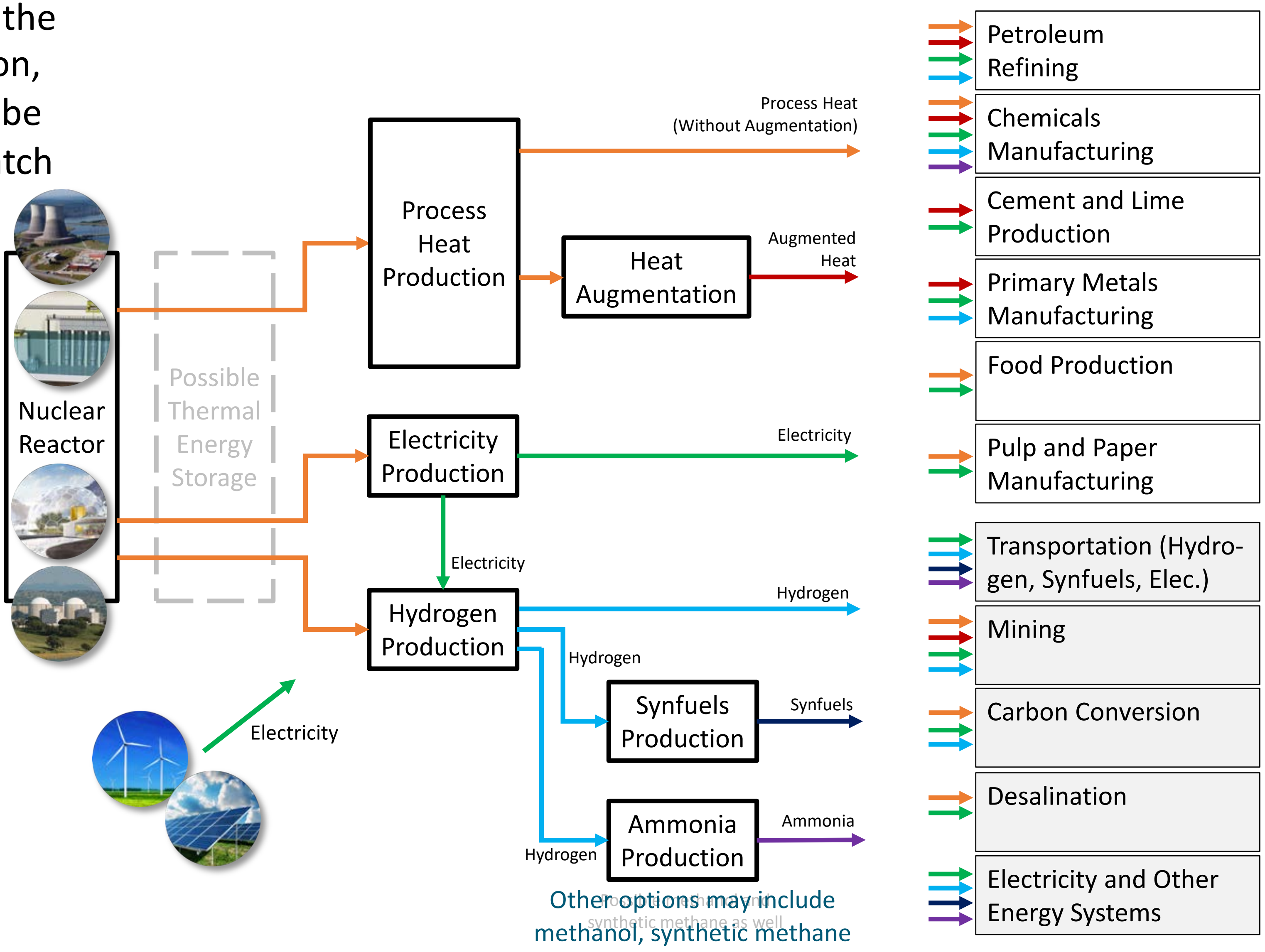
Summary of potential nuclear-driven IES opportunities

Reactor sizes align with the needs of each application, heat augmentation can be applied if needed to match process temperature demands.



Source: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, April 2021

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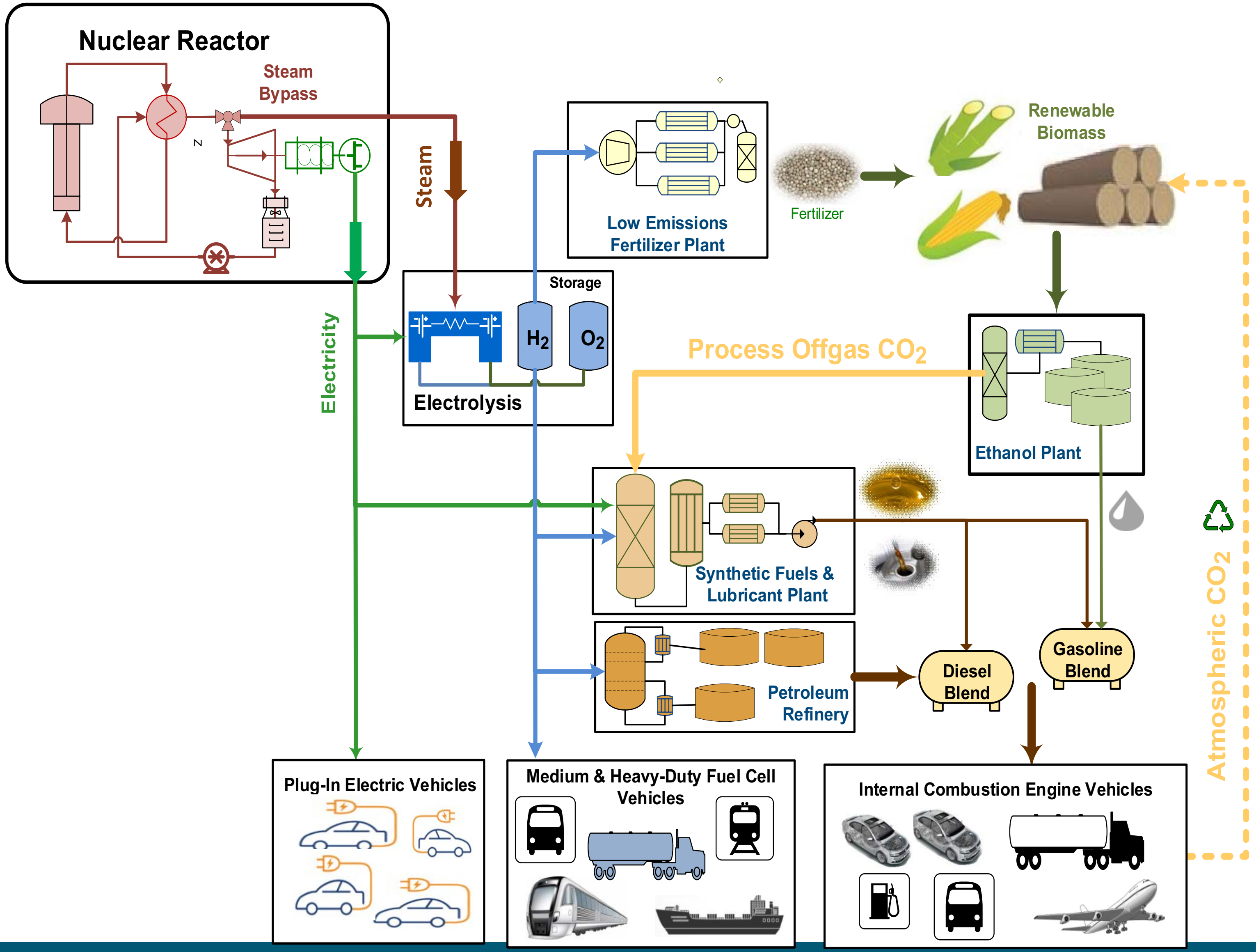
Nuclear-hydrogen production and utilization



Motivation for H_2 production to support multiple processes/ products beyond electricity

1) Provides energy storage, for electricity production or H_2 user (e.g., chemicals and fuels synthesis, steel manufacturing, ammonia-based fertilizers)
2) Provides second source of revenue to the generator; allows generator to operate at nominal power at all times
3) Provides opportunity for grid services, including reserves and grid regulation

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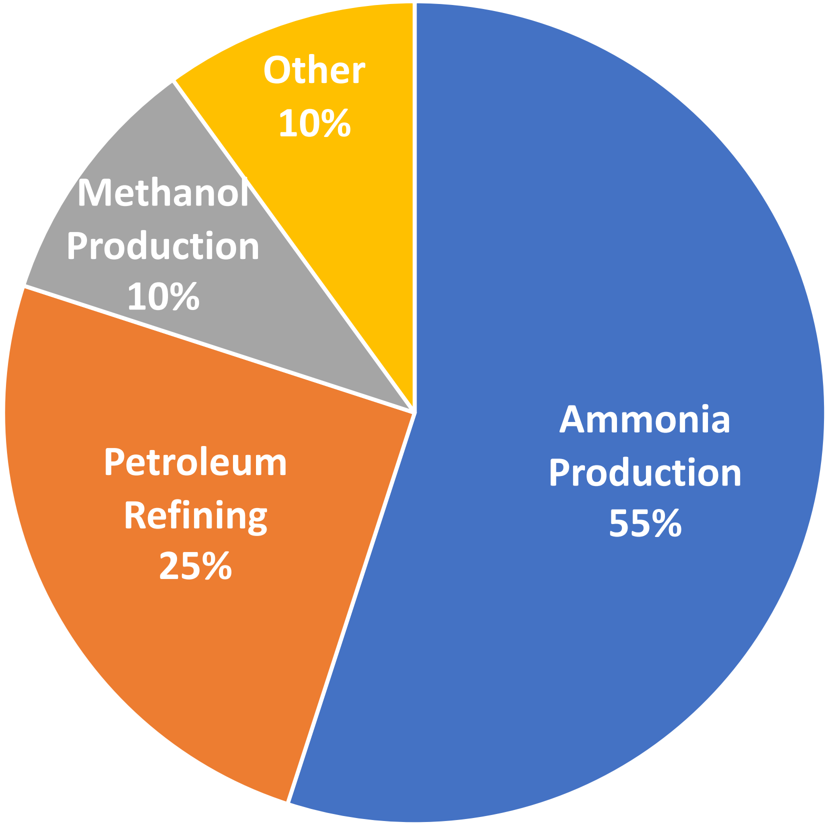
Why hydrogen?

Hydrogen applications in industry

- Agriculture/chemical industry: ammonia, ammonia-based fertilizers
- Petroleum refining: hydrocracking to produce gasoline, diesel
- Methanol production
- Other:
  - Food (e.g., hydrogenated oils)
  - Metalworking
  - Welding
  - Flat glass production
  - Electronics manufacturing
  - Medical applications

Fraction of Global Hydrogen Use by Industry



Data source: Hydrogen Europe
hydrogeneurope.eu/hydrogen-applications

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IES guiding questions

- What are **economically and technically viable** options for integrated energy system (IES) coupling to nuclear power plants in specific grid energy systems?
- What is the **statistically ideal** mix for Nuclear-IES within various markets?
- What are **driving economic factors** that existing and future nuclear technologies can leverage though IES production coupling?
- What are the **optimal coupling strategies** between IES technologies and nuclear plants?

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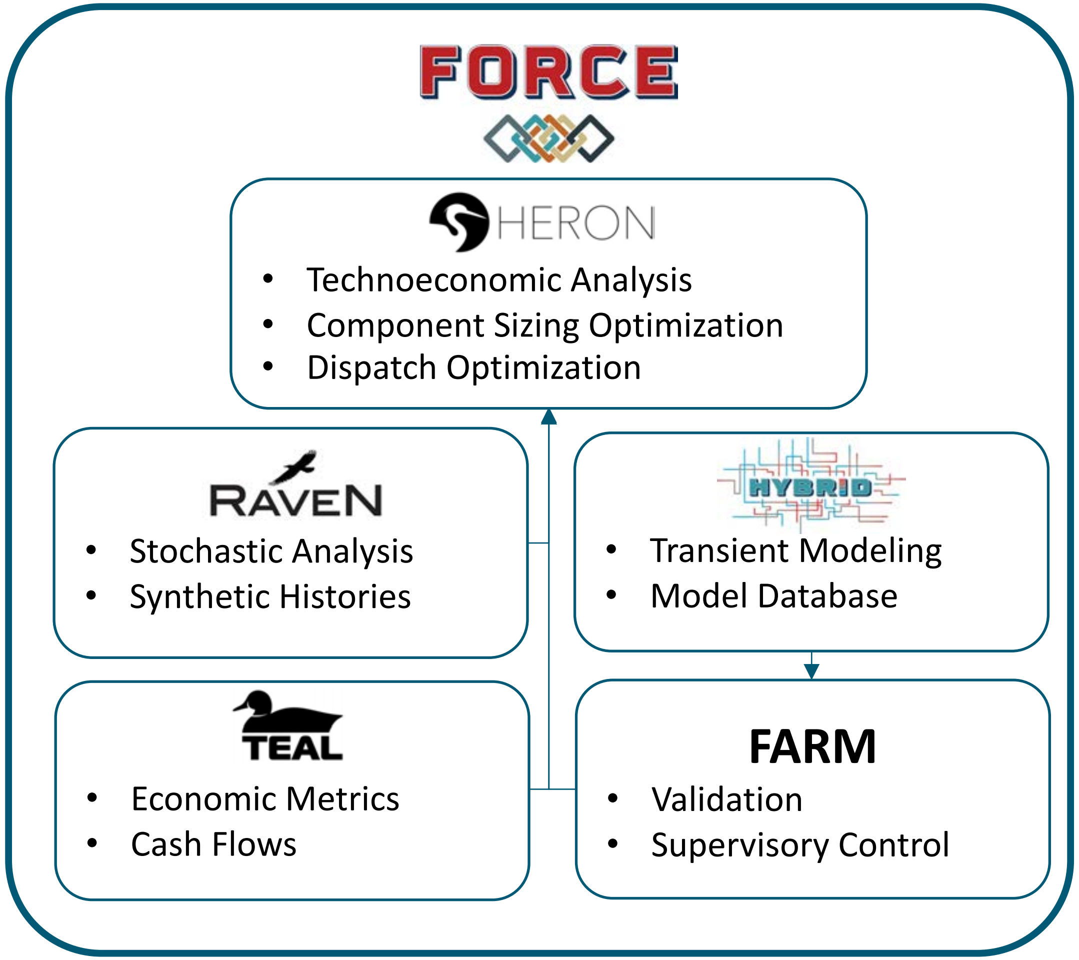
IES analysis and optimization tool suite

- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Optimization
    - Portfolio
    - Dispatch
  - Analysis
    - Economic
    - Stochastic
    - Physical
  - Supervisory Control
  - Workflow Automation



For more information and to access opensource tools, see ***https://ies.inl.gov/SitePages/System_Simulation.aspx****.*
Recorded training modules can be viewed at https://ies.inl.gov/SitePages/FORCE_2022.aspx.

Analysis timeline

Assessments Drive Development

2016: RAVEN for Stochastic Economics

2017: Flexible Nuclear Dispatch

2018: Desalination in Arizona (APS)

2019: Hydrogen in Midwest (Exelon)

2020: Hydrogen in NYISO (EPRI)

Xcel Hydrogen TEA

2021: Thermal Energy Storage

2022:

- Thermal Energy Storage in NYISO
- Carbon conversion
- Synthetic Fuels

Capacity Optimization

Dispatch Optimization

Industry Engagement

Regulated, Deregulated Markets

HERON, TEAL Released

FORCE, HYBRID, FARM Released

- FORCE workshop
- Vertical integration
- Real-time optimization

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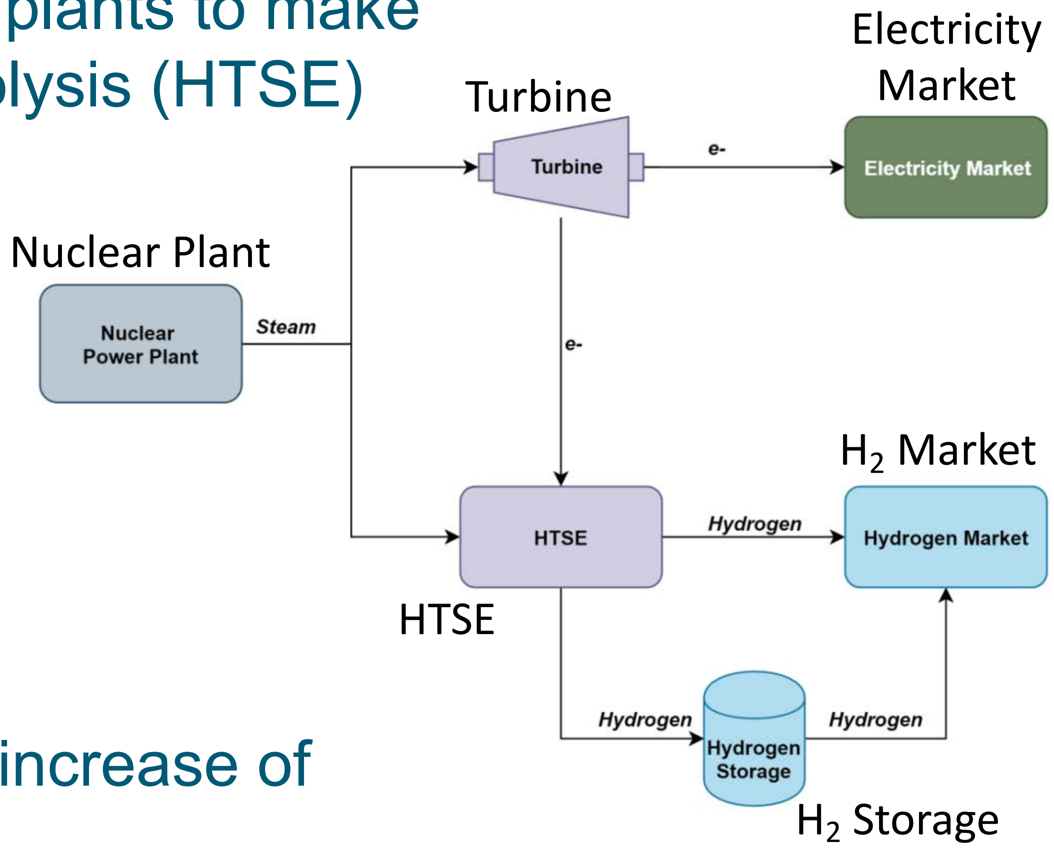
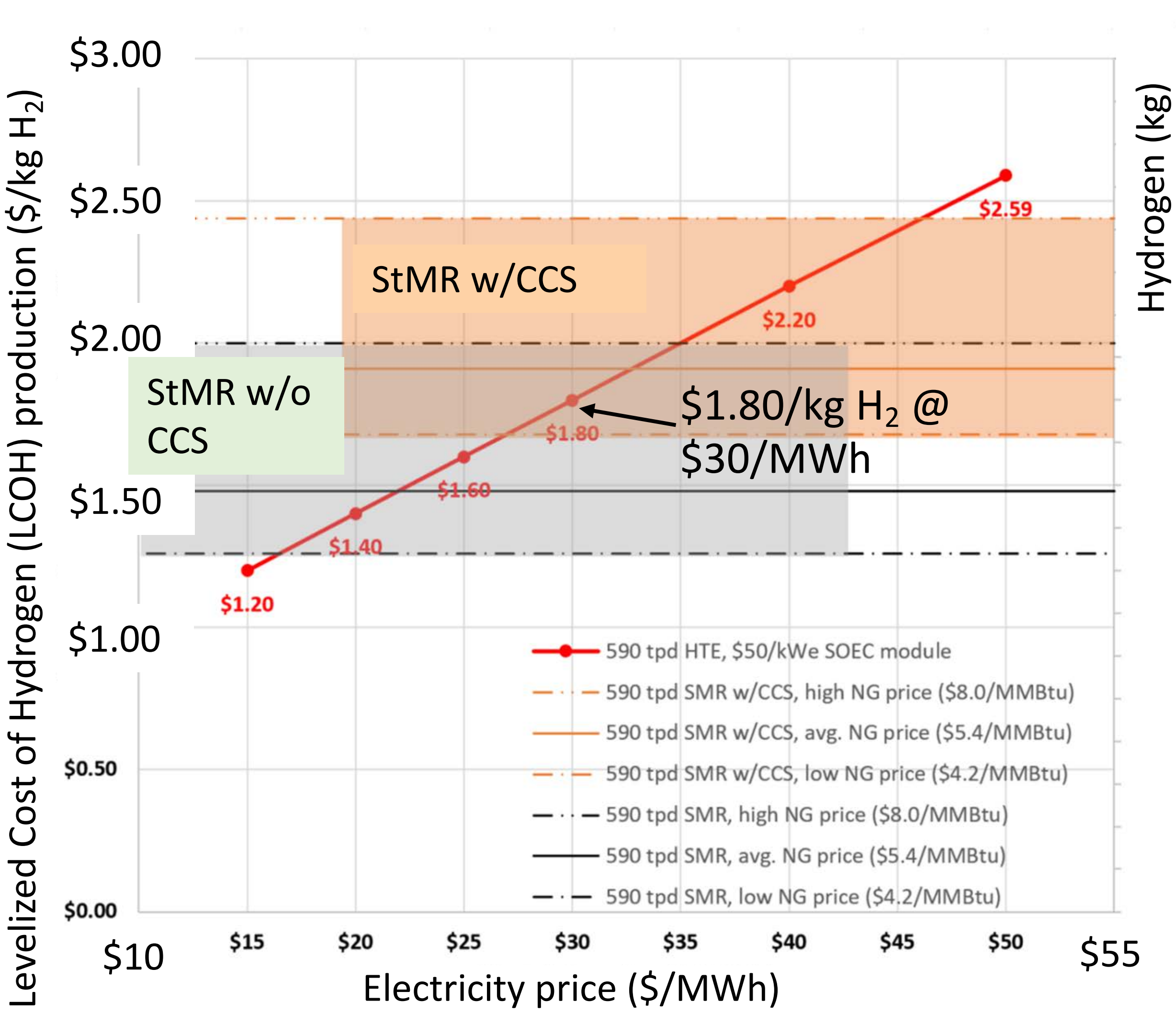
Example: Disruptive potential of nuclear produced hydrogen

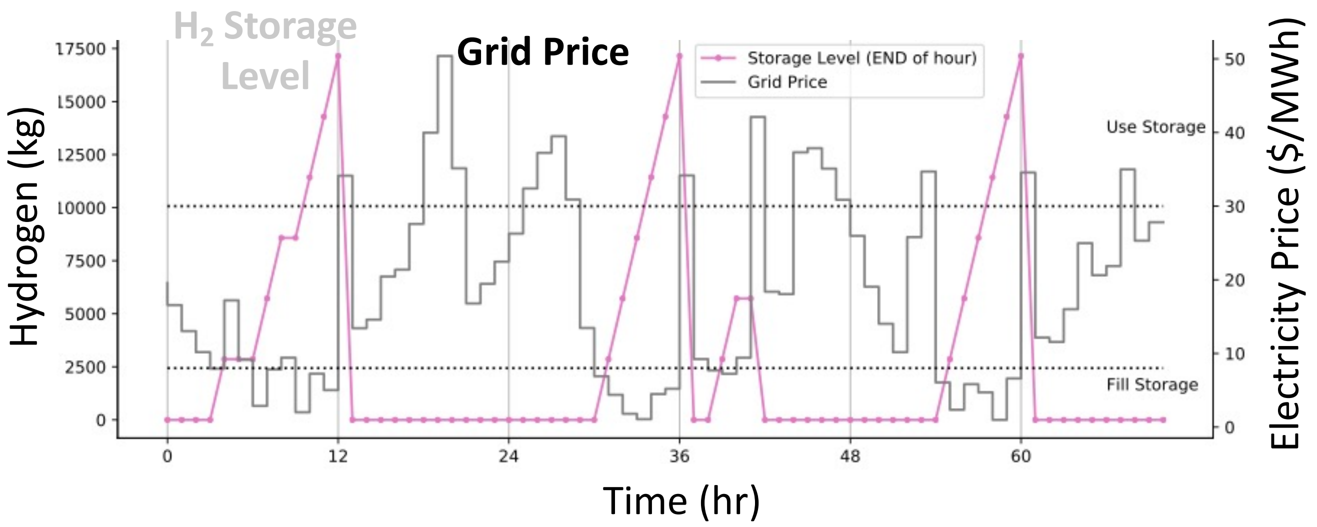
- Collaboration between INL, ANL, NREL, Constellation (Exelon), and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid pricing → grid is more profitable
  - H_2 storage provides flexibility in plant operations, ensures that all demands are met
  - H_2 off-take satisfies demand across steel manufacturing, ammonia and fertilizer production, and fuel cells for transportation
- Analysis results suggest a possible revenue increase of $**1.2 billion ($2019)** over a 17-year span



Example: Disruptive potential of nuclear produced hydrogen



LWR-HTSE LCOH as a function of electricity price compared to the Steam Methane Reforming (StMR) plant (with and without carbon capture and sequestration [CCS]) LCOH with low, baseline, and high natural gas pricing.



- **Outcome:** Award from the DOE EERE Hydrogen & Fuel Cell Technologies Office with joint Nuclear Energy funding 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)

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Nuclear-H_2 production demonstration projects

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- **Constellation (Exelon): Nine-Mile Point NPP**
  - 1 MWe Low Temperature Electrolysis (LTE)/PEM, nel hydrogen
  - Using "house load" power
  - PEM skid testing underway at NREL
  - H_2 production beginning ~October 2022
- **Energy Harbor: Davis-Besse NPP**
  - 1-2 MWe LTE/PEM Vendor 2
  - Power provided by completing plant upgrade with new switch gear at the plant transmission station
  - Installation to be made at next plant outage
  - Contract start October 2021; H_2 production ~2023/24
- **Xcel Energy: Prairie Island NPP**
  - 150 kWe High Temperature Electrolysis (HTE)/SOEC Vendor 1
  - Tie into plant thermal line engineering is being planned
  - Design complete Q4 2022; Installation, testing complete Q1 2024
- **APS/PNW Hydrogen: Palo Verde Generating Station**
  - 15-20 MWe LTE H2 production, ~6-8 tons H2/day
  - Co-locate H_2 production at the site of use
  - H_2 storage + H_2 to gas peaking turbines (50%), syngas pilot
  - Contract arrangements currently in discussion

Constellation

energy harbor

Xcel Energy

aps

Nine Mile Point Nuclear Power Plant LTE/PEM, nel hydrogen

Davis-Besse Nuclear Power Plant LTE-PEM Vendor 2

Thermal & Electrical Integration at Xcel Energy Prairie Island NPP HTE/Vendor 1

Palo Verde Gen Station Hydrogen Production for Combustion and Synthetic Fuels

H2@Scale U.S. Department of Energy

LWRS LIGHT WATER REACTOR SUSTAINABILITY

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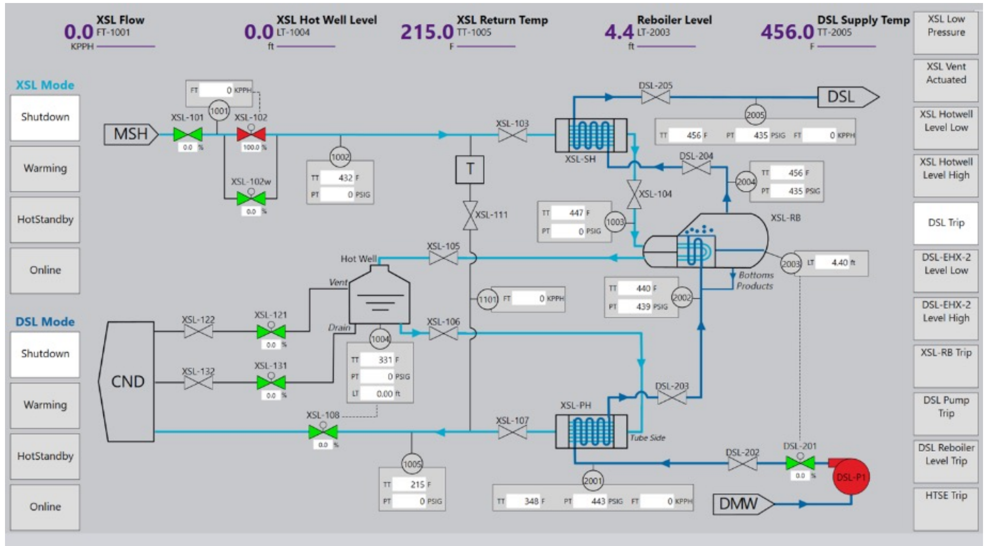
Operations with flexible thermal and electrical power dispatch

- The INL Human Systems Simulation Laboratory was used to test concepts for dispatching thermal and electrical power from nuclear reactors to a H_2 electrolysis plant
  - Two formerly licensed operators tested 15 scenarios
  - A modified full-scope generic Pressurized-Water Reactor was used to emulate the nuclear power plant
  - A prototype human-system interface was developed and displayed in tandem with the virtual analog panels
  - An interdisciplinary team of operations experts, nuclear engineers, and human factors experts observed the operators performing the scenarios
- This exercise emphasized the need to support the adoption of thermal power dispatch by
  - Leveraging automation to augment any additional operator tasking
  - Monitoring energy dispatch to a second user



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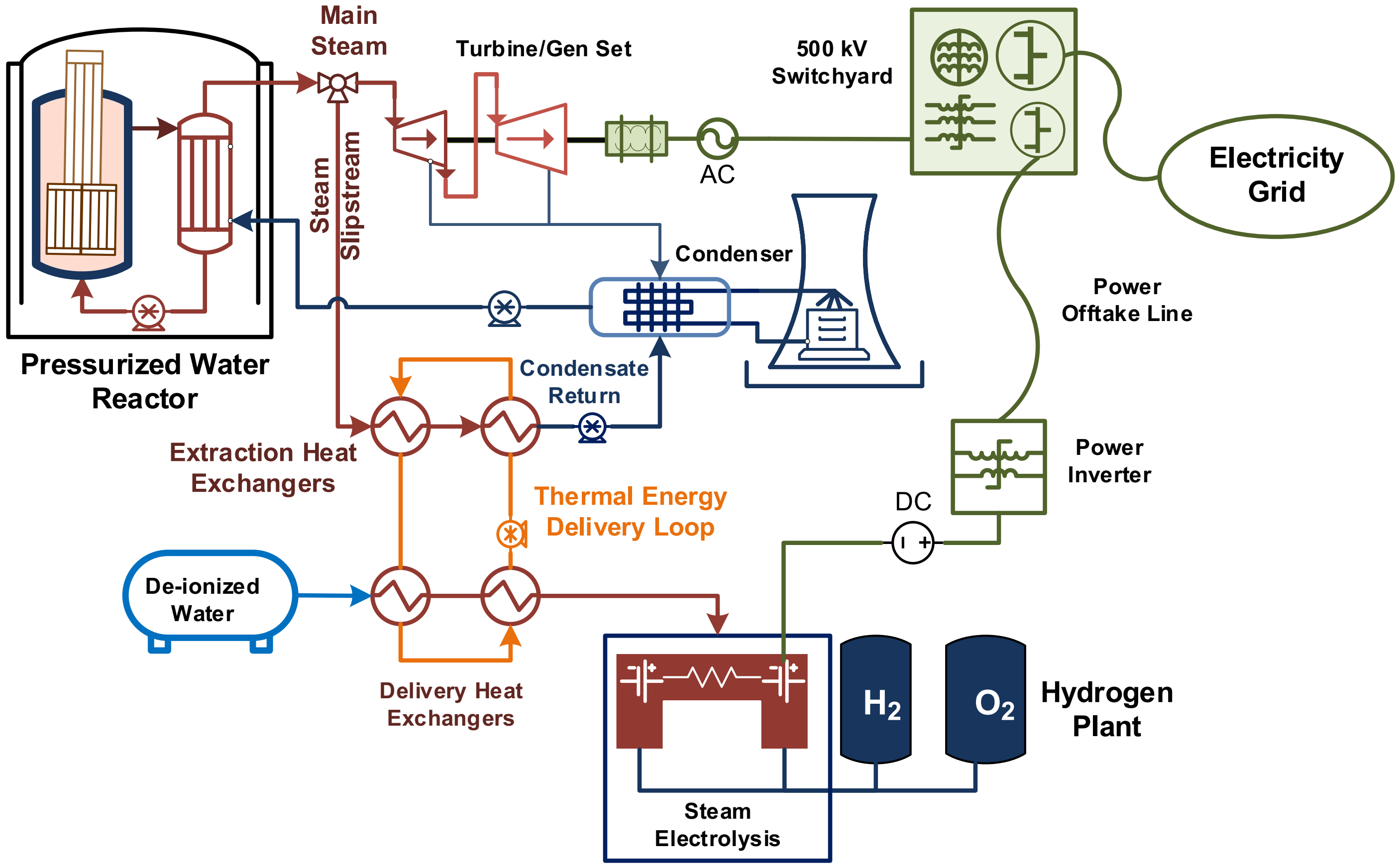
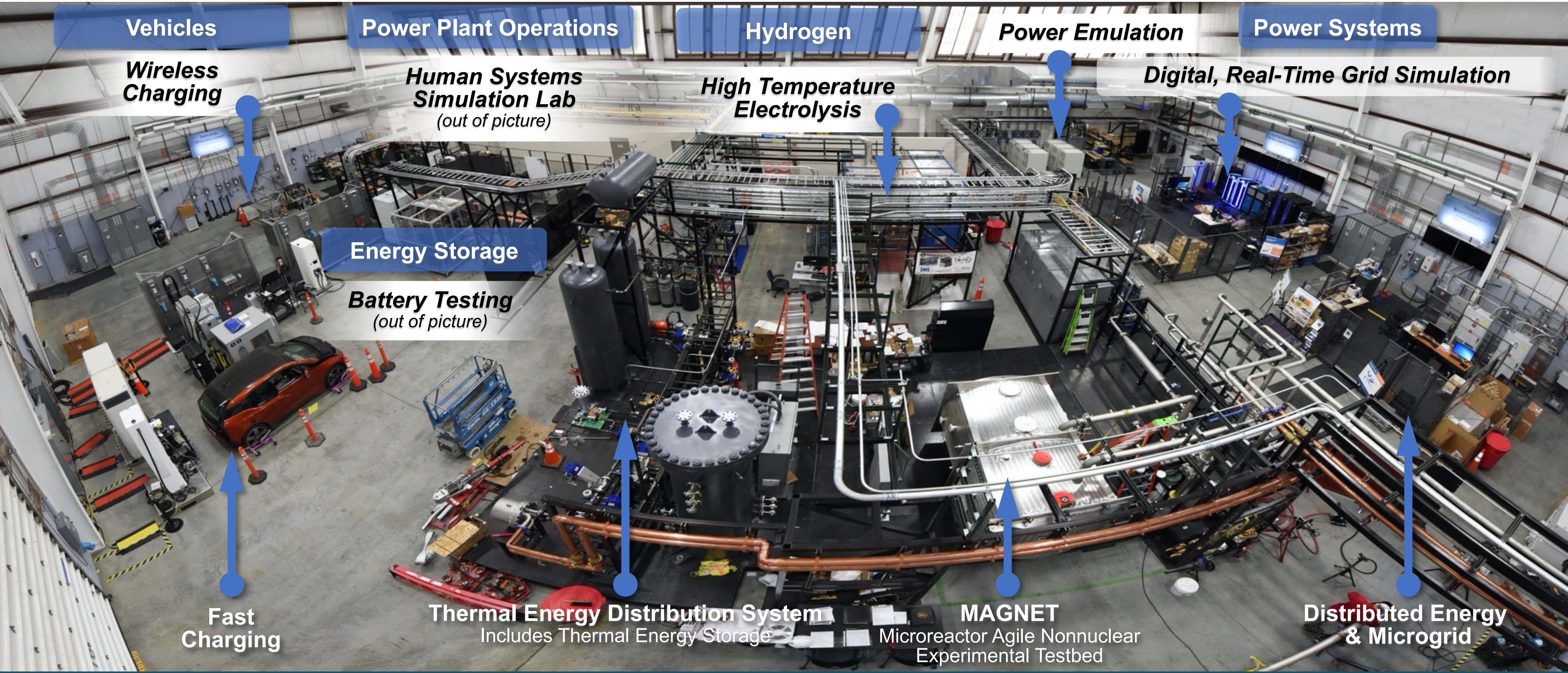
Thermal integration of steam electrolysis

Safety analysis summary conclusions

- The LWRS generic probabilistic risk assessment (PRA) investigation into licensing considerations concluded that following the assumptions made:
    - The licensing criteria is met for a large-scale HTE facility sited 1 km from a generic PWR and BWR
    - The safety case for less than 1 km distance is achievable
- Report available: INL/EXT-20-60104, *Flexible Plant Operation and Generation Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant*, OSTI link: https://www.osti.gov/biblio/1691486



Dynamic Energy Transport and Integration Laboratory (DETAIL) for electrically heated testing of integrated systems



National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure

- Goal: Demonstrate two advanced reactors by 2025
- Strategy:
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components
- Capabilities:
  - NRIC DOME (Demonstration of Microreactor Experiments)
    - Advanced Microreactors up to 20 MWth
    - High-Assay Low-Enriched Uranium (HALEU) fuels < 20%
  - NRIC LOTUS (Laboratory for Operations and Testing in the US)
    - Up to 500 kWth experimental reactors
    - Safeguards category one fuels
  - Experimental Infrastructure
    - Molten Salt Thermophysical Examination Capability
    - Helium Component Test Facility

NRIC
National Reactor Innovation Center

Anticipate initial reactor testing in ~2024. Flexible testbed to support testing of multiple reactor concepts using the same infrastructure ~annually.

For more information on NRIC and to download resources, see https://nric.inl.gov/.

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Advanced Reactor Integrated Energy System (AR-IES) Demonstration Platform

Advanced Reactor Company X: I want to connect to a thermal load, and/or a thermal energy storage system. How will it perform? What are my options? How would the overall integration look like? How will energy dispatch be optimally controlled?

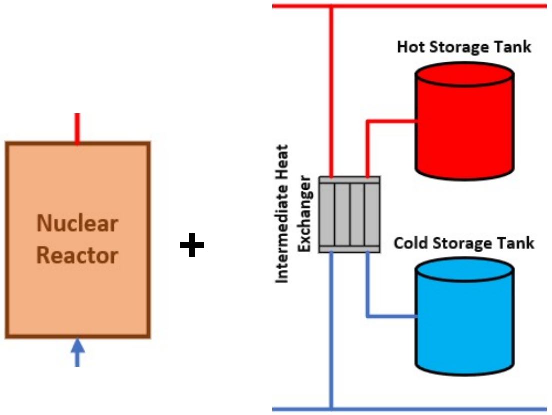
Overall objective:

In collaboration with NRIC, the IES program will develop, design, and construct an advanced reactor integrated energy system (AR-IES) demonstration platform.

Selected storage technology:

Liquid-based sensible heat Storage based on two-tank molten salt system.

Note: This selection should not be interpreted as the primary storage option for all AR-IES.



Two Tank Sensible Heat

dispatch heat to

Controllable load

bank of variable speed chillers (testing/demonstration)

or

Power peaking / Turbine

or

Industrial heat input or Secondary Process (Steel, Ammonia, H_2, etc..)

or

....

Goal:

Demonstrate how advanced reactors can be coupled to thermal energy users, and how thermal energy storage can enable coupled operation of various thermal loads/users.

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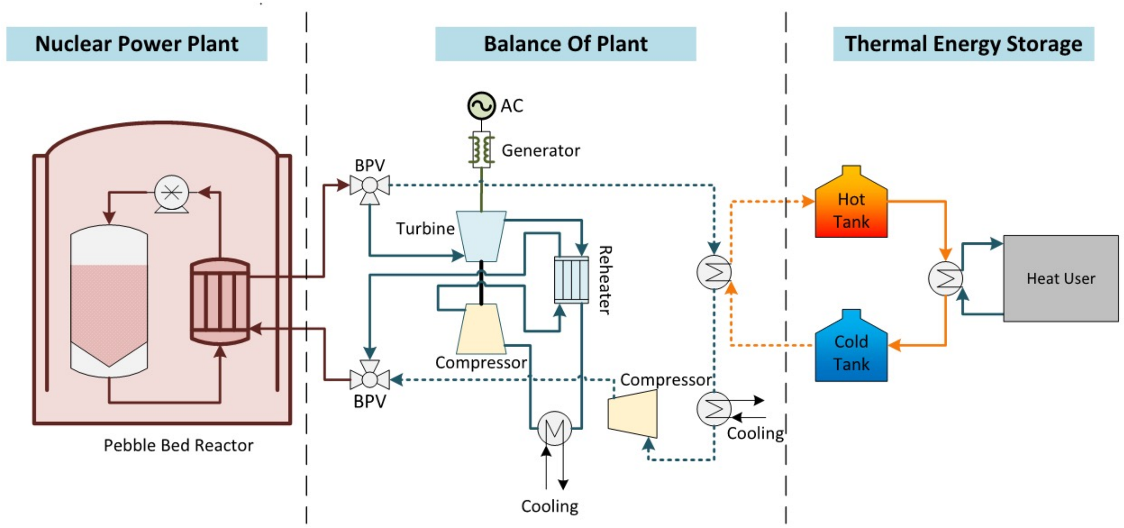
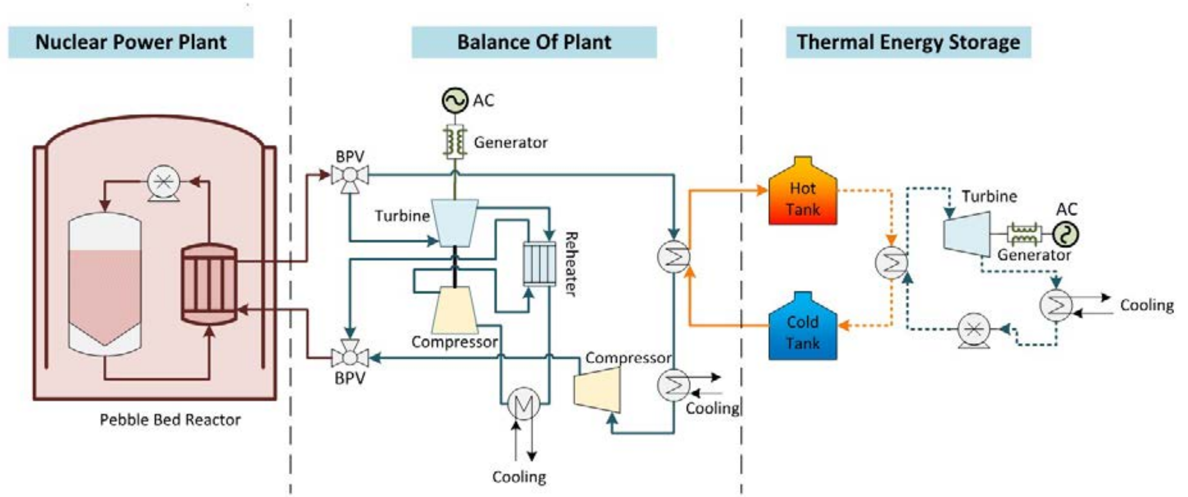
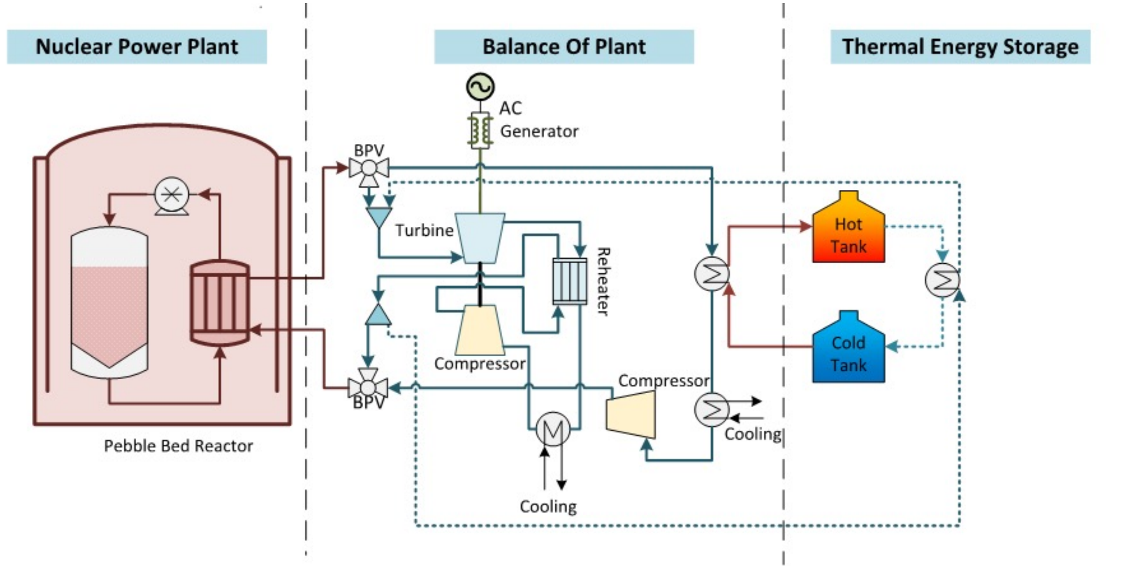
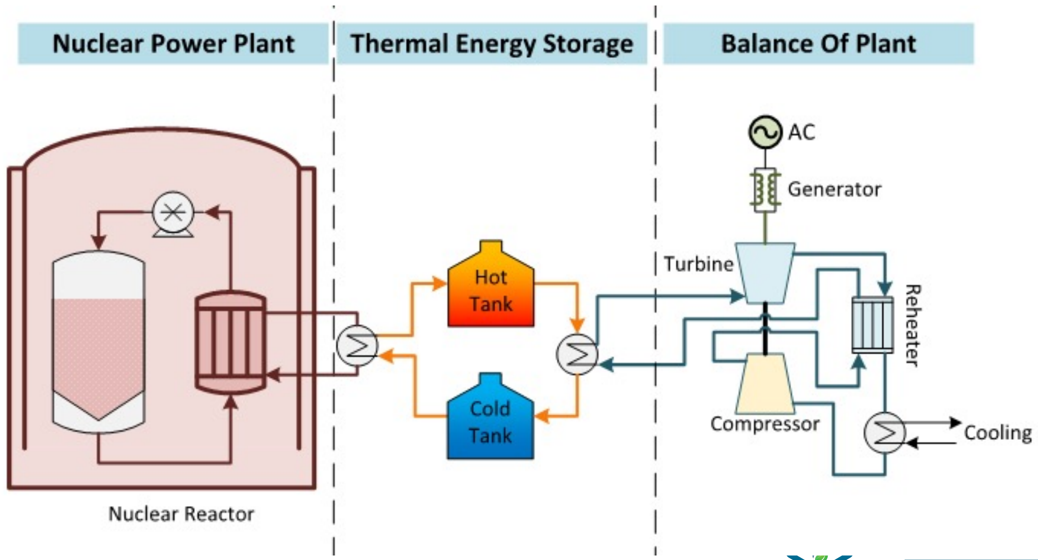
20

Coupling options









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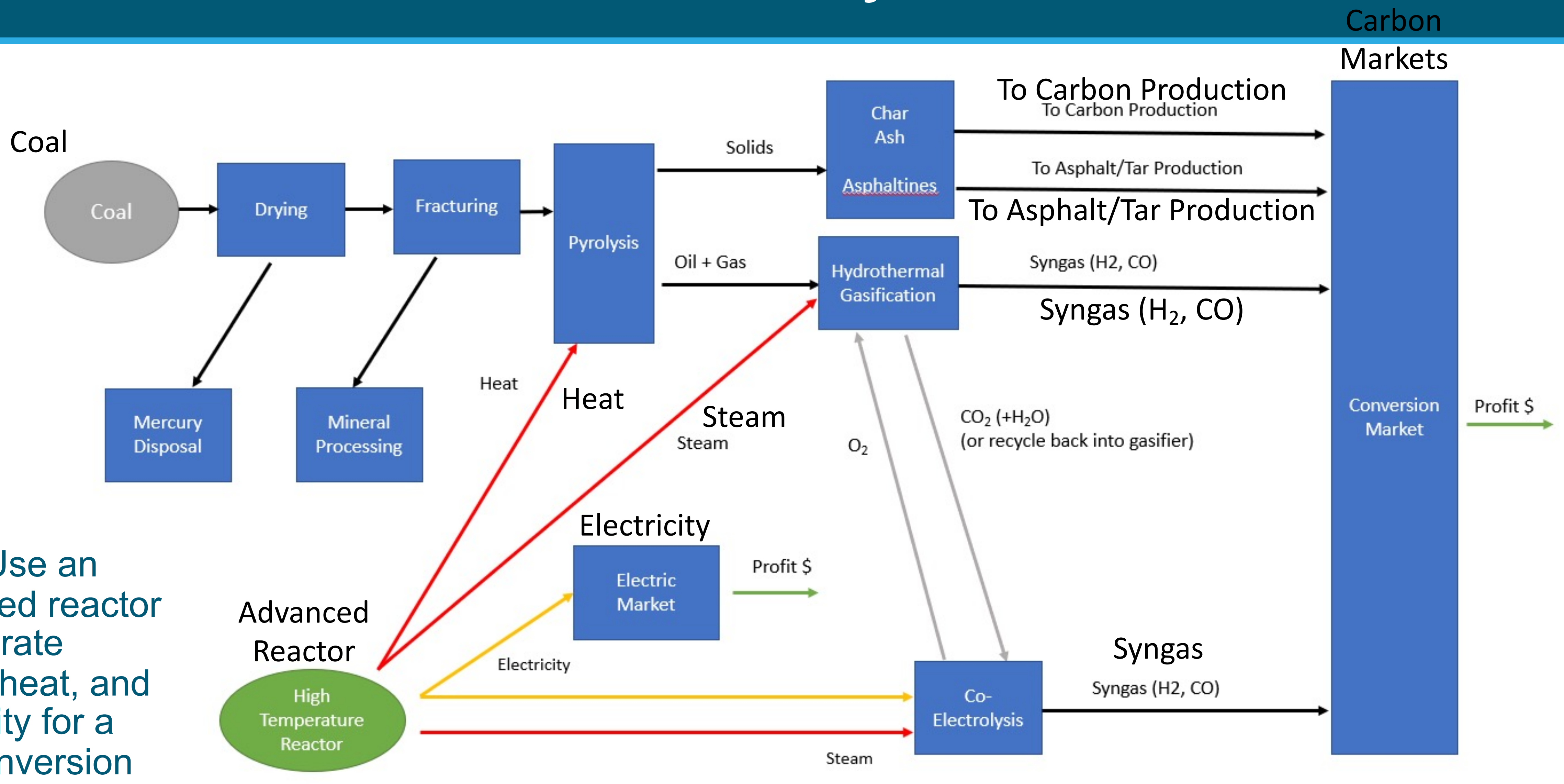
Nuclear–Carbon Conversion Case Study

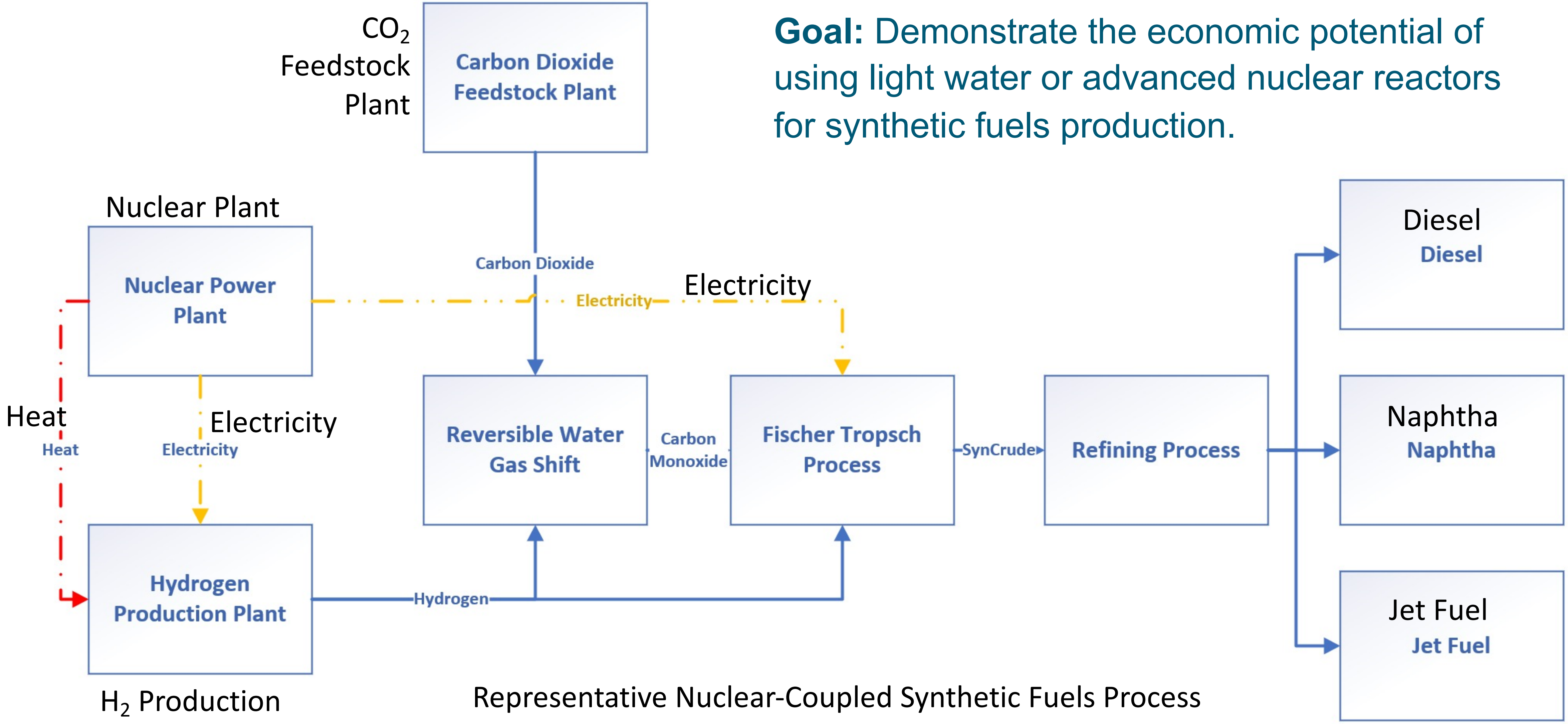


Goal: Use an advanced reactor to generate steam, heat, and electricity for a coal conversion plant.

Representative Coal Conversion Process

Nuclear Synthetic Fuels Production

Goal: Demonstrate the economic potential of using light water or advanced nuclear reactors for synthetic fuels production.



Representative Nuclear-Coupled Synthetic Fuels Process

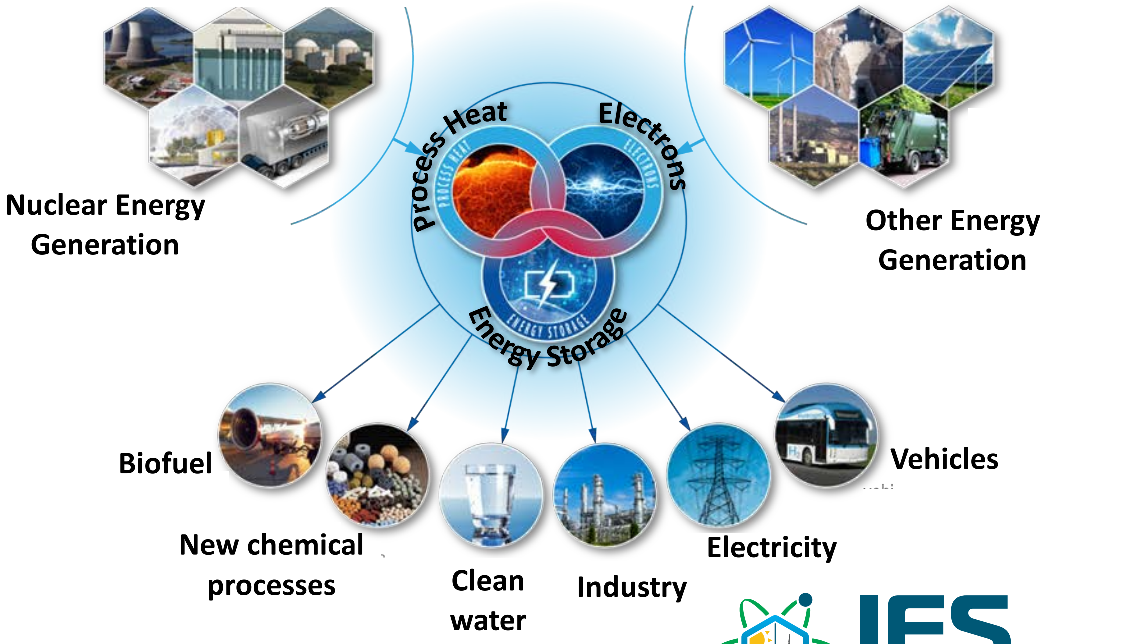
Summary of nuclear-integrated energy systems progress

The DOE-NE IES program conducts research, development, and deployment activities **to expand the role of nuclear energy beyond supporting the electricity grid**. Expanded roles include supplying energy to various industrial, transportation and energy storage applications. Focusing IES development on **enhanced utilization of low- or non-emitting energy generation** options will help the U.S. to achieve the bold goal to achieve a **100% clean energy economy and net-zero emissions**.

Integrated energy systems leverage the contributions from nuclear fission beyond electricity

Light water reactors, high temperature advanced reactors, small modular reactors, microreactors, etc.

Variable renewables, municipal waste, fossil with carbon capture, etc.



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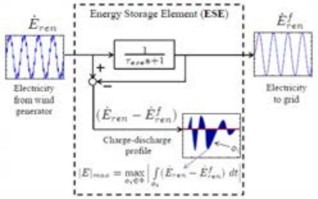
IES FY22 major program achievements

FORCE

FORCE Tool Development

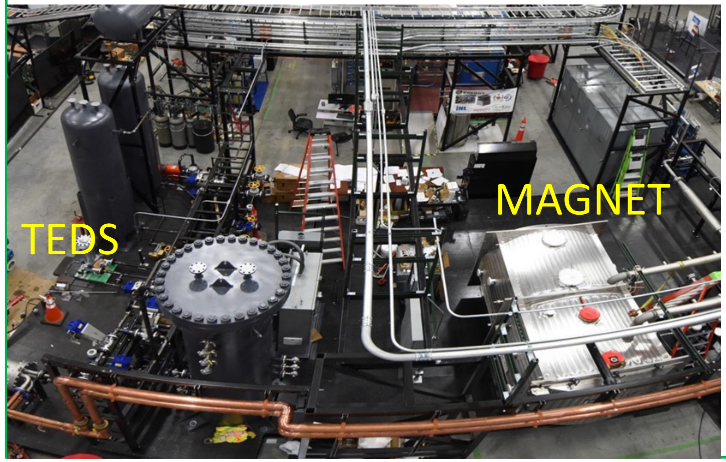
Expanded capabilities of our Framework for Optimization of Resources and Economics (FORCE) simulation ecosystem to **expand the capability for evaluating additional IES configurations**.



Use Cases and Industry Collaborations

With inputs from industry, **performed initial techno-economic assessment** of nuclear energy use to support **synfuel production**, **carbon conversion** and **thermal energy storage**.

Laboratory-scale Experimental Demonstrations



- Dynamic Energy Transport and Integration Laboratory (DETAIL) integrates independent systems funded from multiple programs.
- **Thermal integration of** Thermal Energy Distribution System (**TEDS**) and **MAGNET** has been started.
- Explored **Real-time Optimization (RTO), Digital Twin (DT)** and **experiment scaling** capabilities for FORCE tool suite to support DETAIL experiments.

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