INL/MIS-22-66032-Revision-0

Nuclear Energy for Economy-wide Net Zero Solutions: Advancing Nuclear-Hydrogen Production

February 2022

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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Nuclear Energy for Economy-wide Net Zero Solutions: Advancing Nuclear-Hydrogen Production

CSA Hydrogen Seminar

February 15, 2022

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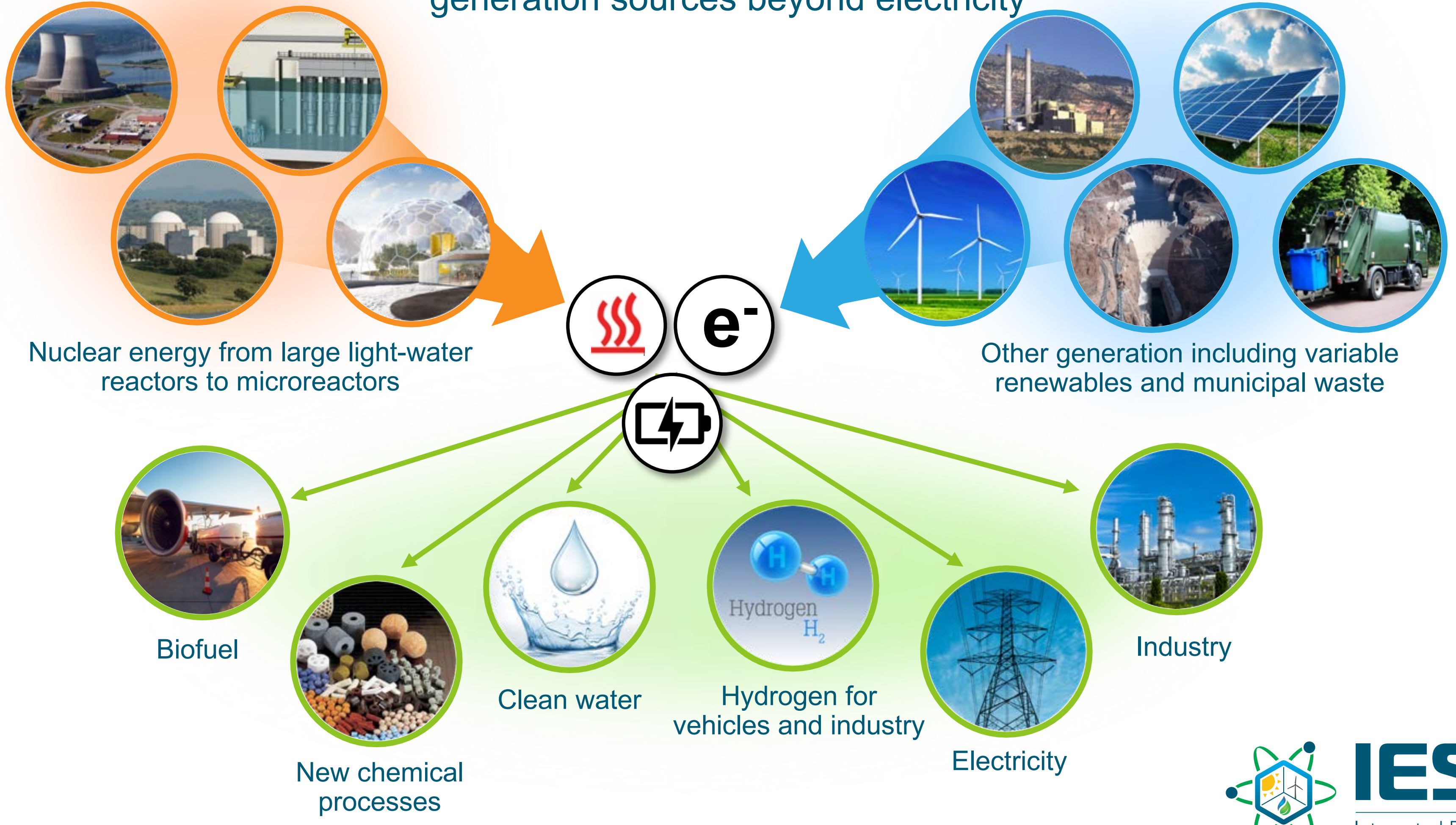
Cross-sectoral energy solutions provide opportunities to achieve net-zero while maintaining grid stability and affordability

Goals:

- Maximize energy utilization and generator profitability
- Minimize environmental impacts
- Maintain affordability, grid reliability and resilience

Future Energy System

Integrated grid system leverages contributions from nuclear fission and other low emission energy generation sources beyond electricity



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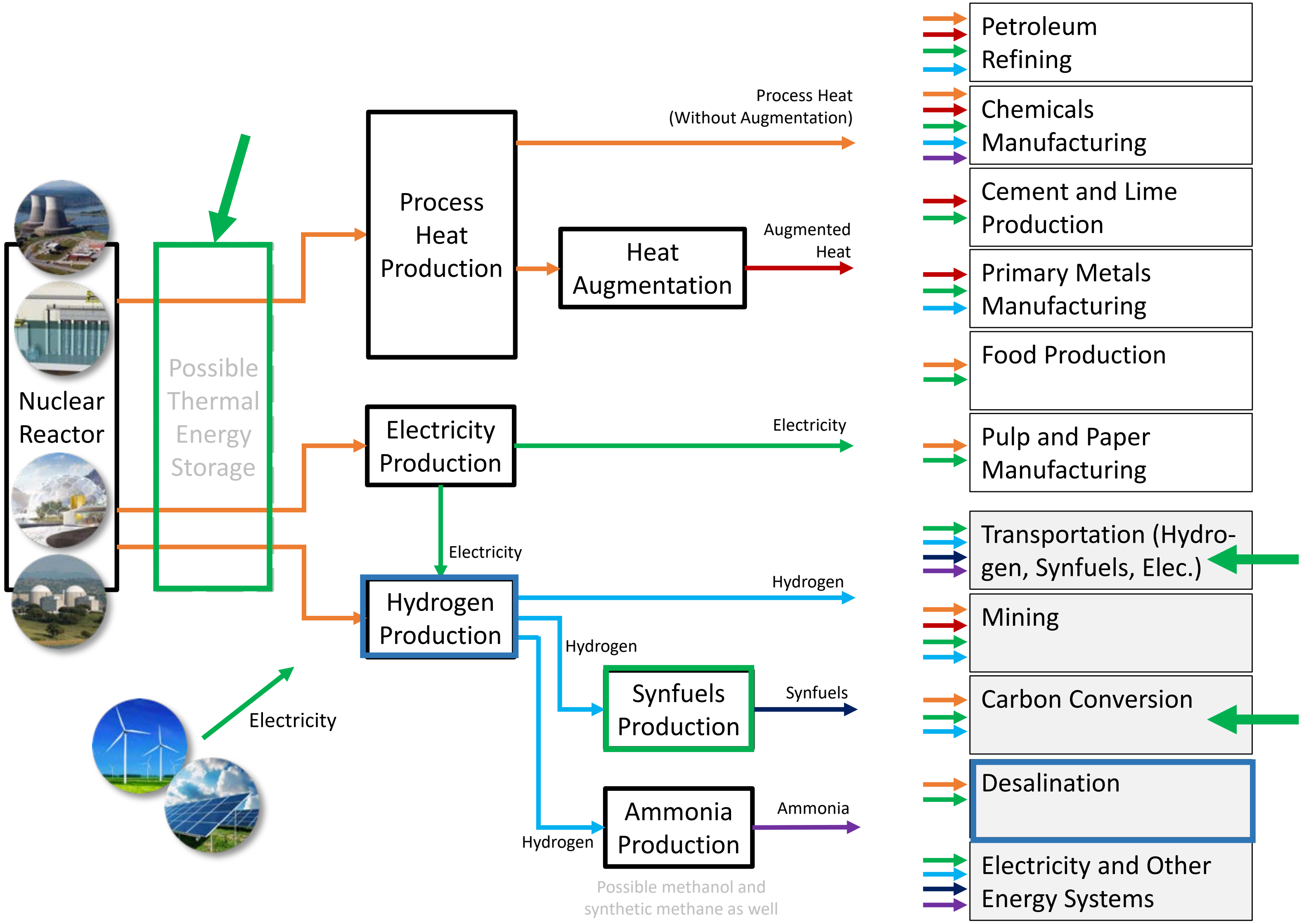
Summary of potential nuclear-driven IES opportunities



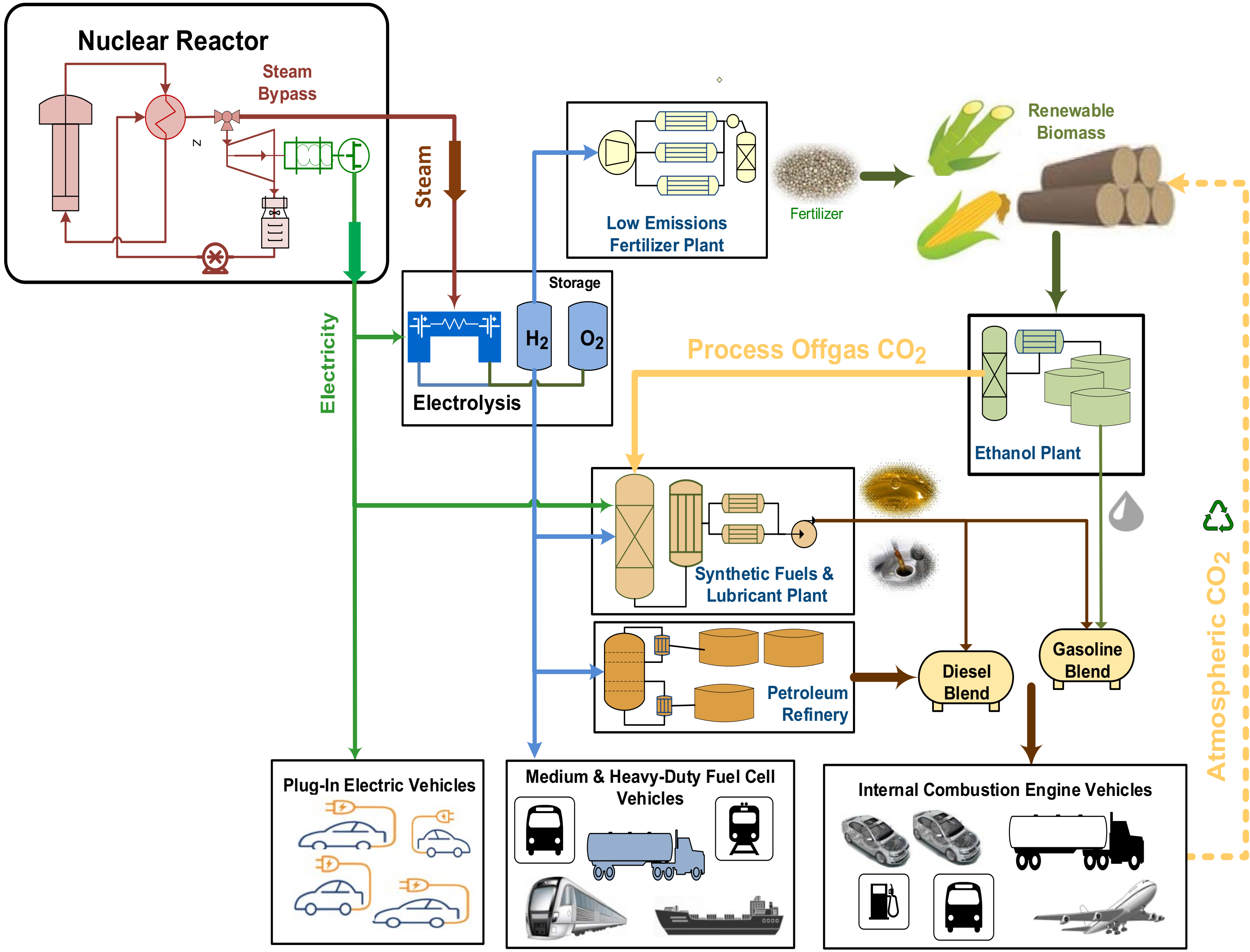
IES involve

- Thermal, electrical, and process intermediates integration
- More complex systems than co-generation, poly-generation, or combined heat and power
- May exploit the economics of grid-coordinated energy systems
- May provide grid services through demand response (import or export)

Reactor sizes and temperatures align with the needs of each application

Source: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, INL EXT-21-61413, Rev. 1, April 2021

Nuclear-hydrogen production and utilization



Motivation for hydrogen 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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Identifying the right IES configuration: Key steps in IES modeling and optimization

Step	Notes
1. Identify IES scenarios of interest	Renewable availability, reactor type, energy needs, e.g., flexible electricity supply, heat, hydrogen, desalination
2. Specify data inputs for each scenario	Societal energy demand, approximate plant capacities, refueling cycle, outages, lifetimes, maintenance schedules, etc. Include uncertainty ranges
3. Specify economic inputs for each scenario	Capex, opex, energy price time series, interest rates, etc. using region-specific data Include uncertainty ranges
4. Apply suite of analysis tools to evaluate each scenario	Optimal sizing of coupled systems relative to societal energy demand and other production resources, optimal dispatch of energy from each resource, operational constraints, ranges of potential capex and opex during plant lifetimes, etc.

Suite of IES modeling, analysis, and optimization tools

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Tools for technoeconomic assessment of IES configurations with workflow automation

- **FORCE**
  - Integrate physical plant modeling with technoeconomic optimization
- **HERON**: Holistic Energy Resource Optimization Network
  - Dispatch flexible systems and optimize technoeconomic analysis
- **RAVEN**: Risk Analysis Virtual ENvironment
  - Integrate physical input uncertainties and probabilistic time series data
- **HYBRID**: High fidelity, dynamic model repository
  - Simulation of physical plant processes
- **TEAL**: Tool for Economic AnaLysis
  - Integrate economic input uncertainties and calculate financial metrics
- **FARM**: Feasible Actuator Range Modifier
  - Supervisory control

See https://ies.inl.gov/SitePages/System_Simulation.aspx for more information and to access open source tools. Training opportunity for FORCE, March 17, 18, 23, 24 (12 hours) – see flyer for details.

Framework for Optimization of ResourCes and Economics (FORCE)

HERON
- Technoeconomic Analysis
- Component Sizing Optimization
- Dispatch Optimization

RAVEN
- Stochastic Analysis
- Synthetic Histories

HYBRID
- Transient Modeling
- Experiment Validation

TEAL
- Economic Metrics
- Cash Flows

FARM
- Process Analysis
- AI Training, Control

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Plant- and region-specific case analyses: Net Present Value (NPV) optimization

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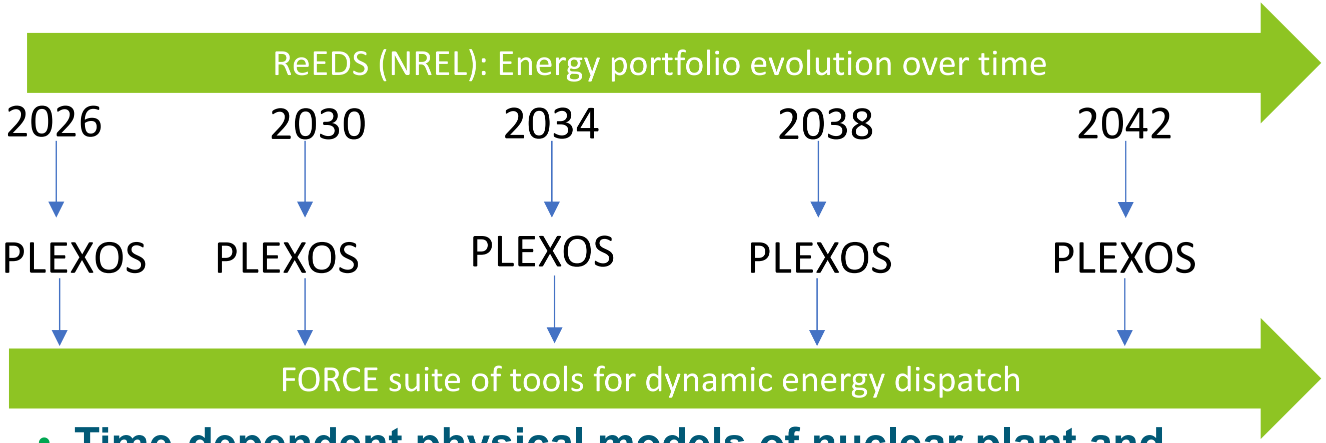
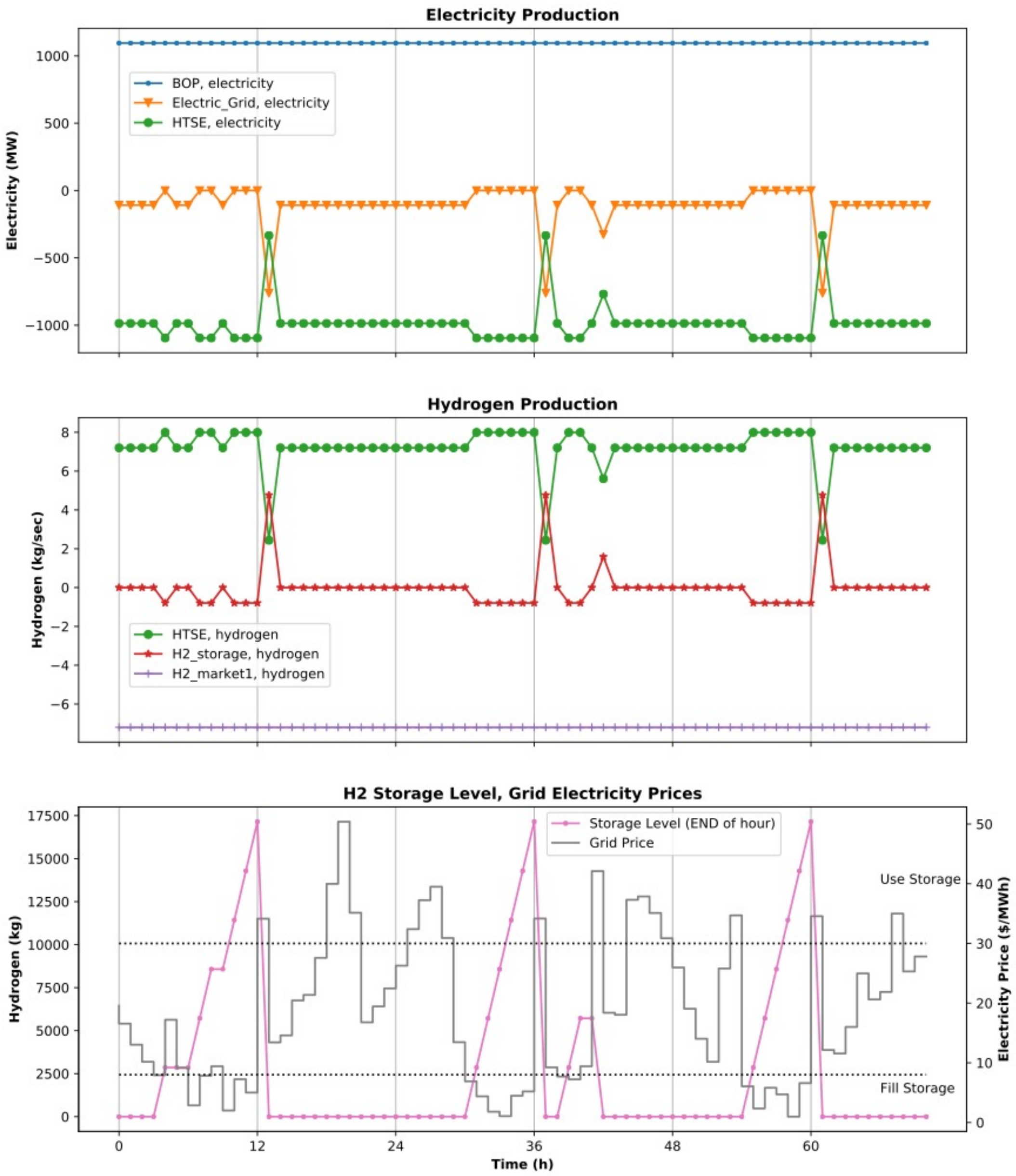
- **Method to generate synthetic data for future grid pricing**
  - National Renewable Energy Lab (NREL): ReEDs and PLEXOS used for capacity expansion and discrete time step grid pricing
  - INL: FORCE tools used to generate continuous, hourly grid price data; includes ancillary product (e.g., H_2) markets



- **Time-dependent physical models of nuclear plant and hydrogen production systems**
  - Dispatch heat and electricity between grid and hydrogen production to optimize revenue
  - Optimized hydrogen plant size and storage capacity based on discounted cash flow economics; ensures 24/7 availability of hydrogen to markets
  - Applied operational constraints to all subsystems

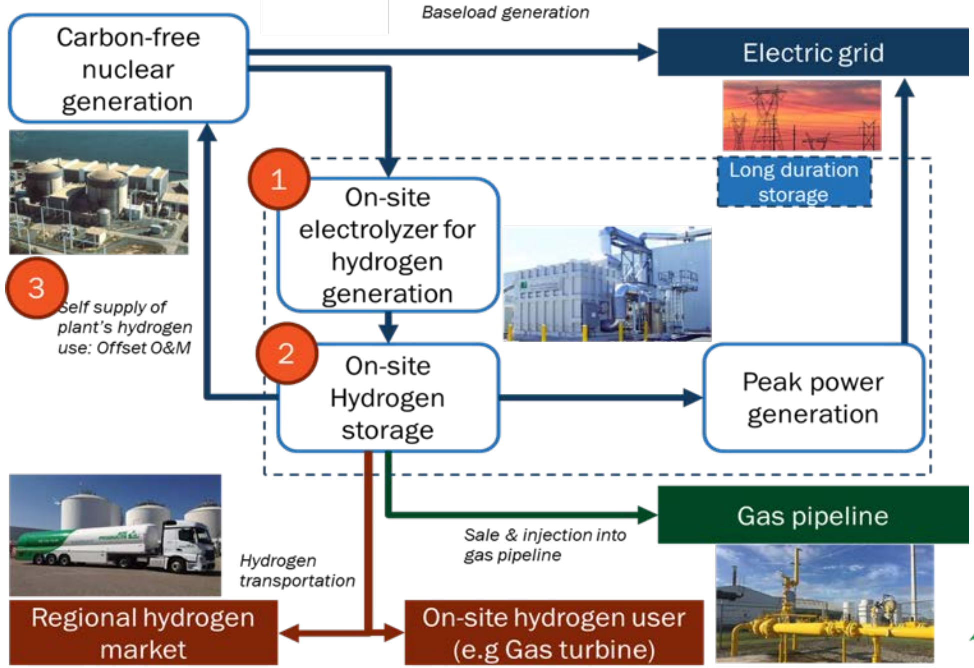


Nuclear-H_2 production demonstration projects: Constellation

- **Constellation (previously Exelon): Nine-Mile Point NPP, New York State**
  - Low Temperature Electrolysis (LTE)/PEM, 1 MWe
  - Vendor — nel hydrogen
  - Using "house load" power
  - PEM skid testing is underway at NREL
  - H_2 production ~October 2022

Nine Mile Point Nuclear Power Plant LTE/PEM (nel hydrogen)

Analysis Report: *Evaluation of Hydrogen Production for a Light Water Reactor in the Midwest*



	Key Milestones & Deliverables
Year 1 (BP1)	• Completed site selection and 30% engineering design • Completed procurement specifications for equipment and issued Requests for Proposals • Completed initial environmental review • Completed preliminary regulatory review • Developed BP2 estimate and schedule • Preformed Business Case Analysis
Year 2 (BP2)	• 100% engineering design, decision to install • Complete manufacture, test of electrolyzer.
Year 3 (BP2)	• Start of steady state operation of electrolyzer • Simulation of scale-up electrolyzer operation • Demonstration of dynamic operation on site

Exelon. H2@Scale U.S. Department of Energy LWRS IES Integrated Energy Systems

Tri-utility consortium to advance nuclear-H_2 demonstration

Phase 1
- Install LTE skid **[Energy Harbor]**
- Techno-economic assessments **[Xcel Energy, APS]**

Phase 2
- Install HTE skid **[Xcel Energy]**
- Complete design for Reversible HTE skid **[APS]**

Phase 3
- Large-scale LTE, mix H_2 with natural gas in turbine, syngas pilot **[APS]**

Phase 4
- Expansions on Phase 2 work, H_2 storage, industrial integration, etc. **[location TBD]**

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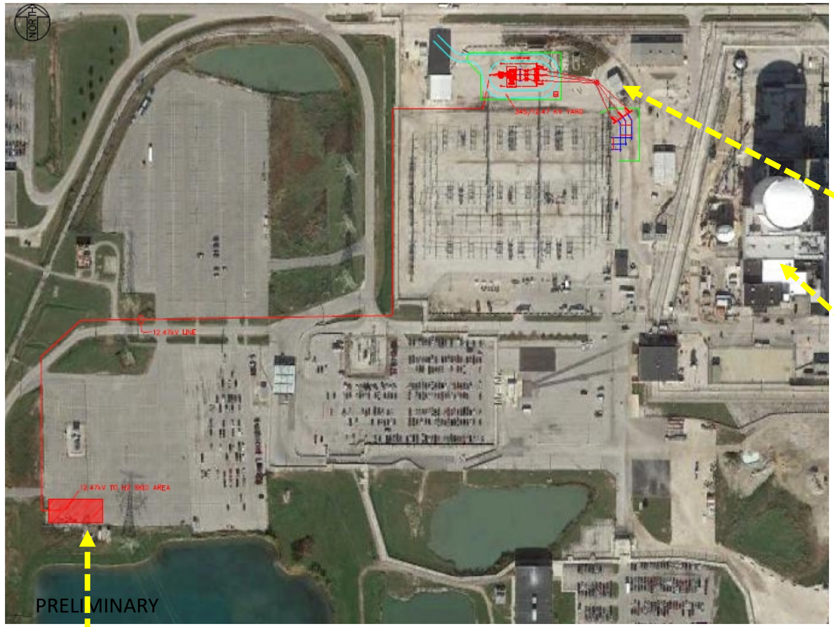
Nuclear-H_2 production demonstration projects: Energy Harbor

- **Energy Harbor: Davis-Besse NPP, Ohio**
  - 3-utility consortium, phased project
  - LTE/PEM, 1-2 MWe
  - LTE vendor currently being selected
  - 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

Analysis Report: Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest



Davis-Besse Nuclear Power Plant LTE-PEM Vendor

energy harbor

Xcel Energy

aps

H2@Scale U.S. Department of Energy

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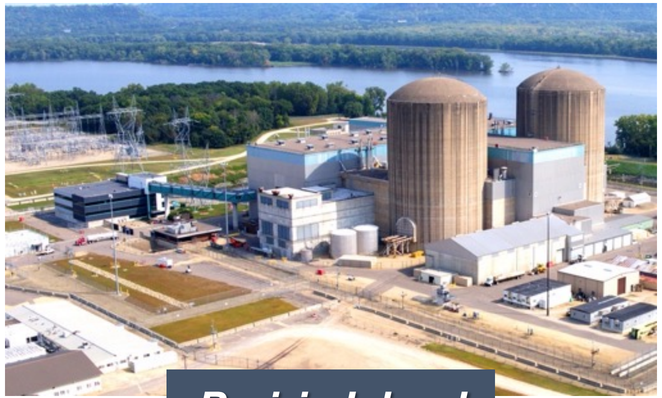
Nuclear-H_2 production demonstration projects: Xcel Energy

- **Xcel Energy**
  - High Temperature Electrolysis/SOEC Vendor 1
  - 150 kWe HTE for 90 kg H_2/day (projected)
  - Small amount of steam extraction
  - Tie into plant thermal line engineering is being finalized
  - Engineering design complete Q4 2022
  - Installation and testing complete Q1 2024

Thermal & Electrical Integration at an Xcel Energy Nuclear Plant HTE/Vendor TBD



Prairie Island

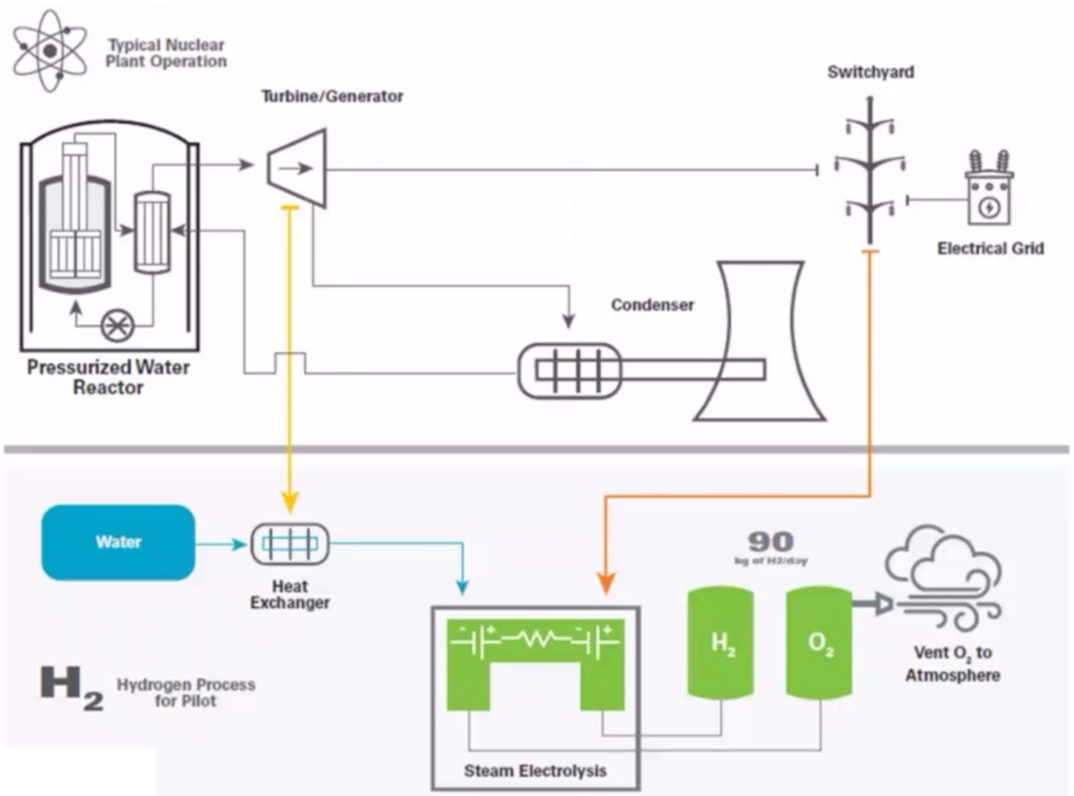


Figure courtesy Xcel Energy

Nuclear-H_2 production demonstration projects: APS/PNW Hydrogen

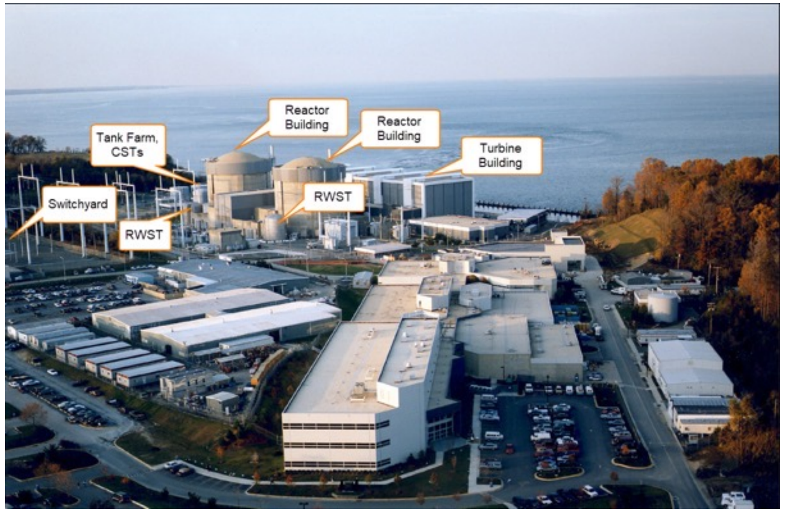
- **Arizona Public Service, PNW Hydrogen: Palo Verde Generating Station (PVGS)**
  - Larger scale hydrogen production, 15-20 MWe
  - ~6-8 tons H_2/day, with H_2 storage
  - Colocate H_2 production at the site of use, natural gas peaking plant (~80 miles from PVGS)
  - H_2 to gas peaking turbines
    - Goal: 50% H_2 / 50% NG
  - Award announced Oct 2021
  - Request for proposal in preparation for hydrogen production system, infrastructure (~18-24 months lead time)
  - Service expected in early 2024

Hydrogen Production for Combustion and Synthetic Fuels

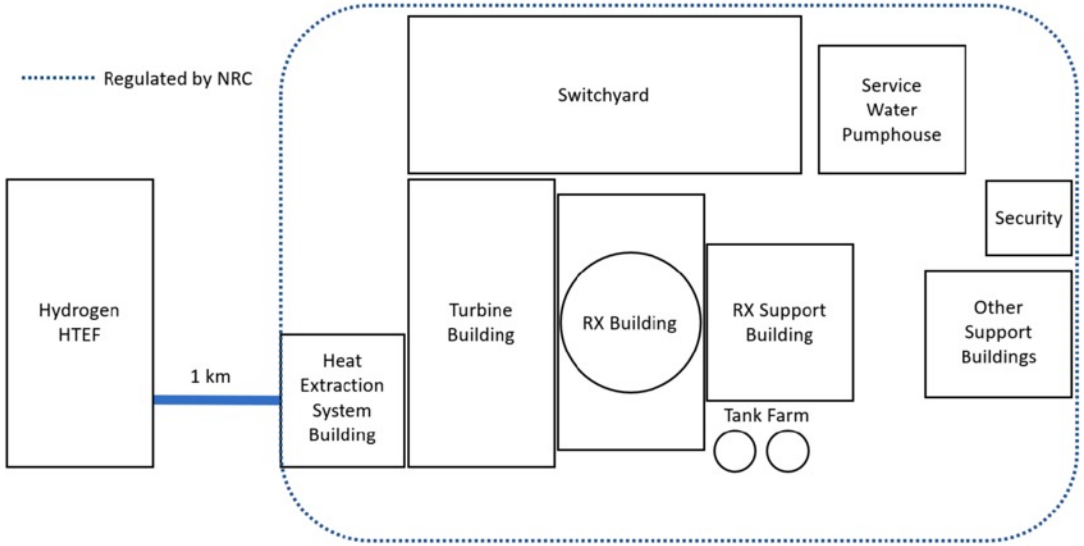
Evaluation of nuclear-H_2 safety hazards

- Top hazards identified
  - Internal to NPP
    - Steam line break in the heat extraction system
    - LOOP frequency increase from HTE facility accident

      LOOP: Loss of switchyard components means a loss-of-offsite-power
  - External to NPP
    - HTE facility hydrogen leak
    - HTE facility hydrogen detonation
- Primary Probabilistic Risk Assessment (PRA) effects on mitigation
  - Unisolated large steam leak in the HES scenario

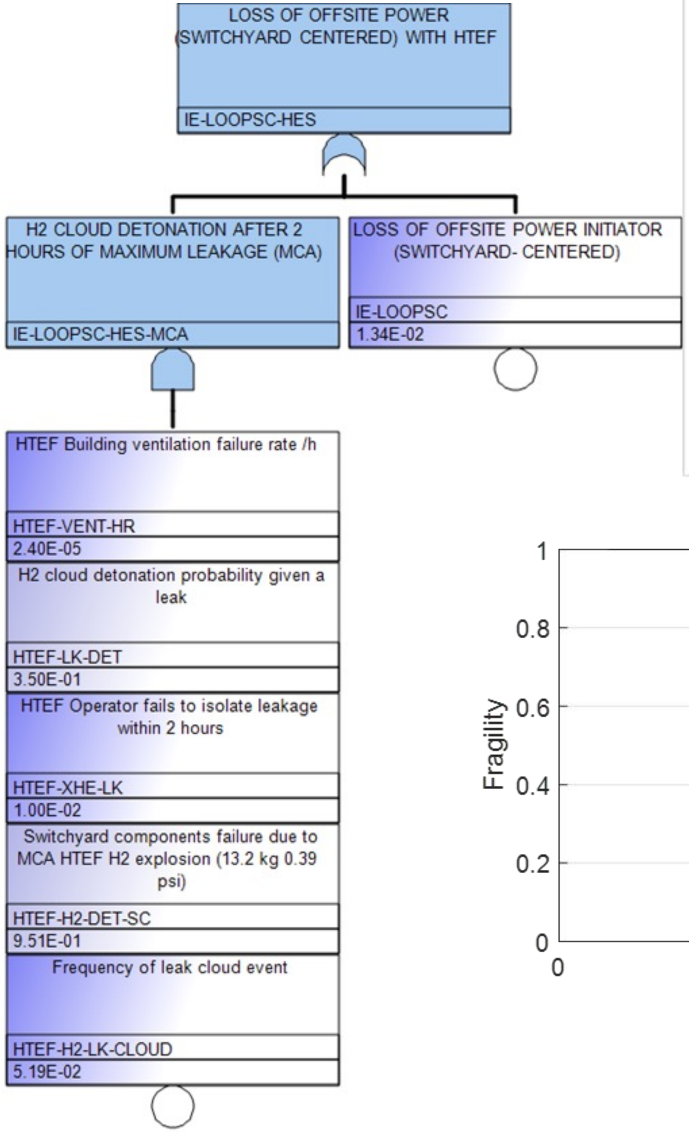


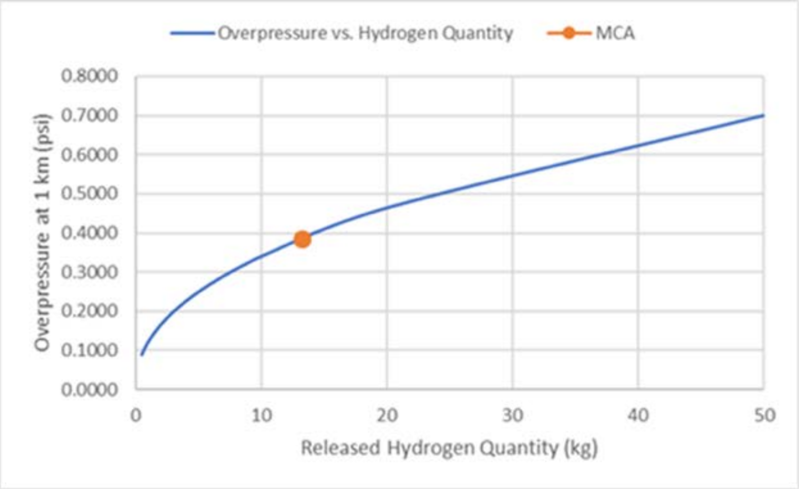
NRC jurisdictional boundary for LWR servicing an HTE facility

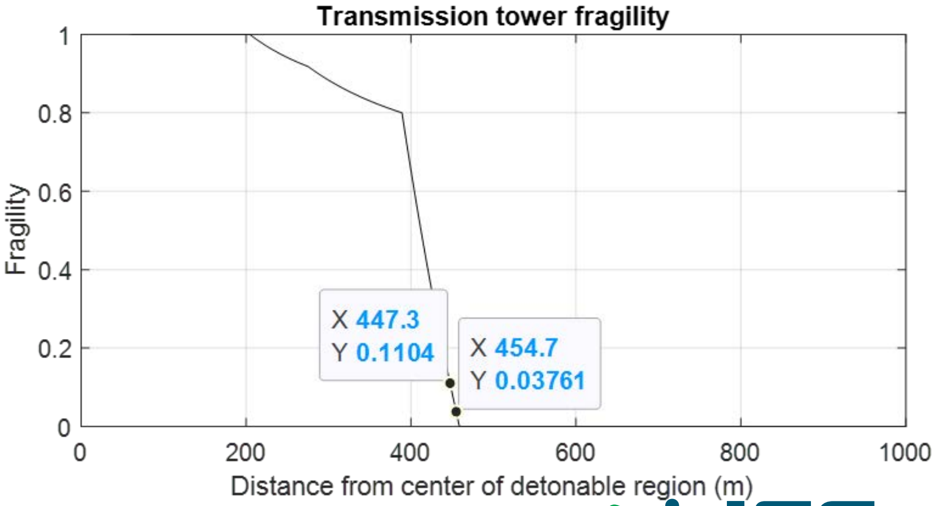


Preliminary PRA – Nuclear Plant Connected to Commercial Hydrogen Plant

- Completed hazard analysis and preliminary PRA for both a pressurized water (PWR) and boiling water (BWR) reactor
- Considered consequences of hydrogen leaks and explosions and thermal supply system ruptures
- Significant outcomes of the study
  - Provides a roadmap for site-specific PRA support of licensing approval of a LWR coupled to a hydrogen production facility
  - Results show strong support for licensing the modification using 10 CFR 50.59 and risk informed decision support through RG-1.174
  - Indicates minimal safe operational distance based on transmission tower fragility is achieved at 0.5 km for the bounding accident: loss of offsite power at the switchyard







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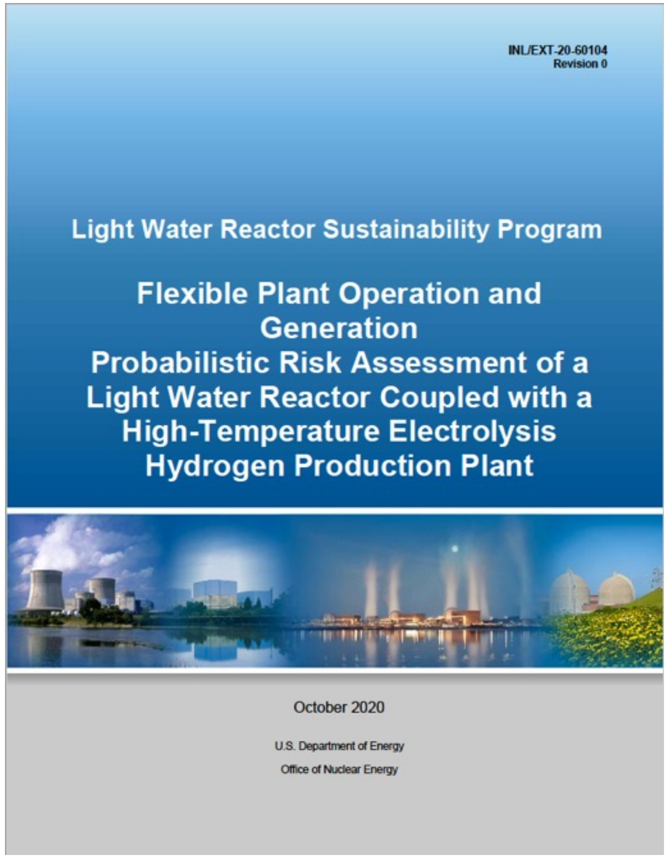
Summary conclusions: PRA for thermal integration of steam electrolysis

- The LWRS generic probabilistic risk assessment (PRA) investigation into licensing considerations concluded that, given the established assumptions:
  - 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
- Other insights
  - The individual site NPP and geographical features can affect the results of the generic PRA positively or negatively
  - The generic PRAs presented in the study are examples for official site studies for use in licensing

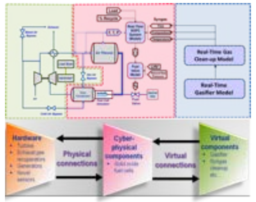
Kurt Vedros, INL, Kurt.Vedros@inl.gov
Robby Christian, INL, Robby.Christian@inl.gov

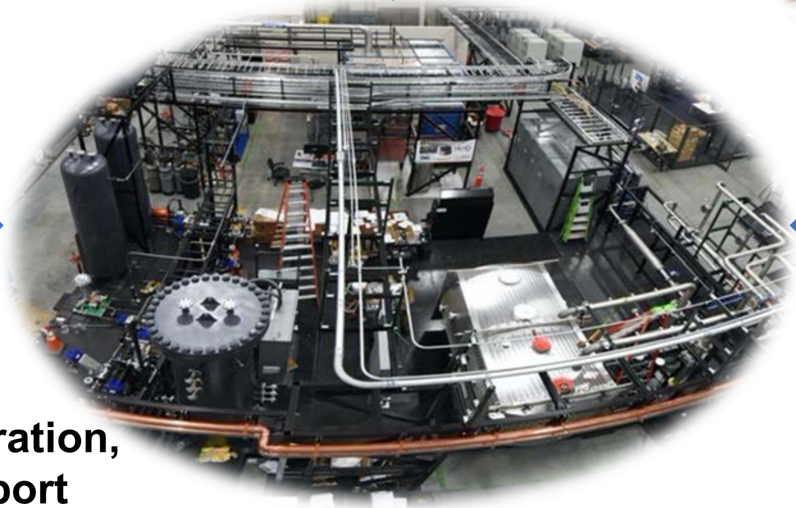
INL/EXT-20-60104, Flexible Plant Operation and Generation Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant
OSTI link: https://www.osti.gov/biblio/1691486



Demonstration of integrated energy systems (IES) (electrically heated)

Human-in-the-Loop Operations





Power Hardware and Grid-in-the-Loop, Microgrid

Realtime connections to remote facilities enhance IES demonstration capabilities

Thermal Energy Generation, Storage, and Transport (Microreactor Emulation)

Hydrogen and other Flexible Industrial Processes

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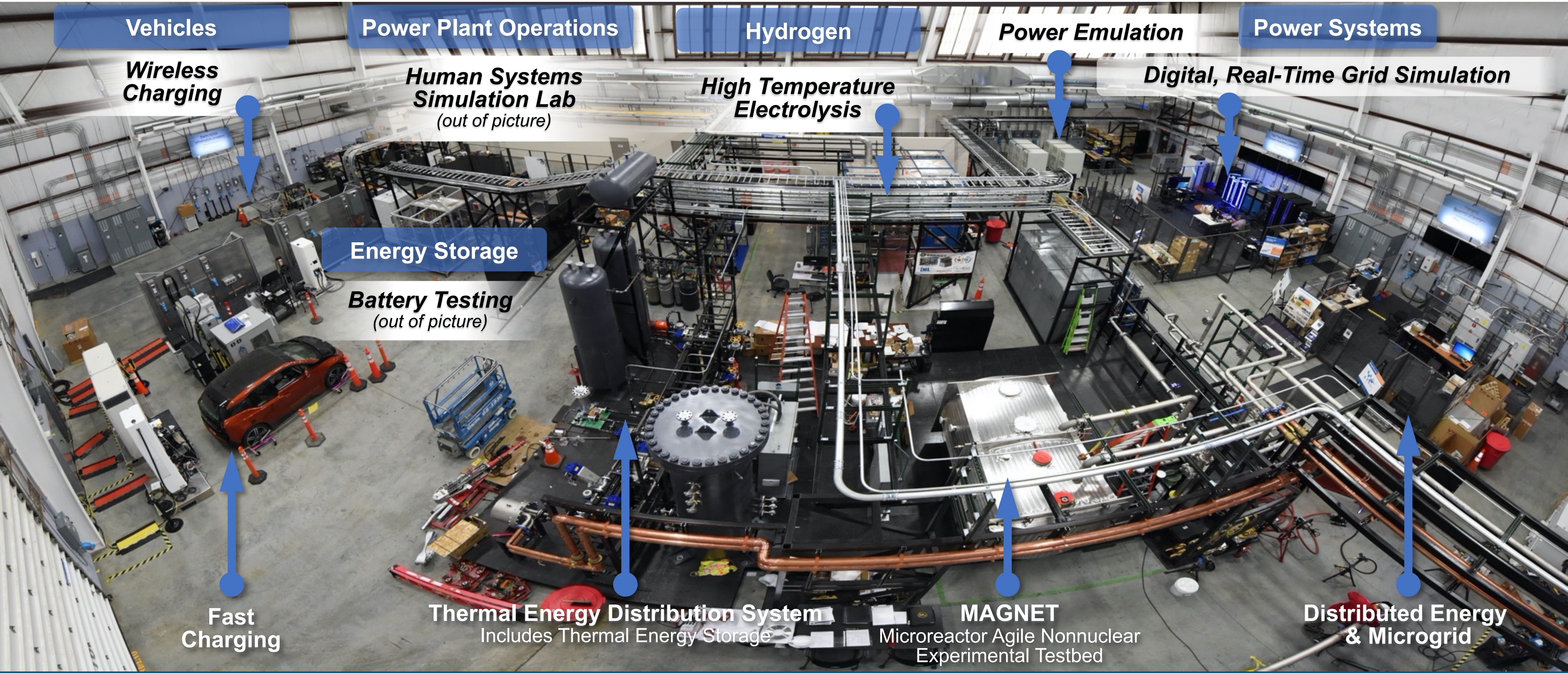
Dynamic Energy Transport and Integration Laboratory (DETAIL)



Progress in 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 hydrogen 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 through
  - Leveraging automation to augment any additional operator tasking
  - Monitoring energy dispatch to a second user

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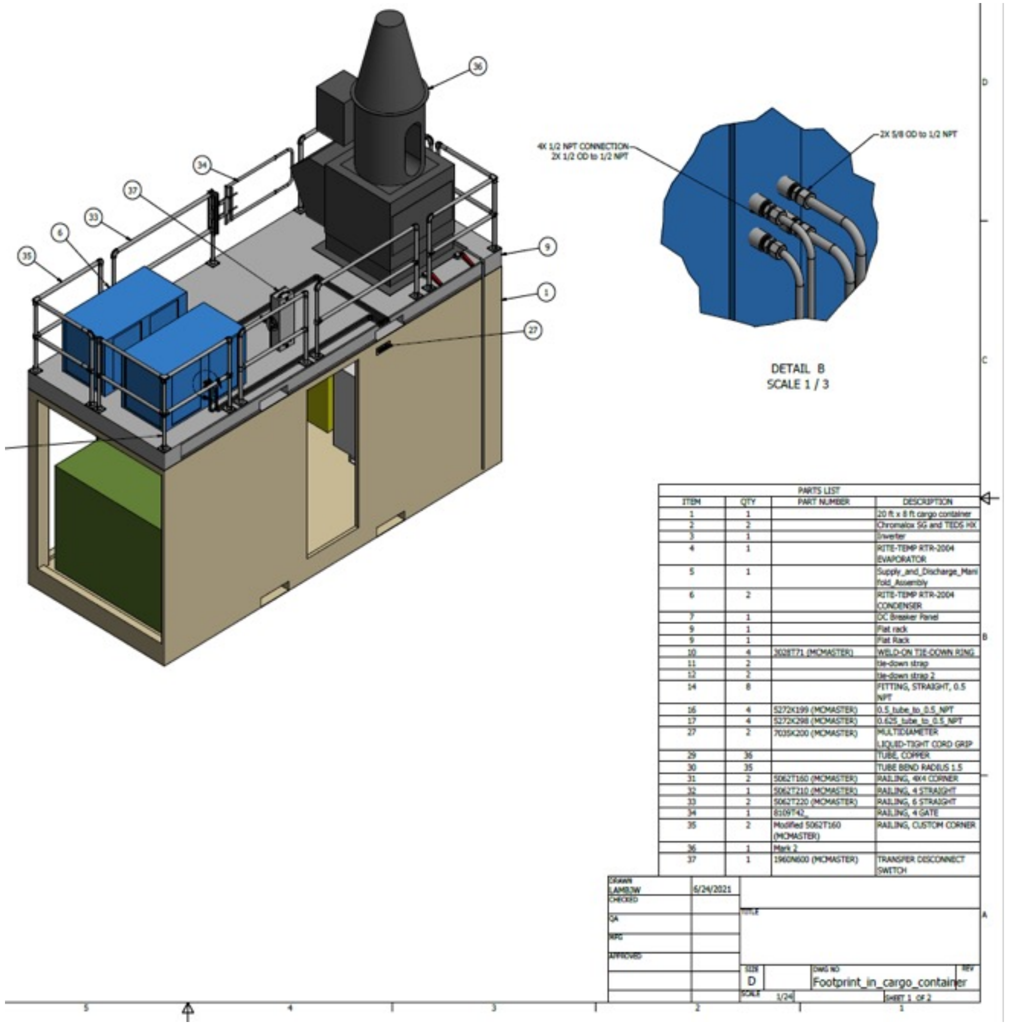
Hydrogen system design and integration at INL

System integration in the INL Energy Systems Laboratory highbay will accommodate concurrent operation of multiple H_2 demonstrations

- 100-kW Bloom Energy SOEC system
  - Installed Sept. 2021, initial operation January 2022)
  - Planned operation through Sept. 2022 (~5,000 hrs)
- 250-kW FuelCell Energy SOEC system
  - Expected installation May 2022 (DOE-NE funded/cost shared)
  - Planned operation through Sept. 2023 (>5,000 hrs)
- 50-kW SOEC system funded by DOE-EERE HFTO
  - Planned operation through 2023 with stacks from multiple vendors
- 30-kW electrolysis mode/10-kW fuel cell mode operation
  - Basic build of system funded by DOE-EERE HFTO
  - Project funds customized parts for reversible operation, such as heat exchangers, bypass lines, stack connections



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Summary of codes for hydrogen system testing

- ASME B31 “Pressure Piping”
  - B31.1 “Power Piping”, B31.3 “Process Piping” & B31.16 “Hydrogen Piping”
  - Provide requirements for piping systems design, inspection, maintenance to prevent process failure
- NFPA 2 “Hydrogen Technologies”
  - Hydrogen equipment enclosures, including quantities, separation distances, ventilation, sprinklers, exhaust, etc.
- NFPA 70 “National Electric Code”
  - Classification: Areas in which hydrogen may be present due to abnormal events are classified as Class 1, Division 2. Recommended extent of classification is 15 ft from source of hydrogen from typical processing plants
- NFPA 497 “Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas”
  - Guidelines for determining extent of classification area. Recommended extent is 15 ft from source of of hydrogen for typical processing plants volumes

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Summary of of codes for hydrogen system testing

- NFPA 86 “Ovens and Furnaces”
  - Requirements for industrial heat processing equipment. Requirements for low-oxygen ovens, including maximum allowable oxygen concentrations, are somewhat applicable, although hydrogen production is not directly similar to conditions that exist in typical Class A furnaces (furnaces that operate at approximately atmospheric pressure and have the potential for explosion or fire hazards.
- NFPA 853 “Installation of Stationary Fuel Cell Power Systems”
  - Separation distances, valving and shut-off requirements, hydrogen exhaust
- CGA G-5.5-2021 “Standard Hydrogen Vent Systems”
- CGA S-1. 1-1.3 “Pressure Relief Device Design”

Design capability

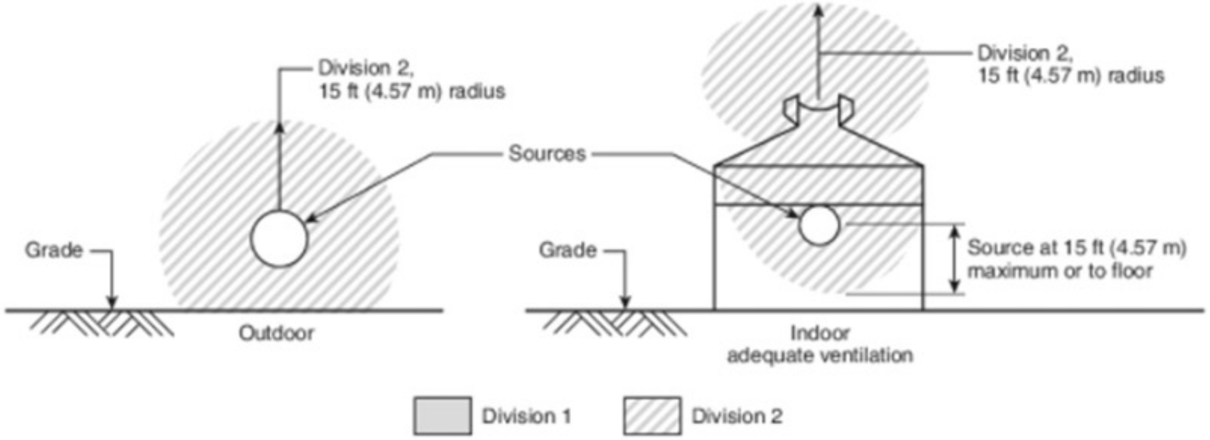


FIGURE 5.10.8(b) Gaseous Hydrogen Storage Located Outdoors or Indoors in an Adequately Ventilated Building. This diagram applies to gaseous hydrogen only.

NFPA 497: Class 1, Division 2 extends for areas in which hydrogen may be present due to system leaks

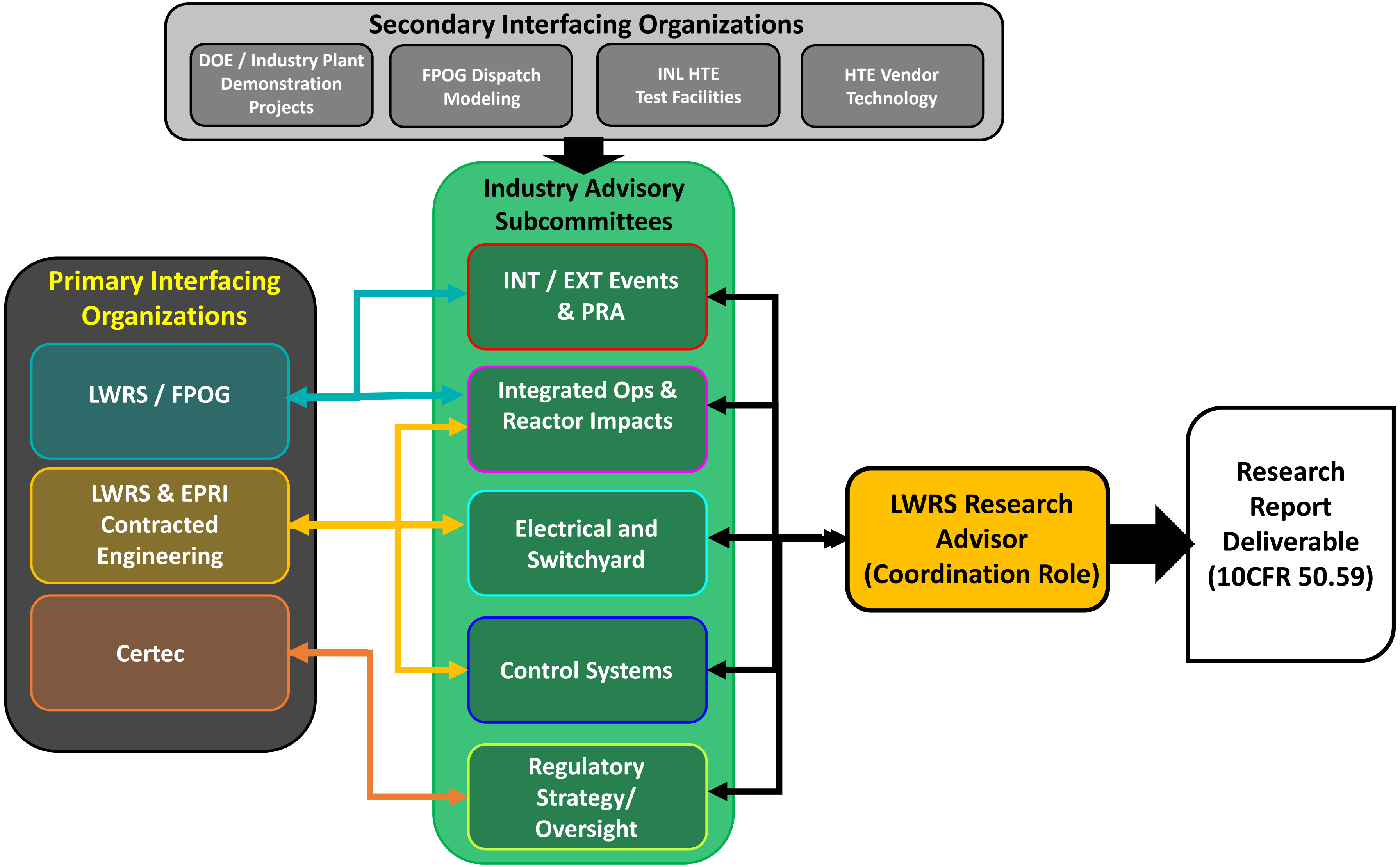
NFPA 2: H2 Equipment Enclosure (HEE) Requirements for volumes > 200 ft^3

Δ Table 7.1.22.9.1 Protection Features Based on Use

HEE or a compartment in an HEE contains:	GH_2 storage	GH_2 storage	Hydrogen generation, compression and/or processing equipment	Support equipment room (in an HEE)
Enclosure Volume:	<200 ft^3	≥200 ft^3	Not limited	Not limited
Contains or is connected to a source of hydrogen:	Yes	Yes	Yes	No
Automatic isolation from GH_2 storage	Not required	Not required	Required	Not applicable
Ventilation	Natural or mechanical	Natural or mechanical	Mechanical	No additional requirement
Storage compartment separation	Not applicable	Not applicable	Required	Required
Electrical equipment	Per *NFPA 70*, Chapter 5	Per *NFPA 70*, Chapter 5	Per *NFPA 70*, Chapter 5	Unclassified
Bonding/grounding	Required	Required	Required	Per *NFPA 70*
Explosion control	Not required	Required	Required	Not required
Detection	Loss of ventilation*	GH_2, Loss of ventilation*	GH_2, Fire and Loss of ventilation	GH_2 if necessary to meet the requirements of 7.1.23.10.3.1

*Where mechanical ventilation is provided

Hydrogen Regulator Research & Review Group (H3RG)



Flexible Plant Operations & Generation Pathway (FPOG)

INL Leads:

Jason Remer
Jack Cadogan

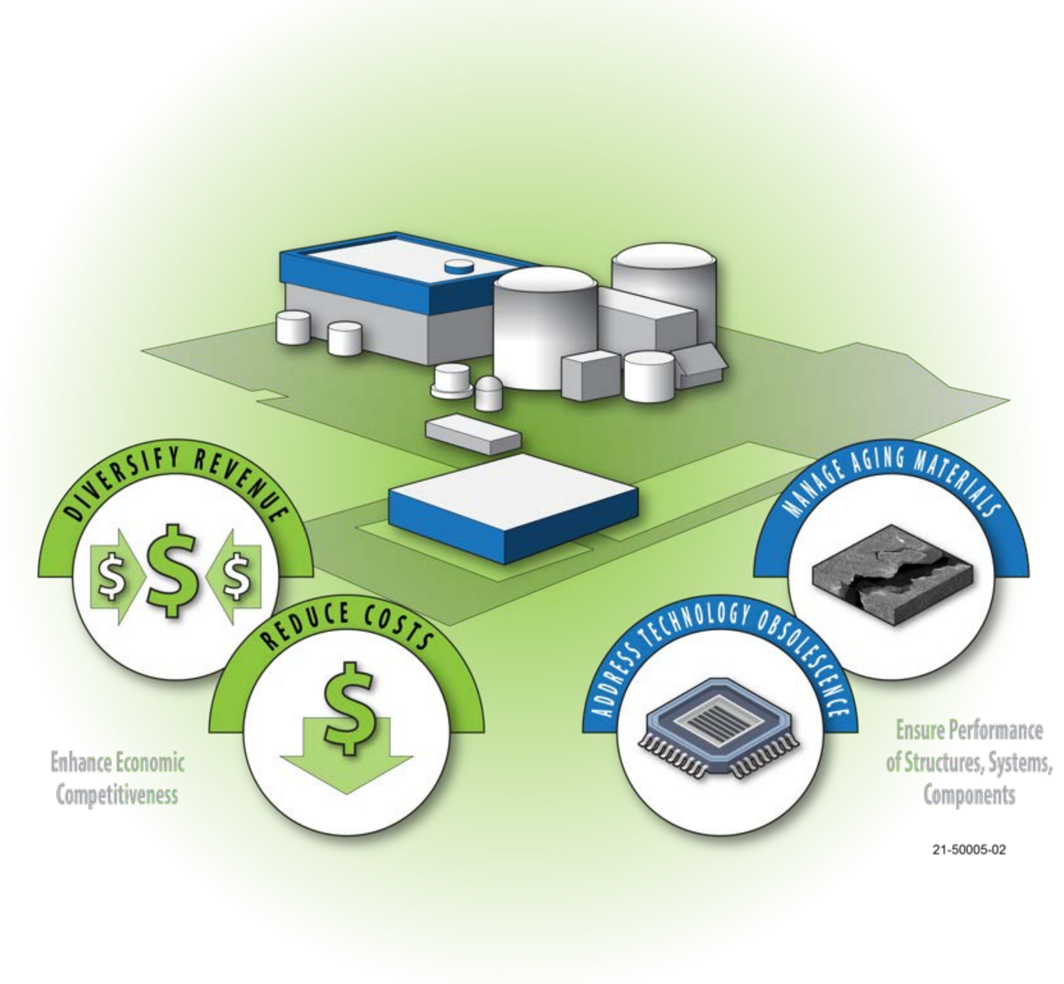
First H3RG meeting held in January

Purpose: H3RG Formation and Structured Approach

- Alignment on H3RG process and regulatory research deliverables on 50.59 evaluation of nuclear integrated hydrogen
- Leverage industry regulatory, engineering, and operations expertise
- Review and comment on lab-directed AE proposed licensing approaches
- Proposed high temperature electrolysis (HTE) areas requiring further licensing development
- Identify possible License Amendment triggers and solutions for large scale fully integrated HTE

Going Forward

- Hydrogen 101 Webinar February 17
- Monthly meetings of H3RG, focused subcommittee meeting(s)
- Report for first year outcomes anticipated August 2022



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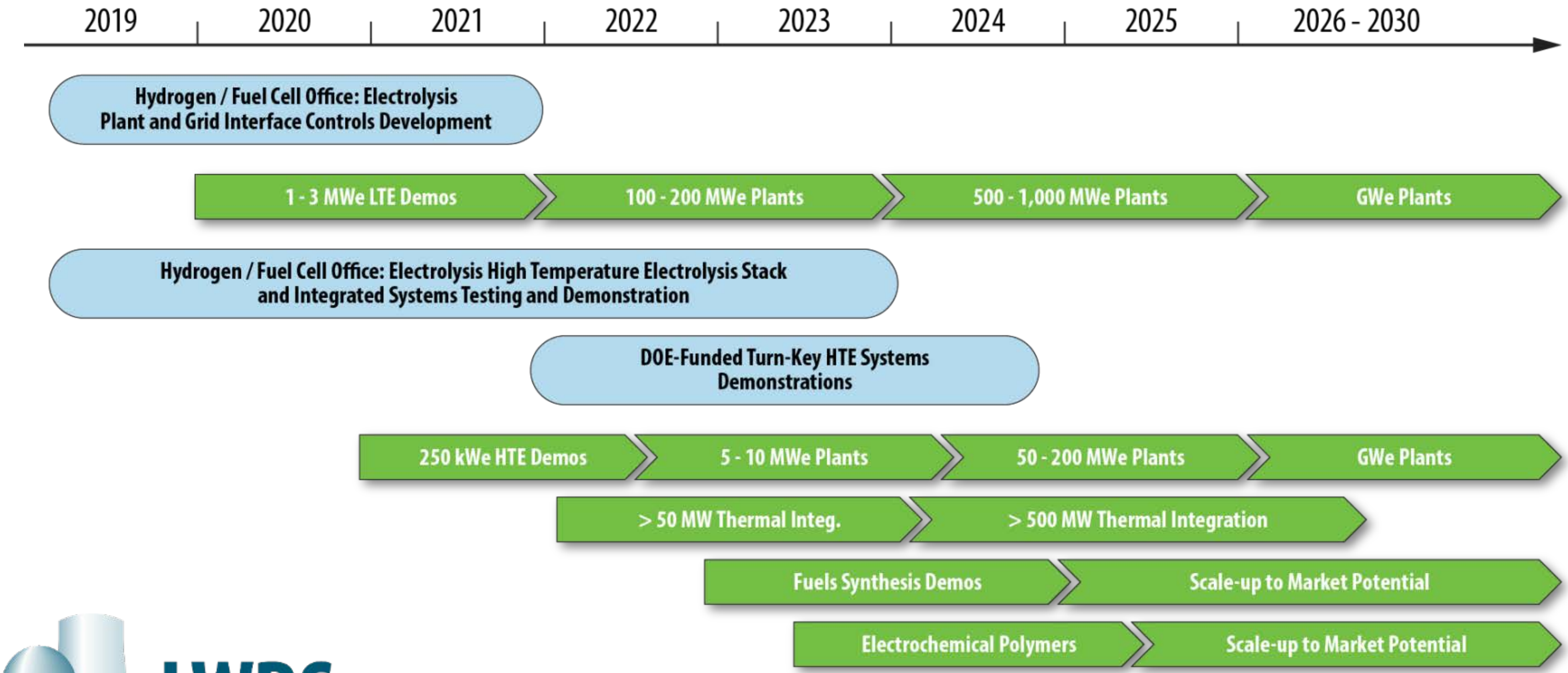
LWRS vision for building out H_2 production, 10-12 NPPs by 2030



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Transitioning to Advanced Reactor Applications

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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.

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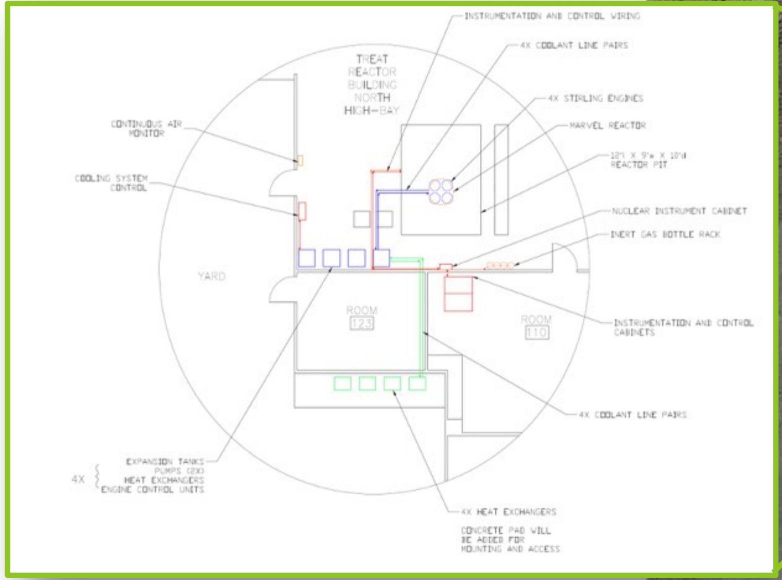
For more information on NRIC and to download resources, see https://nric.inl.gov/.

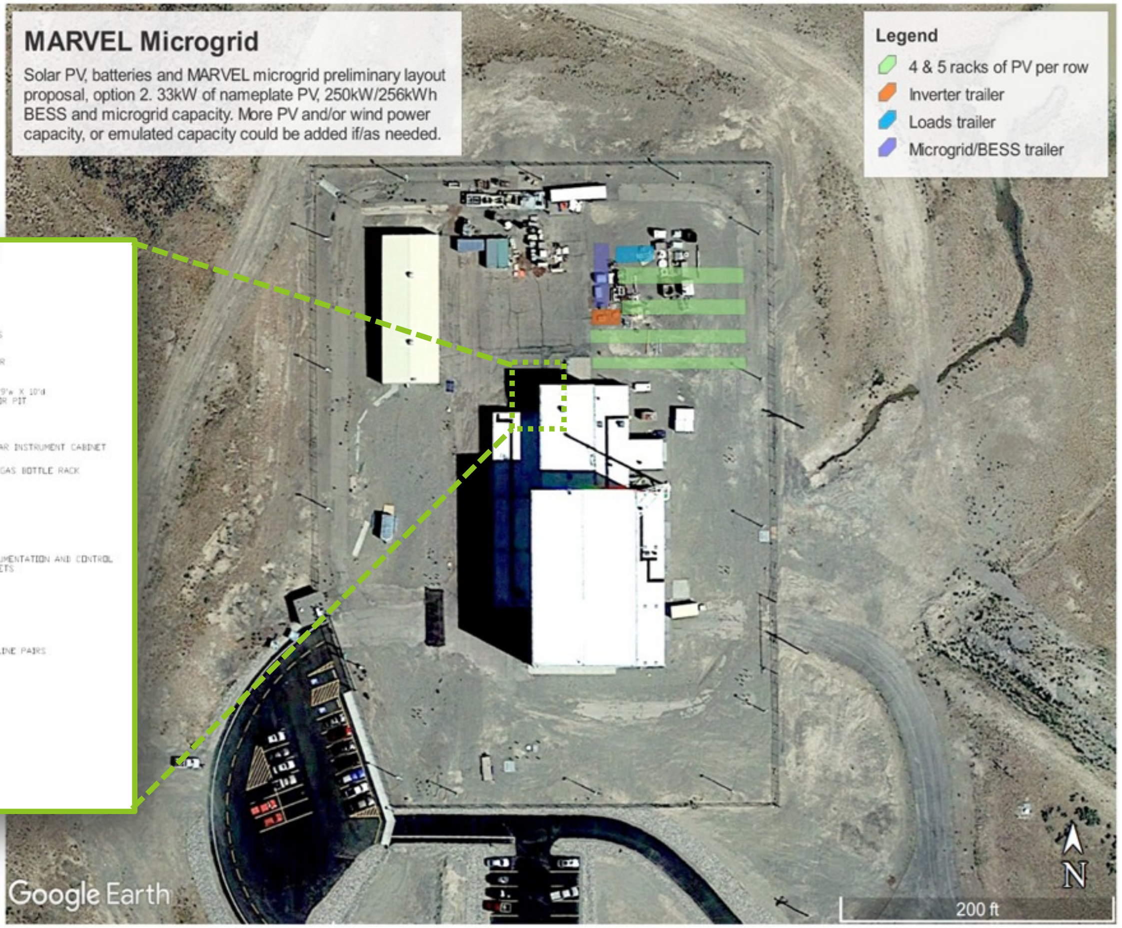
Integration of the MARVEL microreactor with a microgrid

Microreactor Applications Research Validation and Evaluation (MARVEL) Objective:

Operational reactor that produces <u>combined heat and power (CHP)</u> 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: Dec 2022

MARVEL Criticality: Dec 2023

Accelerating advanced reactor demonstration & deployment

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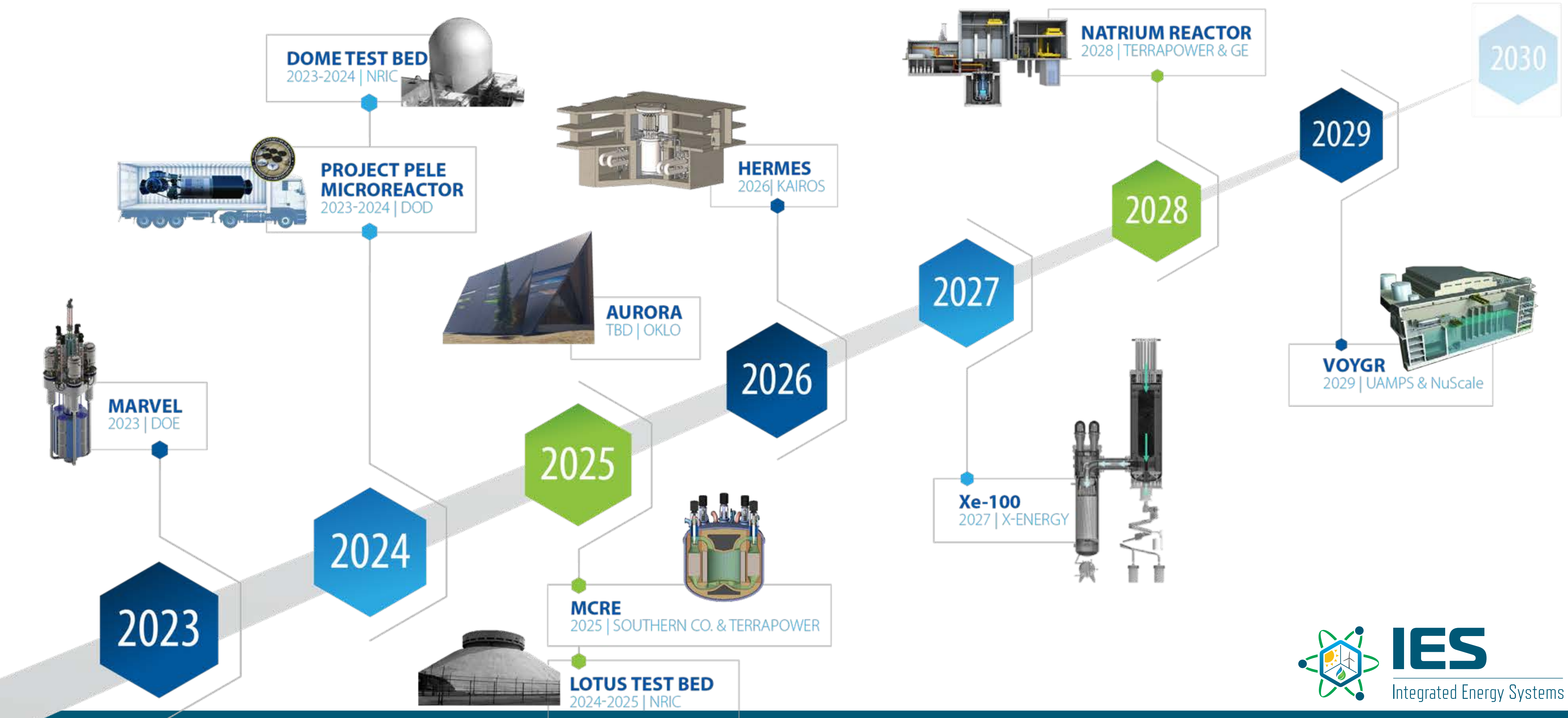

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Advanced reactor IES case studies (FY22)

- **Thermal energy storage:** Utilization of thermal energy storage to support electrical markets and/or industrial integration
- **Synthetic fuel production:** Nuclear heat and steam to produce hydrogen; then, as a feedstock, the hydrogen is used in conjunction with a CO2 source to produce various high value synthetic fuels via the Fischer-Tropsch process
- **Carbon conversion:** Nuclear heat and steam to convert coal, as a feedstock, into valuable products for a variety of carbon markets

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