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Non-Electric Applications of Generation IV Reactors: Accelerating Economy-Wide Decarbonization via Nuclear Energy

April 2022

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Non-Electric Applications of Generation IV Reactors

Accelerating Economy-Wide Decarbonization via Nuclear Energy

Dr. Shannon Bragg-Sitton

Idaho National Laboratory, USA

Chair, GIF Task Force on Non-Electric Applications of Nuclear Heat

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Meet the Presenter

Dr. Shannon Bragg-Sitton is the Director for the Integrated Energy & Storage Systems Division in the Energy & Environment Science & Technology Directorate at Idaho National Laboratory, which includes Power and Energy Systems, Energy Storage and Electric Transportation, and Hydrogen and Electrochemistry departments.

She also serves as the National Technical Director for the DOE Office of Nuclear Energy Integrated Energy Systems program.

Dr. Bragg-Sitton is currently serving as the Chair of the Gen-IV International Forum Task Force (TF) on Non-electric Applications of Nuclear Heat (NEaNH).

Email: Shannon.Bragg-Sitton@inl.gov

The bottom line up front

- Today, operating nuclear plants and nuclear new-build projects are mainly GWe-size units for electricity generation
- There is worldwide development of reactors that will be available at smaller scale (micro- and small modular reactors [SMRs]), with many being advanced, high temperature designs
- Ambitious goals have been set for economy-wide decarbonization – power grid, industry, and transportation

  → These goals are driving significant activity (and funding) around electrification and provision of heat and H_2—without emissions—to support energy demands

  → Dispatchable nuclear energy can be complementary to a grid with high variable renewable penetration, while simultaneously producing non-electric energy products

- Economics of advanced and SMRs are yet to be confirmed, but we must provide solid information on these paradigm shifting products and systems for industry adoption

Advanced nuclear technologies can deliver broader, more flexible services than electricity production only. Their high power density and dispatchability is a huge asset for decarbonization, especially in combination with variable renewable energy sources.

Future clean energy systems – transforming the energy paradigm

Nuclear Energy Generation

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

Other Energy Generation

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

Integrated energy systems leverage the contributions from nuclear fission beyond electricity

Biofuel

New chemical processes

Clean water

Industry

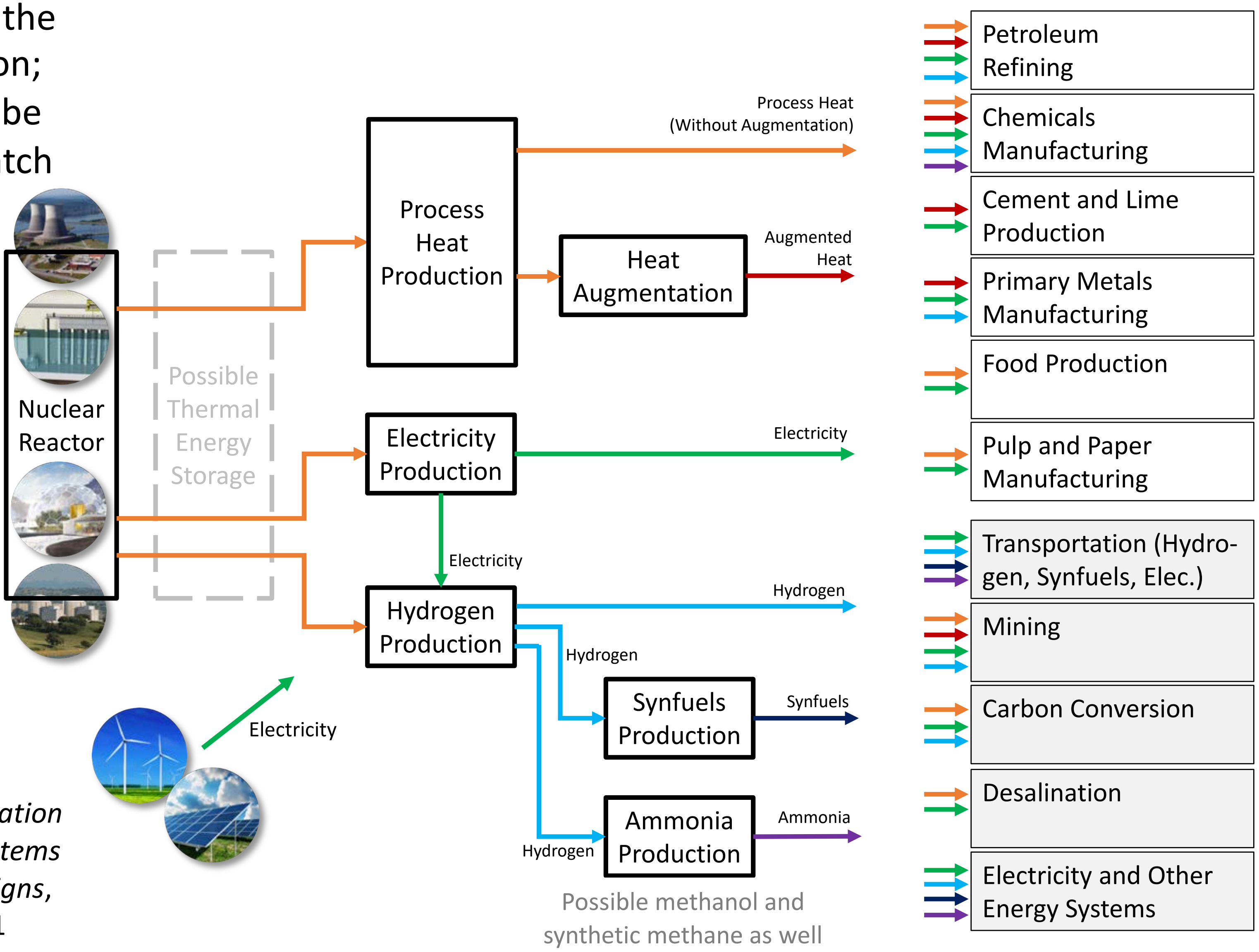
Electricity

Hydrogen for vehicles and industry

IES Integrated Energy Systems

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*, INL EXT-21-61413, Rev. 1, April 2021

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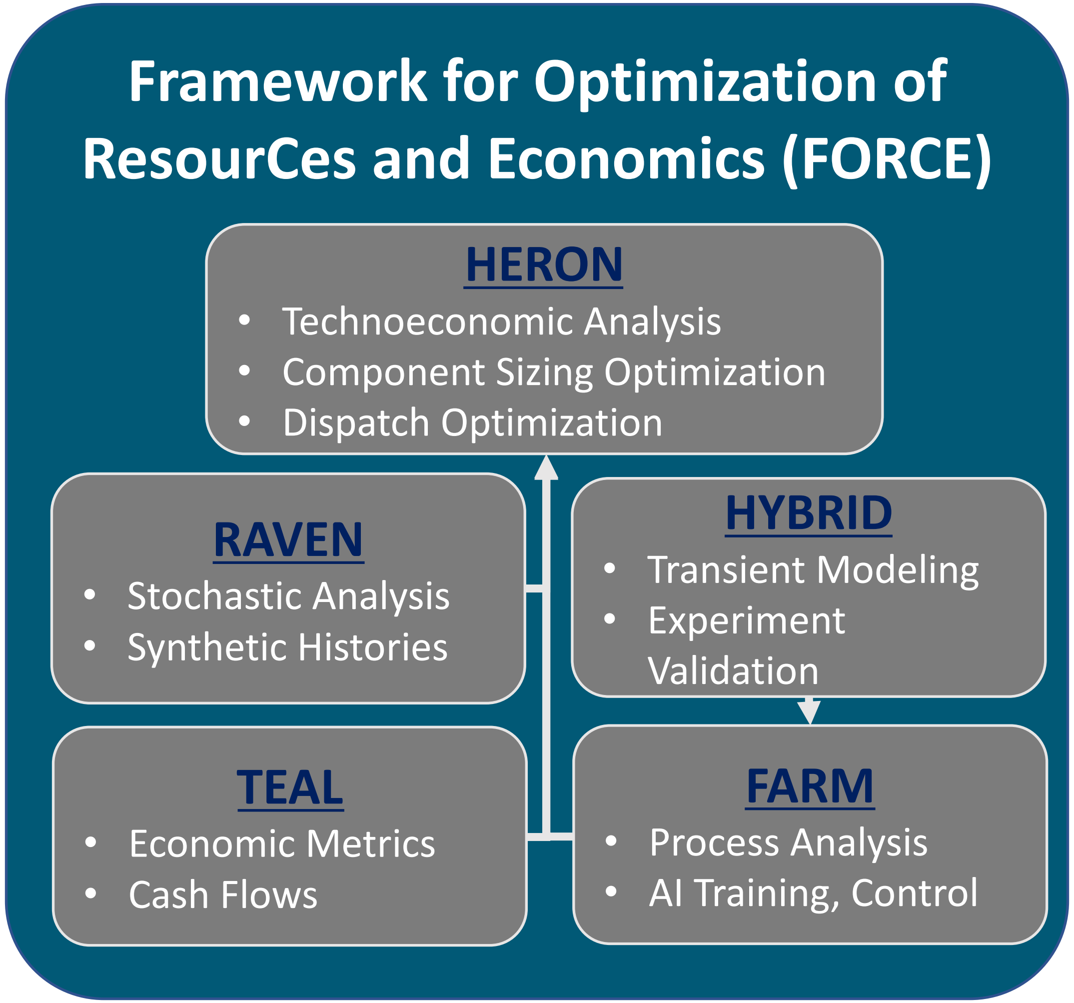
Integrated energy systems analysis and optimization

Technoeconomic Assessment

- Portfolio Optimization
- Dispatch Optimization
- Process Model Simulation
- Economic Analysis
- Supervisory Control
- Stochastic Analysis
- Workflow Automation



For more information and to access opensource tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.

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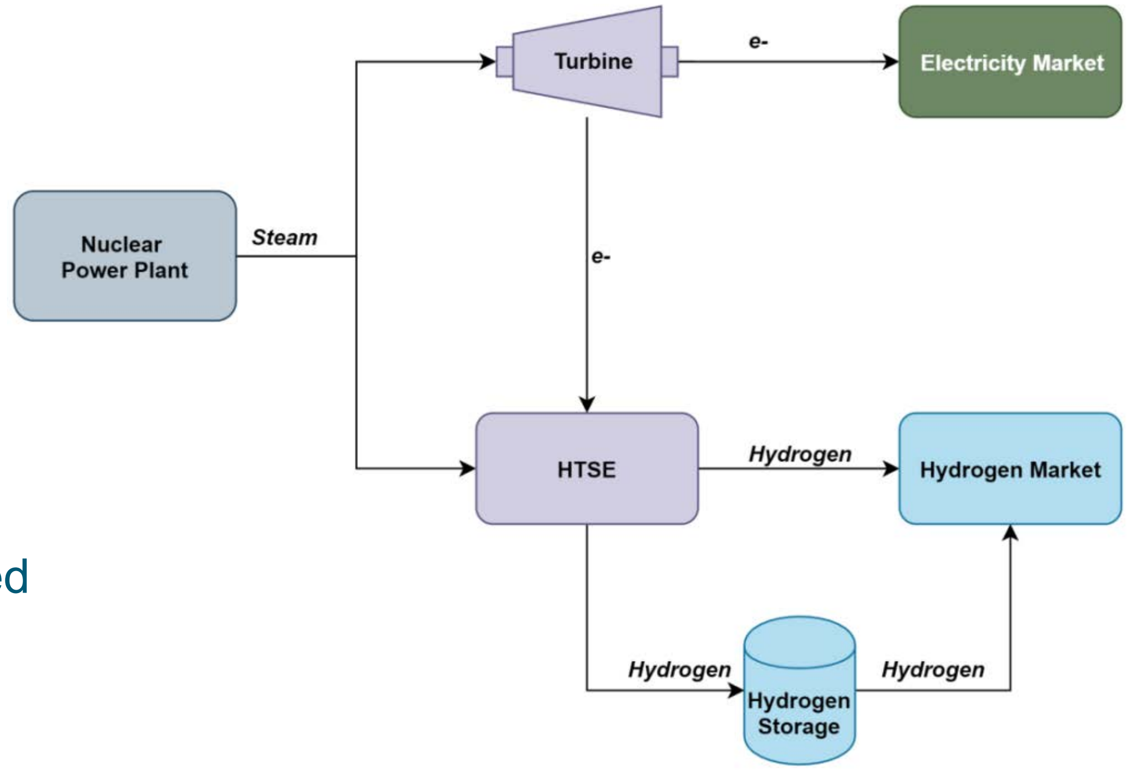
Example: Disruptive potential of nuclear produced H_2

- Collaboration between INL, ANL, NREL, Exelon, and Fuel Cell Energy
- **Goal:** Evaluate the potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity to enhance LWR economics
- **Approach:** Techno-economic analysis of HTSE process in selected operating modes and market conditions
  - Electricity only (business as usual)
  - Dynamic H_2 production (with H_2 storage to enable variable electricity and H_2 dispatch)
- **Assumptions**
  - HTSE does not thermally cycle
  - Dedicated H_2 transport pipelines
  - No subsidies for avoided emissions
  - Ancillary services market not considered
  - H_2 demand must always be met



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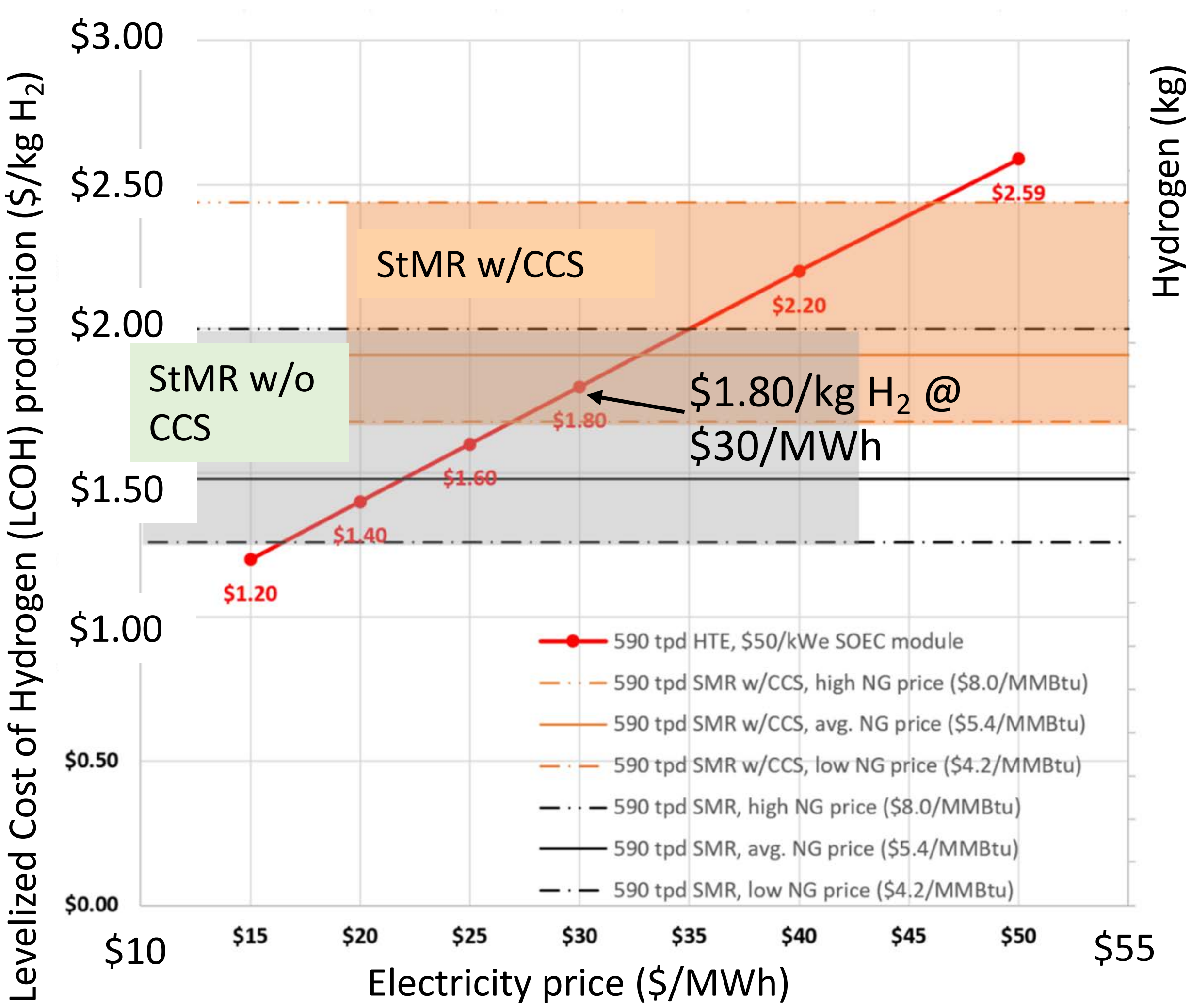
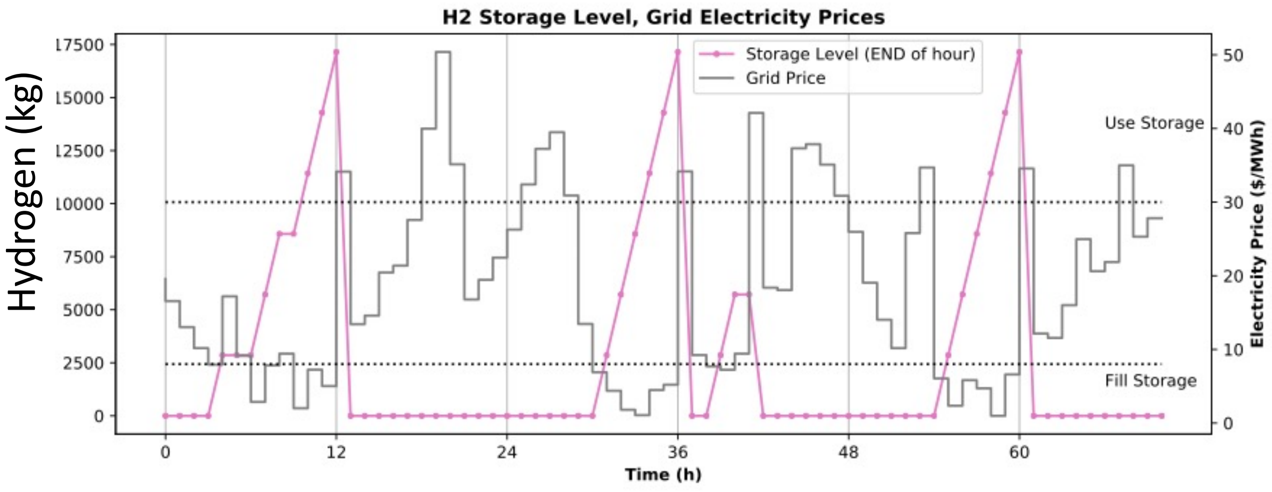
Example: Disruptive potential of nuclear produced H_2



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.



- Analysis tools used to determine optimal dispatch of electricity to meet grid demand (high grid prices) or to produce H2 (low grid prices)
- H_2 is alternate stored or dispatched from storage to ensure the H_2 market demand is also met at all times

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Example: Disruptive potential of nuclear produced H_2

- **Results**
  - Low grid pricing → hydrogen is more profitable
  - High grid pricing → sale to the 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

Nine Mile Point Nuclear Power Plant LTE/PEM Vendor

- **Outcome:** Award from the DOE EERE Hydrogen & Fuel Cell Technologies Office with joint Nuclear Energy funding for follow-on work and low temperature electrolysis demonstration at the Constellation Nine-Mile Point plant; anticipate hydrogen production ~Fall 2022
- **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 demonstration projects

Four projects have been selected for demonstration of hydrogen production at U.S. nuclear power plants (NPP)

- H_2 production using direct electrical power offtake
- Develop monitoring and controls procedures for scaleup to large commercial-scale H_2 plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce H_2 for captive use by NPPs and clean hydrogen markets

Projects

- **Constellation:** Nine-Mile Point NPP (~1 MWe LTE/PEM)
- **Energy Harbor:** Davis-Besse NPP (~1-2MWe LTE/PEM)
- **Xcel Energy:** Prairie Island or Monticello NPP (~150 kWe HTSE)
- **APS/Pinnacle West Hydrogen:** Palo Verde Generating Station (~15-20 MWe LTE/PEM)
- **Fuel Cell Energy:** Demonstration at INL (250 kWe)

Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

Thermal & Electrical Integration at an Xcel Energy NPP HTSE/SOEC

Prairie Island

Monticello

Palo Verde Generating Station, H_2 Production for Combustion and Synthetic Fuels

H2@Scale U.S. Department of Energy — LWRS Light Water Reactor Sustainability — IES Integrated Energy Systems

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

LWRS LIGHT WATER REACTOR SUSTAINABILITY

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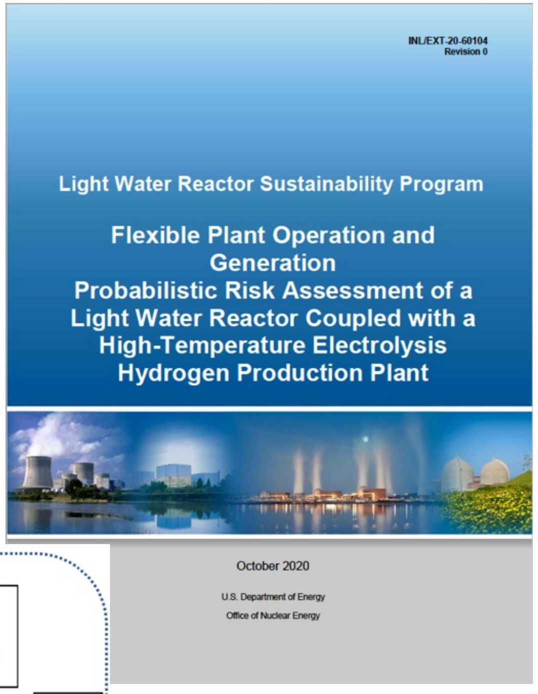
PRA for thermal integration of steam electrolysis: Summary conclusions

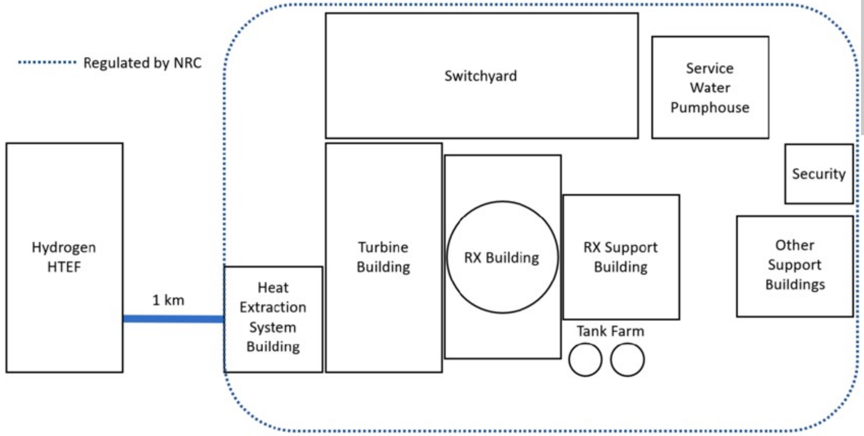
- Generic probabilistic risk assessment (PRA) investigation into licensing considerations
- Identified top hazards
  - Internal: Steam line break, loss of offsite power
  - External: HTE H_2 leak or H_2 detonation
- Key conclusions
  - Licensing criteria is met for a large-scale HTE facility sited 1 km from a generic PWR and BWR
  - Safety case for less than 1 km distance is achievable
- Other insights
  - Individual site NPP and geographical features can affect the results of the generic PRA positively or negatively
  - Generic PRAs 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

OSTI link: https://www.osti.gov/biblio/1691486



NRC jurisdictional boundary for LWR servicing an HTE facility



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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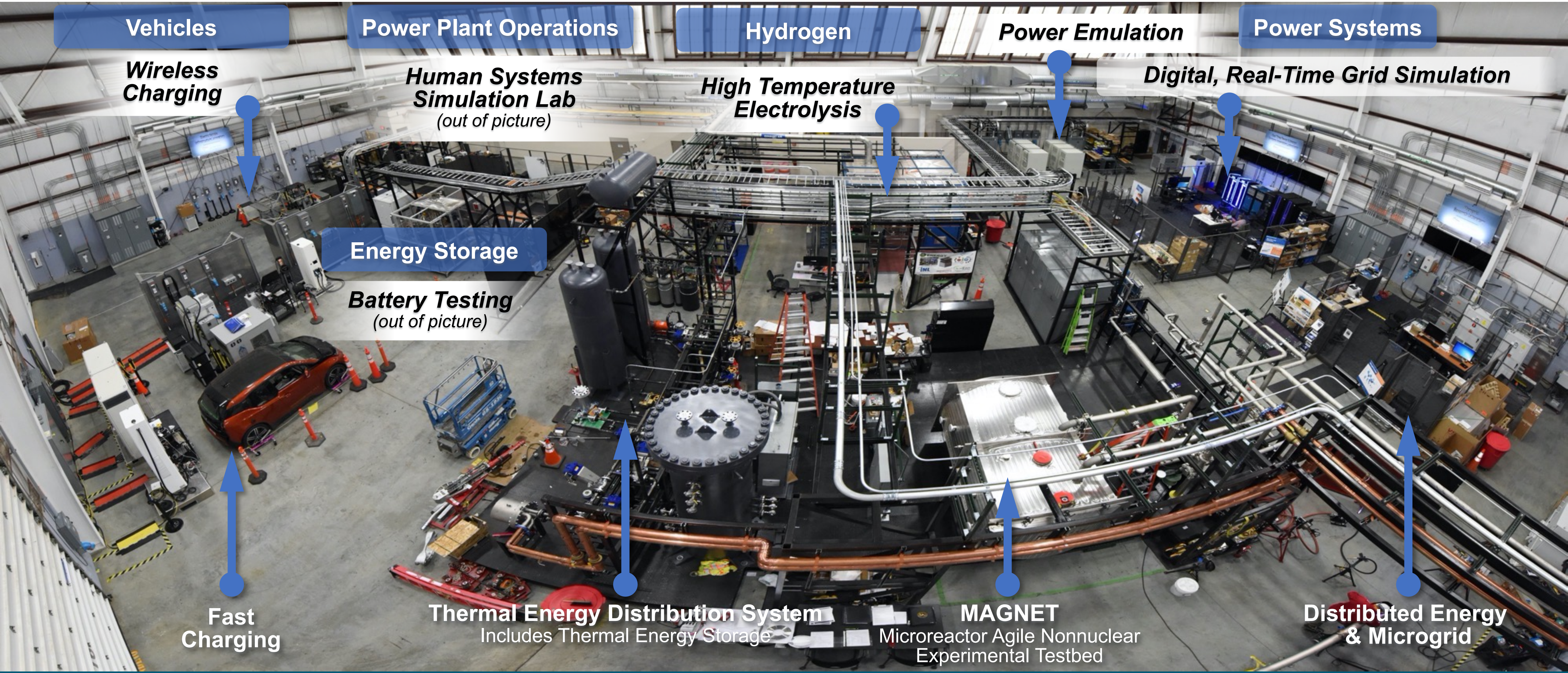
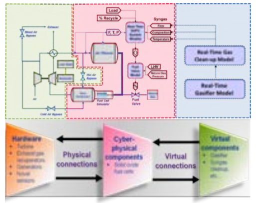
Experimental evaluation:

Model validation, technology demonstration, performance characterization, control system development

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



DETAIL enables cross-complex laboratory connections



Power Hardware and Grid-in-the-Loop

Human-in-the-Loop

Hydrogen and other Flexible Industrial Processes

Thermal Energy Generation and Transport

Integrated Energy Systems

Accelerating advanced reactor demonstration & deployment

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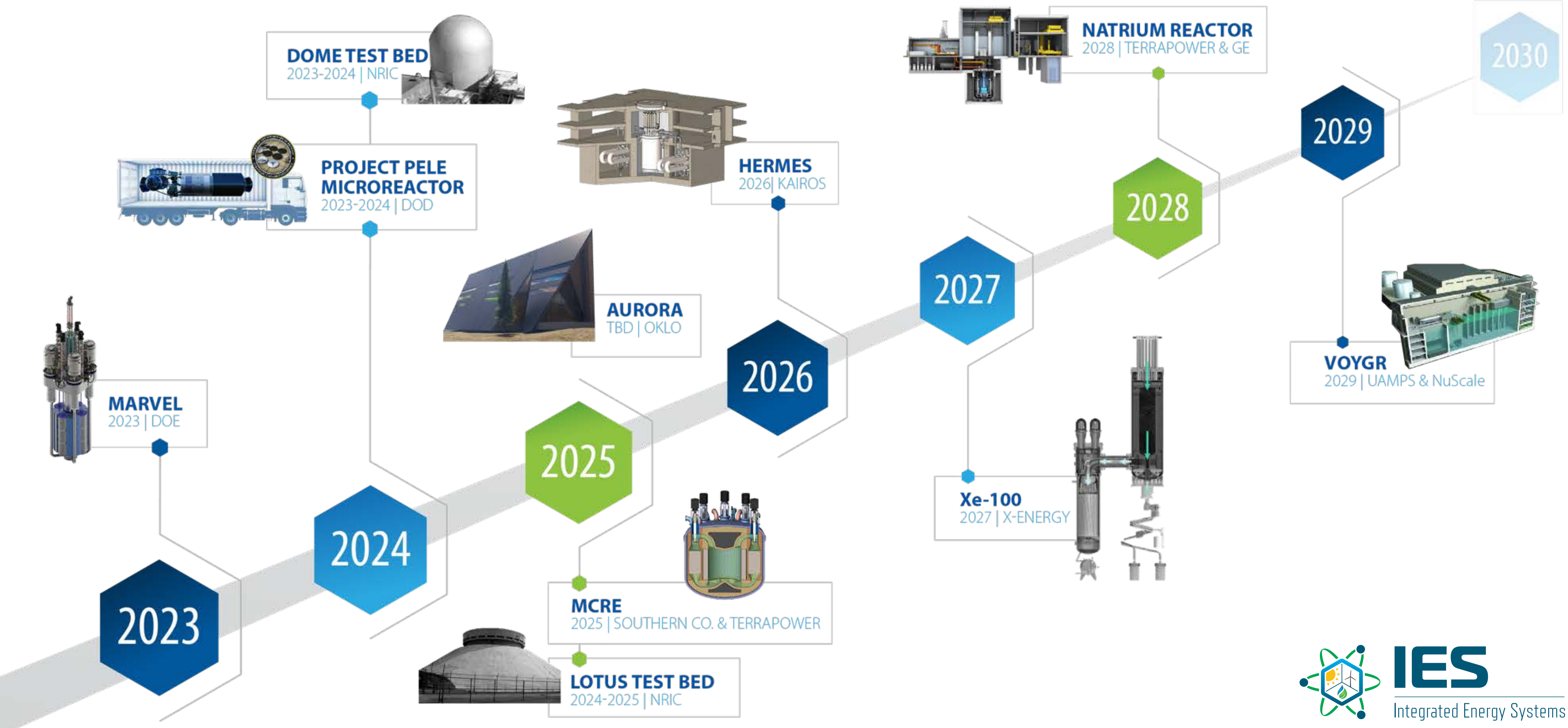

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GIF Task Force on Non-Electric applications of Nuclear Heat (NEaNH-TF)

- Decarbonization of electricity is by far insufficient to meet GHG emission reduction targets
- Non-electric sectors in industry and transport can be weaned from fossil fuel by heat or low-carbon energy carriers (e.g., process steam, H_2, syngas, methanol etc.)

  → Cheap fossil fuel can no longer remain a competitor in these sectors
- GIF-type SMRs can be employed for cogeneration and integration in energy markets with high fractions of renewables; numerous concepts under development and available in literature
- NEANH TF will identify and review these systems, and develop key performance indicators, e.g.,
  - Technology Readiness Level (TRL)
  - Timeliness
  - Adaptability to geographical conditions
  - CO_2 emission reduction potential
  - Cost/Benefit (\$/t CO_2 saved)
  - Boundary conditions for economic viability

Anticipated outcomes:

- Clarify challenges and constraints
- Provide guidance to the energy communities
- Propose R&D to accelerate development and deployment

Key questions to be addressed by NEaNH

- What are the potential assets/benefits of integrated, multi-output systems (a.k.a. “hybrid” systems)?
- What are regionally optimal NEaNH solutions with GIF technology systems?
- What are “optimum” combinations, as a function of deployment location?
  - Reactor type, size
  - Energy applications
- How do the different advanced reactor technologies compare with regard to potential for supporting non-electric process applications?

Many different options under evaluation

Distributed energy systems for a net-zero future