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Dynamic Nuclear Thermal Energy Integration for High Temperature Electrolysis

June 2022

Changing the World's Energy Future

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Idaho National Laboratory

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IES

Integrated Energy Systems

Dynamic Nuclear Thermal Energy Integration for High Temperature Electrolysis

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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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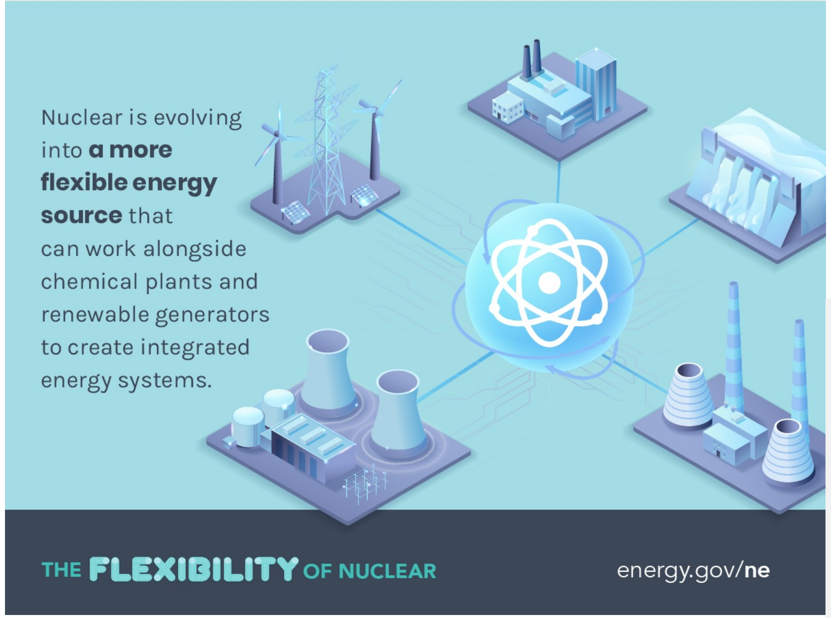
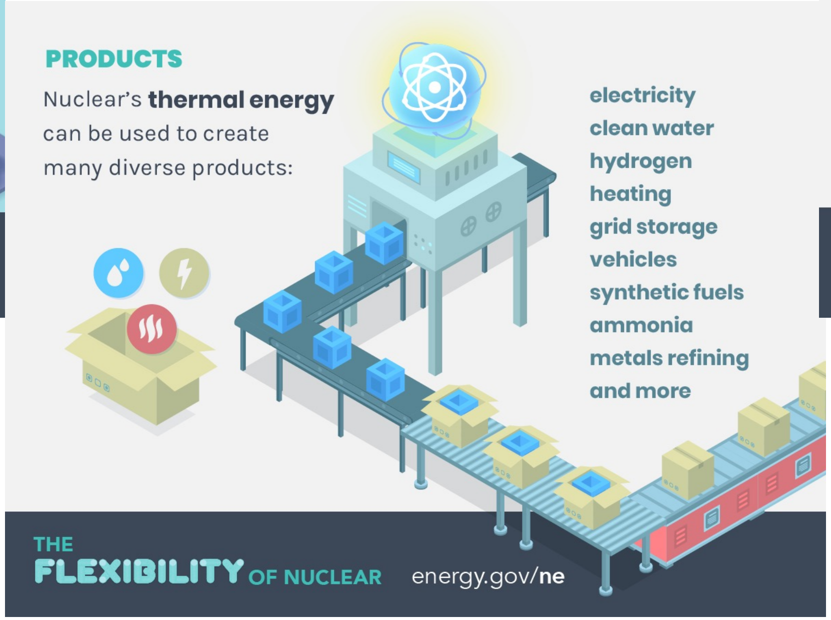
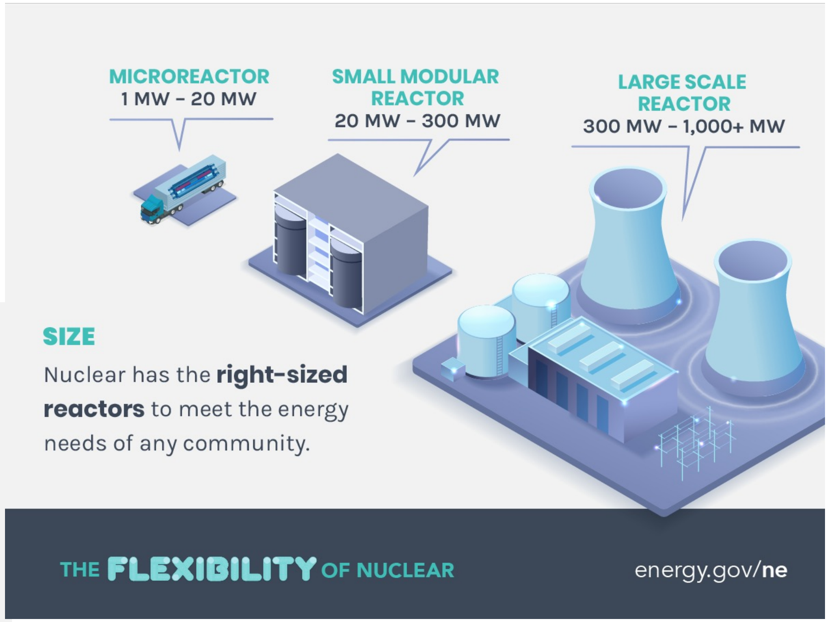
Operational paradigms—nuclear energy flexibility



Nuclear flexibility is key to enabling other clean energy generators to provide deep decarbonization across multiple sectors.





- ***Operational* flexibility**
  - ***Product* flexibility**
    - ***Deployment* flexibility**

U.S. DEPARTMENT OF ENERGY | *Office of* NUCLEAR ENERGY

Flexible Nuclear Energy for Clean Energy Systems, September 2020
https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems

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Summary of potential nuclear-driven IES opportunities

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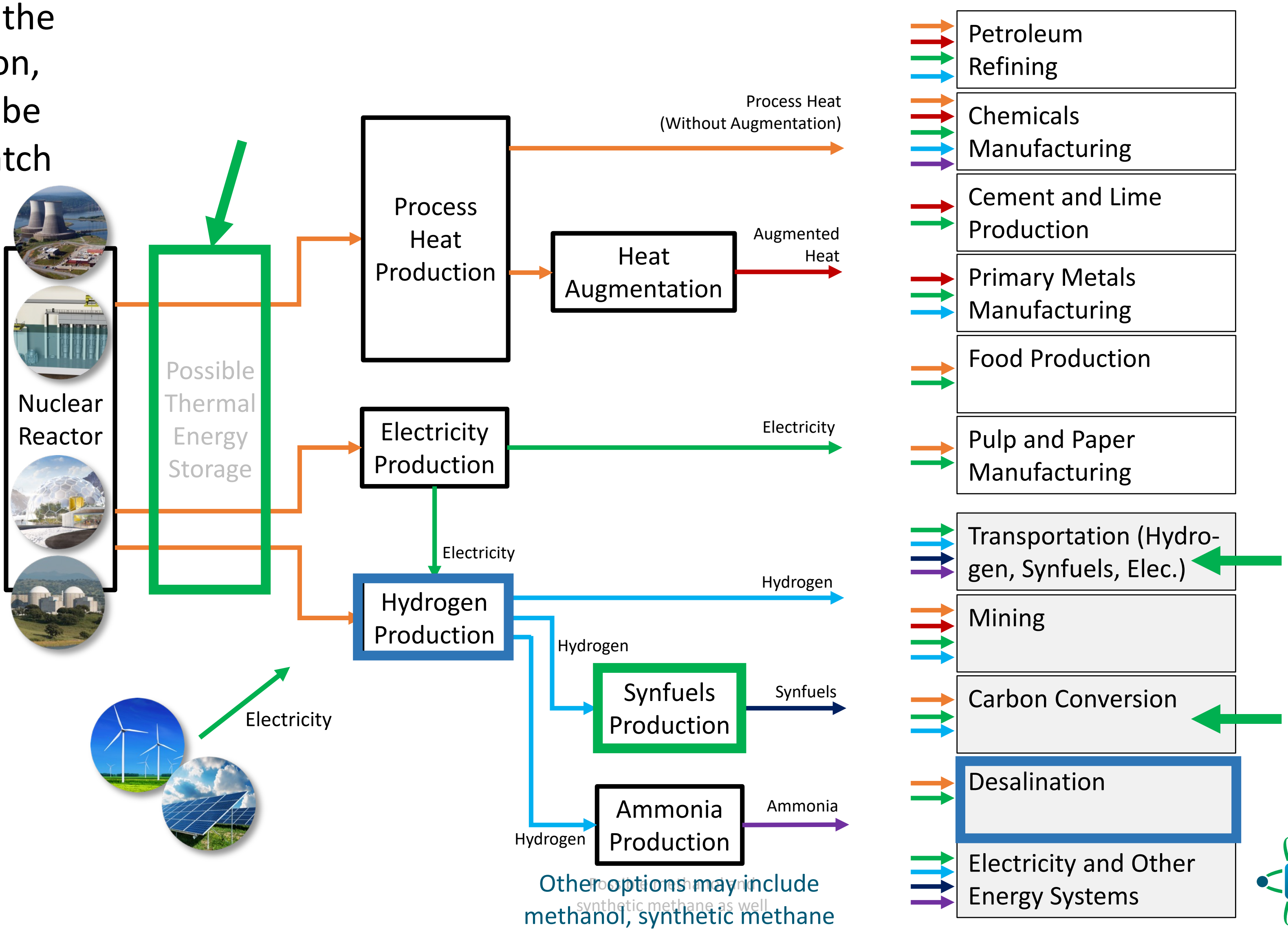
Reactor sizes align with the needs of each application, heat augmentation can be applied if needed to match process temperature demands.



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

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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 **optimal coupling strategies** between IES technologies and nuclear plants?

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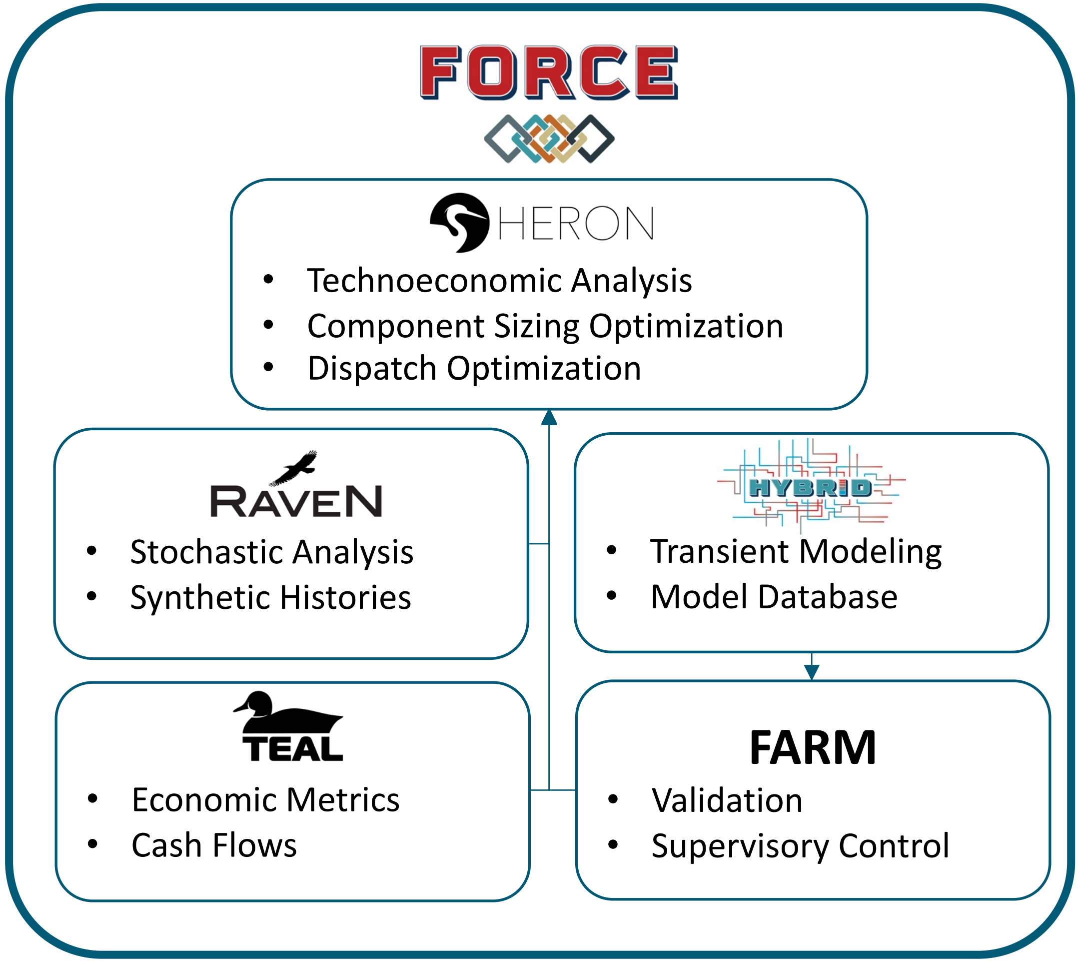
IES analysis and optimization tool suite

- 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.

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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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Nuclear-H_2 production demonstration projects

- **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

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

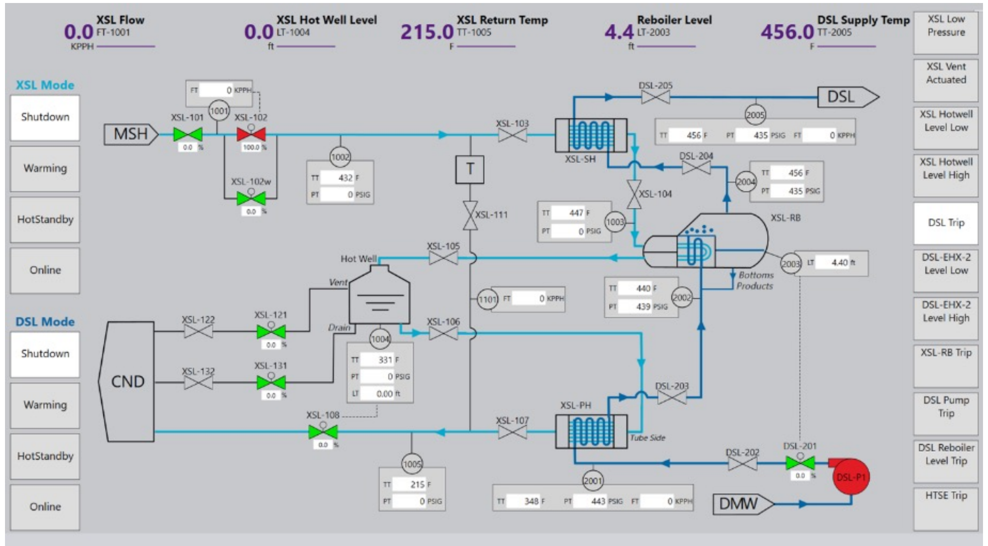
Davis-Besse Nuclear Power Plant LTE-PEM Vendor 2

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

Palo Verde Gen Station Hydrogen Production for Combustion and Synthetic Fuels

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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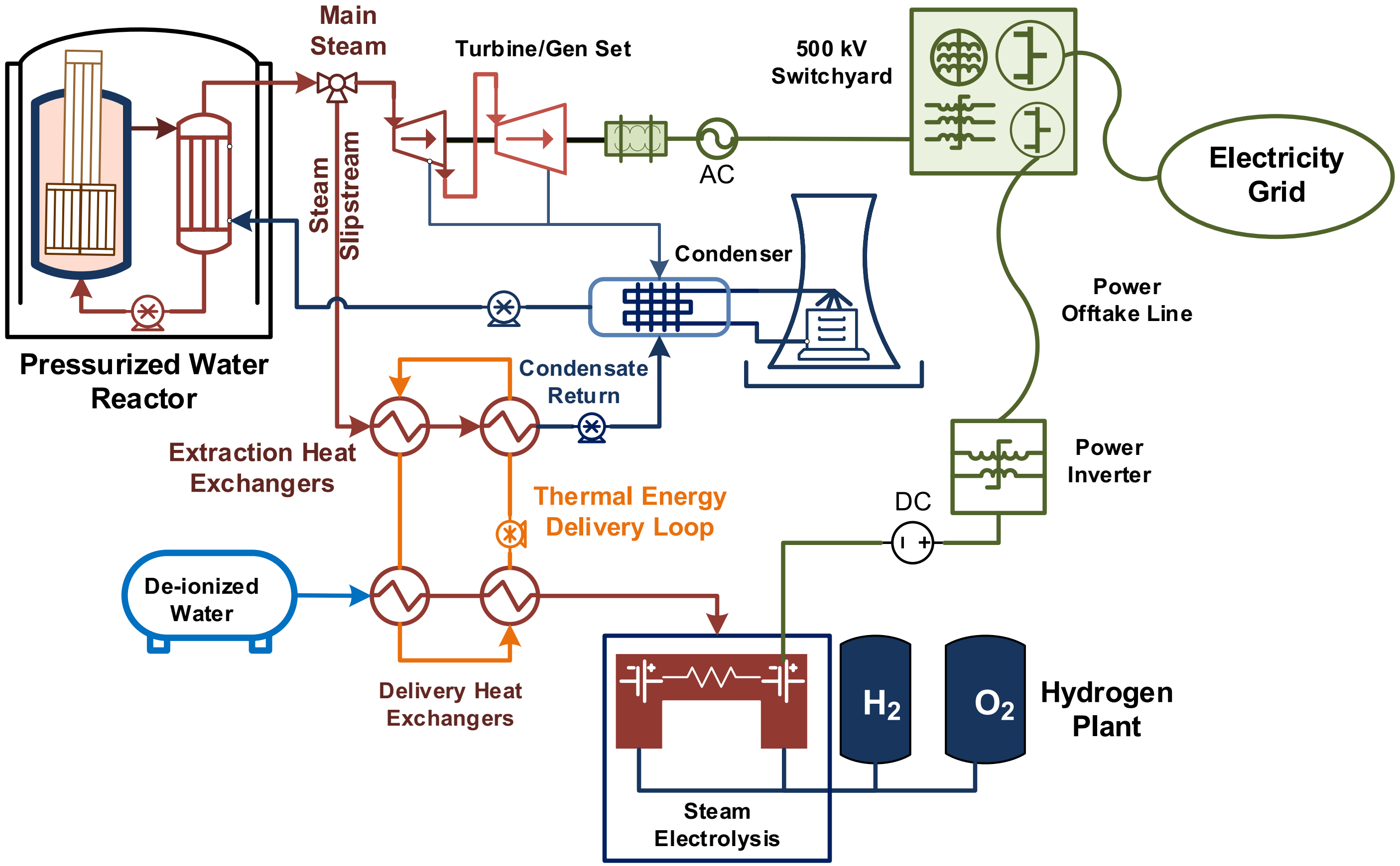
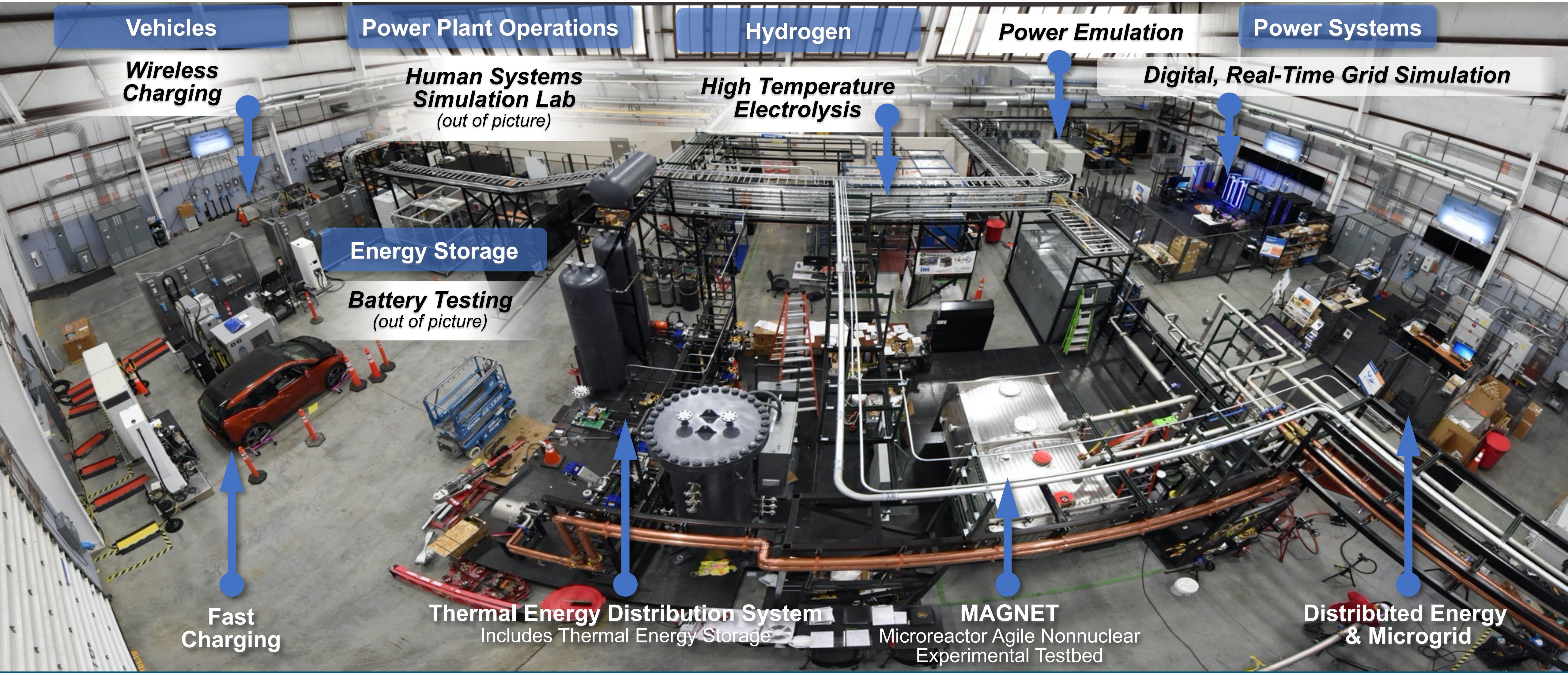
Thermal integration of steam electrolysis

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



DETAIL enables cross-complex laboratory connections

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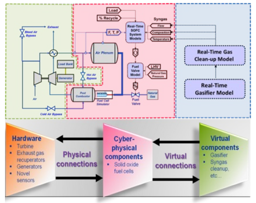
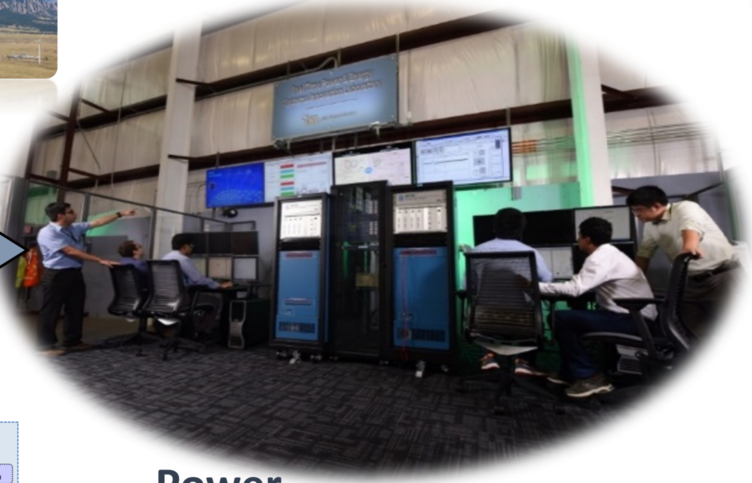
NREL
Transforming ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY



Human-in-the-Loop



Power Hardware and Grid-in-the-Loop

Hydrogen and other Flexible Industrial Processes

Thermal Energy Generation and Transport

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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?

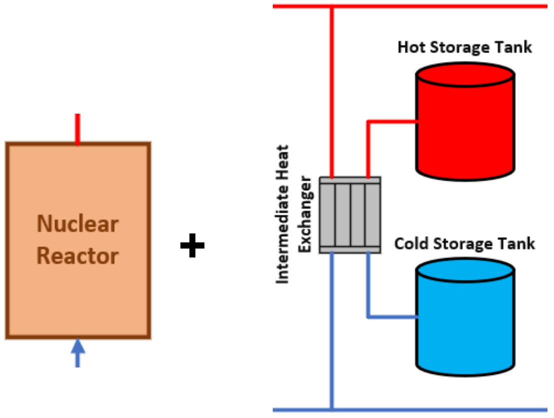
Overall objective:

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

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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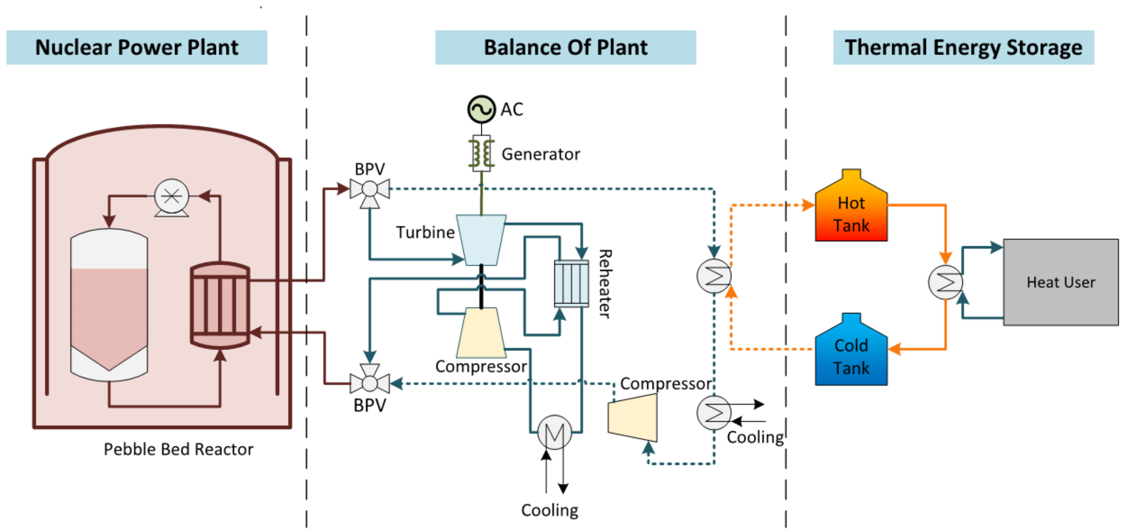
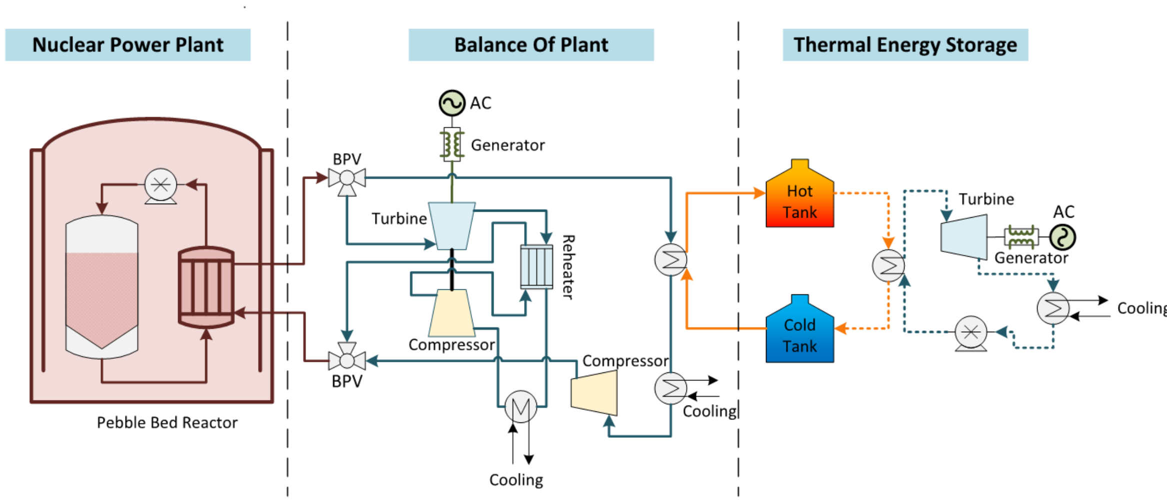
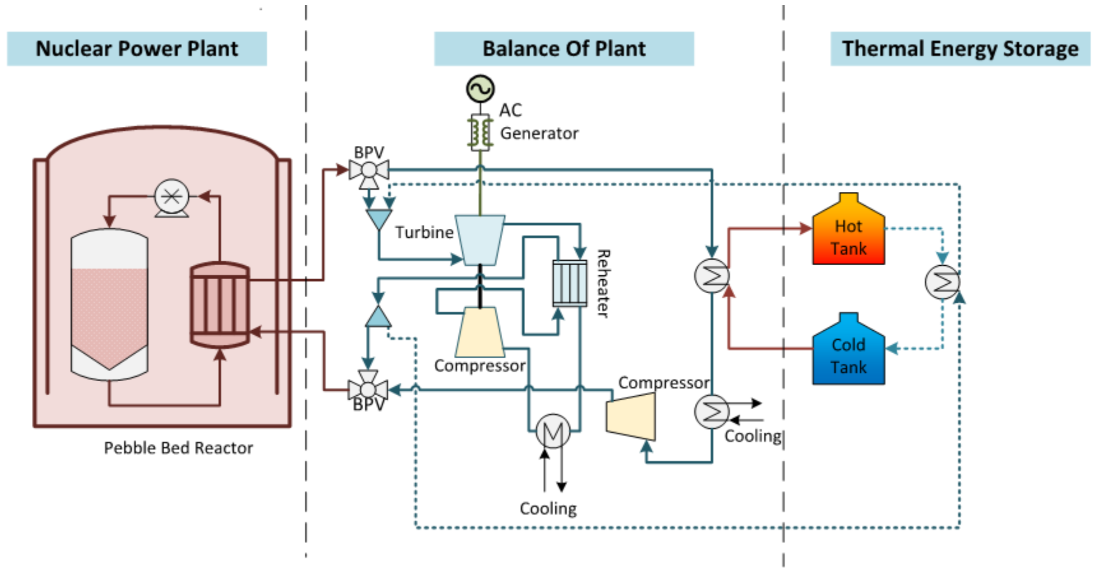
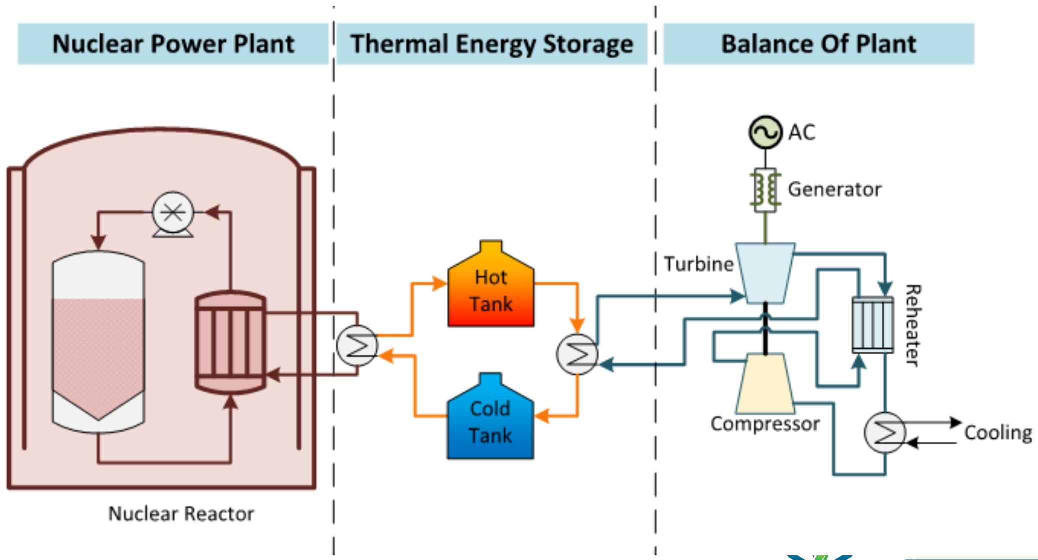
Coupling options







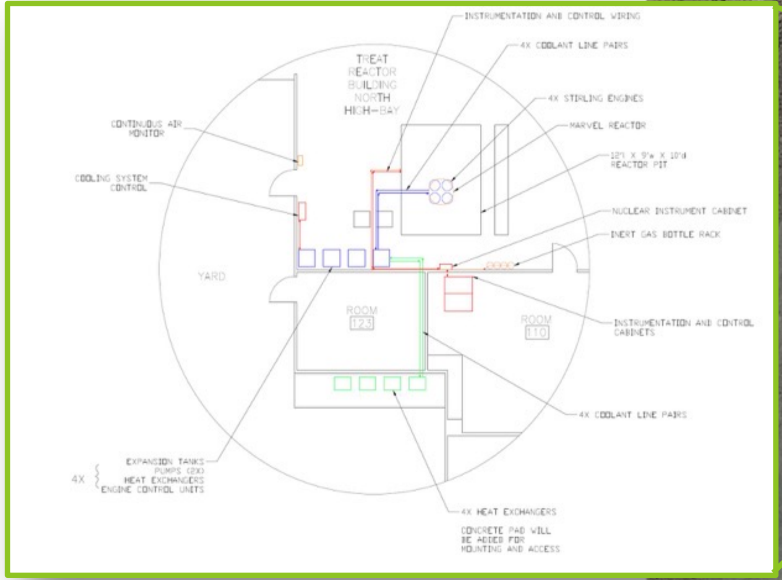


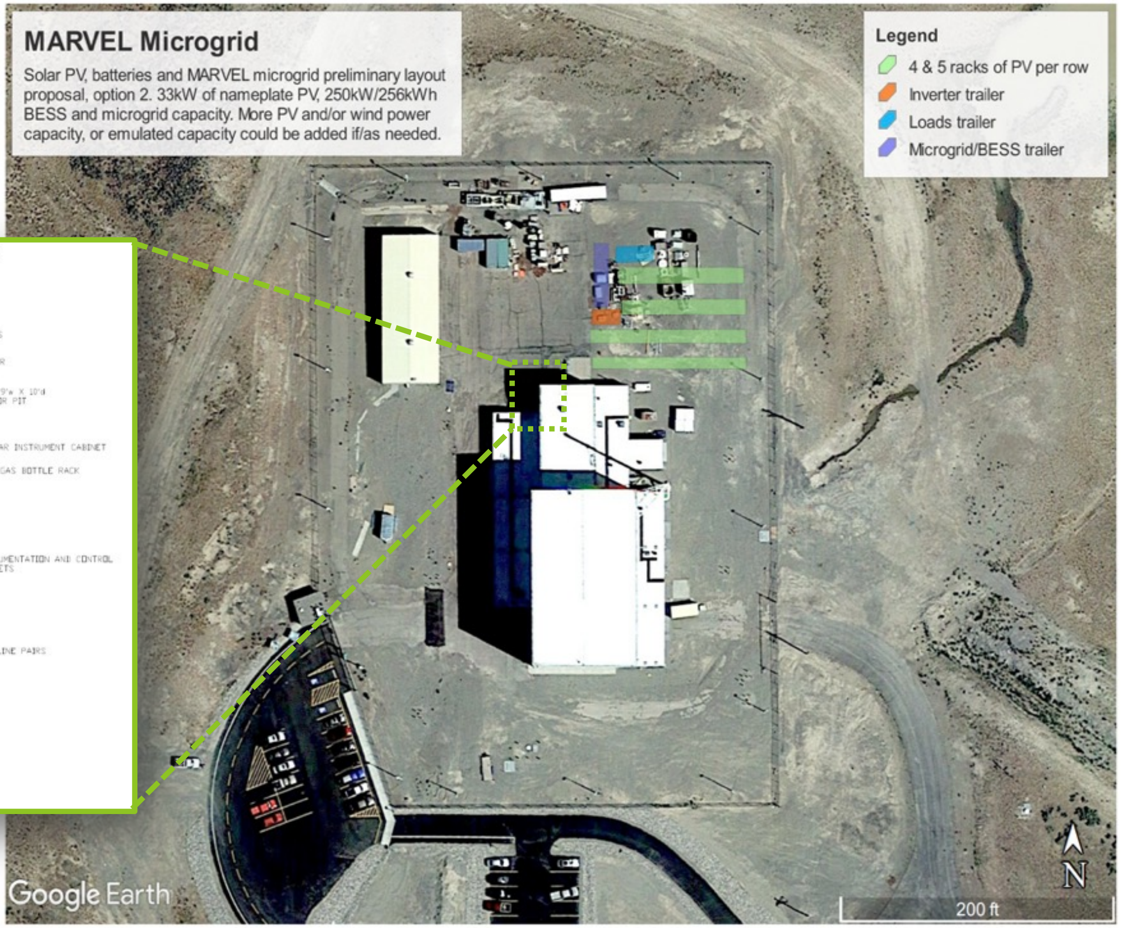
Integration of the MARVEL microreactor with a microgrid

Microreactor Applications Research Validation and Evaluation (MARVEL) Objective:

Operational reactor that produces combined heat and power (CHP) to a functional microgrid

Will demonstrate nuclear microgrid operations and provide opportunity to demonstrate operation with coupled energy users, such as hydrogen production and desalination.





MARVEL Construction: FY 2023

MARVEL Criticality: FY 2024

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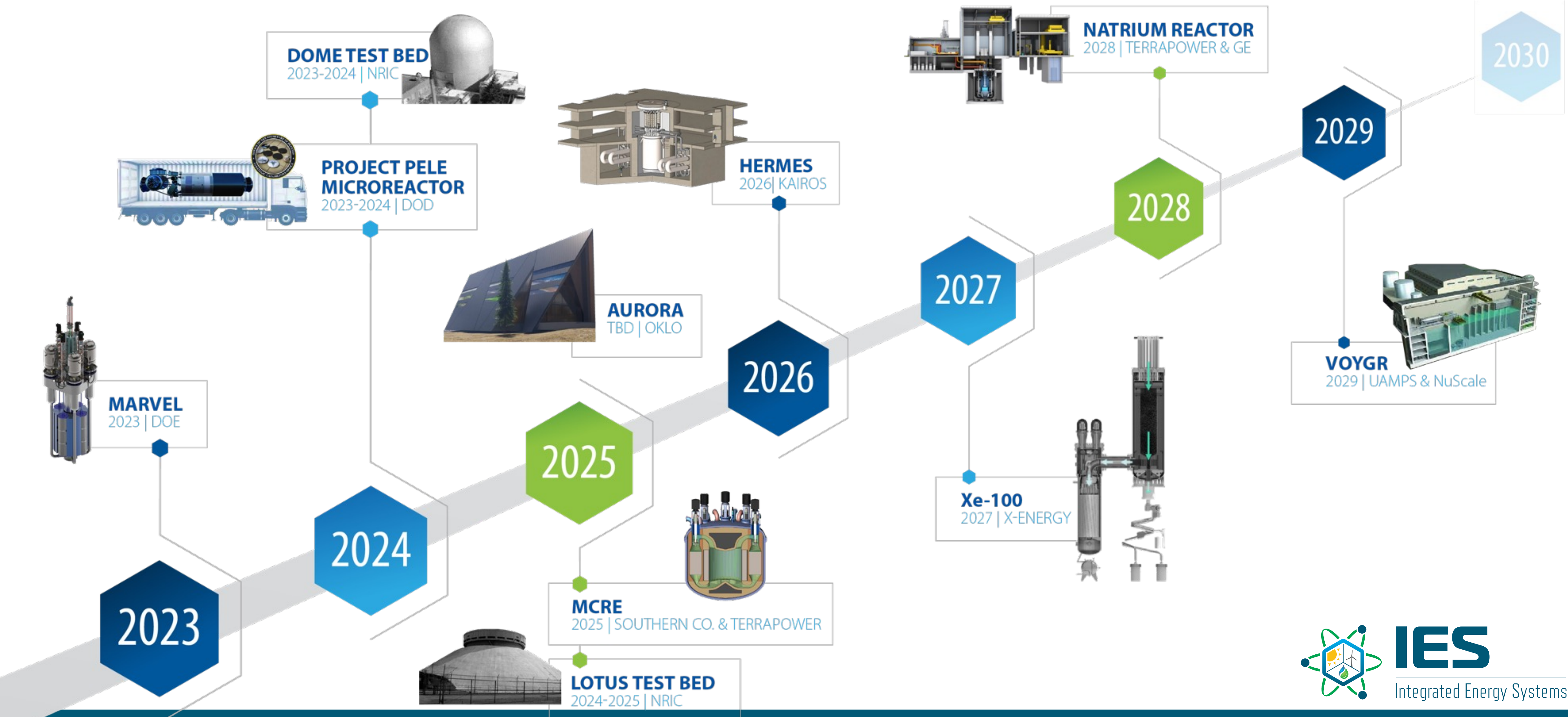
Accelerating advanced reactor demonstration & deployment



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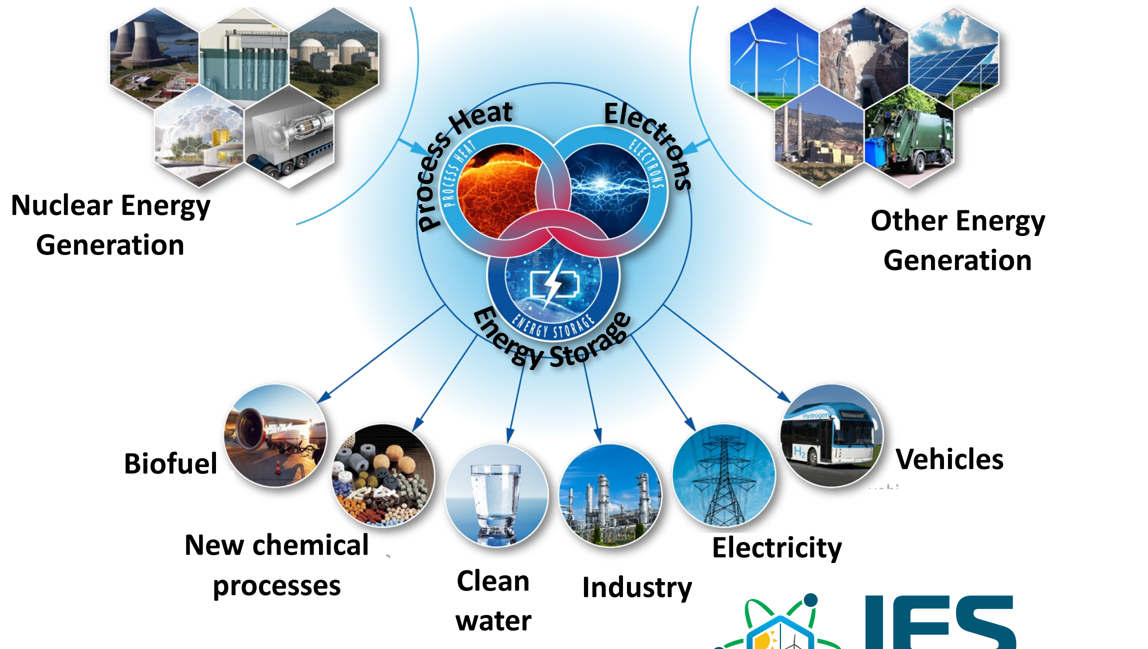
Summary of nuclear-integrated energy systems progress

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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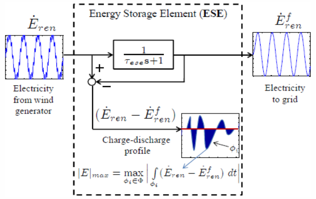
IES FY22 major program achievements

FORCE Tool Development

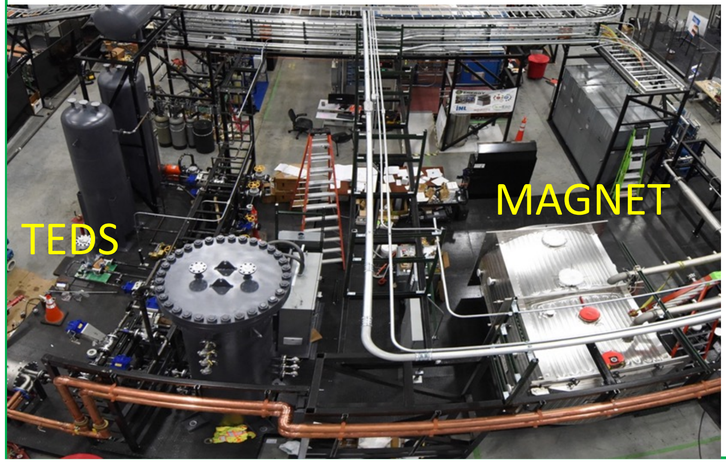
Expanded capabilities of our Framework for Optimization of Resources and Economics (FORCE) simulation ecosystem to **expand the capability for evaluating additional IES configurations**.



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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