INL/MIS-23-74555-Revision-0

Update on Utilization of Nuclear Energy for Hydrogen Production

September 2023

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13 September 2023

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Update on Utilization of Nuclear Energy for Hydrogen Production

78th Meeting of the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC)
OECD Nuclear Energy Agency, Paris, France

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

INL/MIS-23-74555

The U.S. Department of Energy is doubling down on the commitment to clean energy

- *Energy Earthshots^{TM} will accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. They will drive the major innovation breakthroughs that we know we must achieve to solve the climate crisis, reach our 2050 net-zero carbon goals, and create the jobs of the new clean energy economy.* (*https://www.energy.gov/policy/energy-earthshots-initiative*)

Hydrogen Shot ← **Goal: <$1/kg clean H_2 by 2031**
Clean H_2: 4 kg CO_2/kg H_2

Long Duration Storage Shot

Carbon Negative Shot

Enhanced Geothermal Shot

Floating Offshore Wind Shot

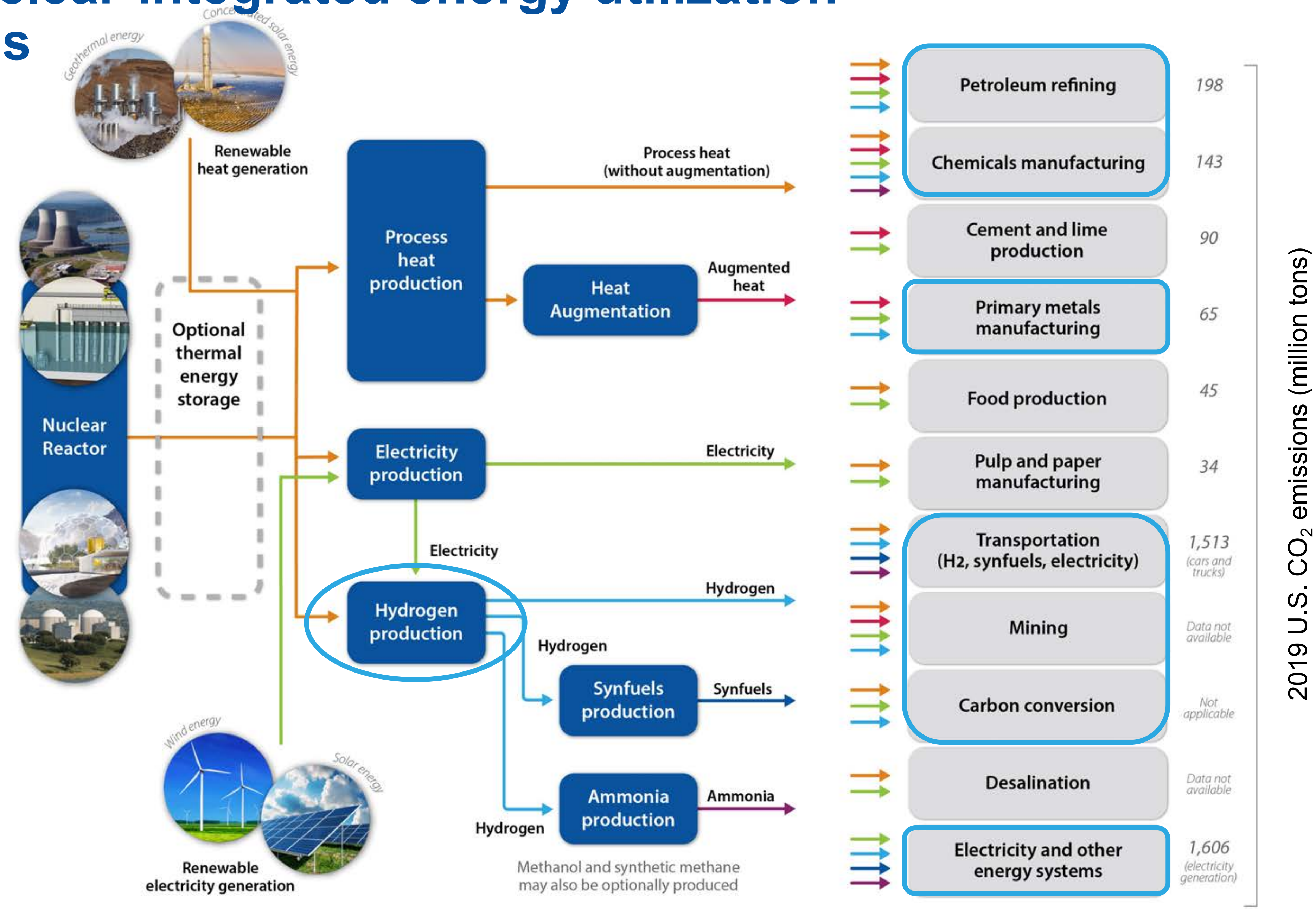
Goal: 85% lower industrial GHG emissions by 2035 → Industrial Heat Shot

Clean Fuels & Products Shot ← **Goal: >85% reduction in GHG emissions by 2035**

ENERGY earthshots U.S. DEPARTMENT OF ENERGY

Potential nuclear-integrated energy utilization opportunities

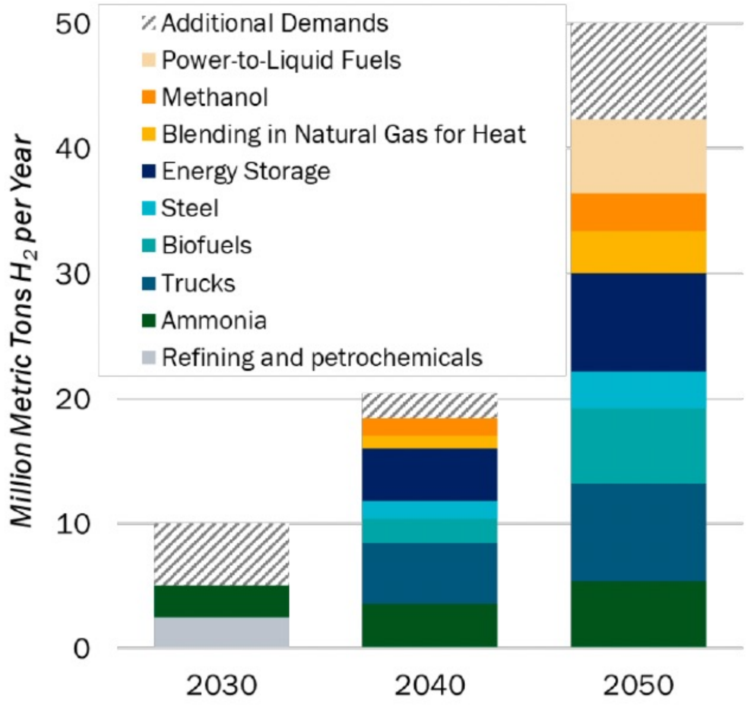
Reactor sizes align with the needs of each application; heat augmentation can be applied if needed to match process temperature demands.



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

National clean H_2 strategy—The opportunity for clean H_2

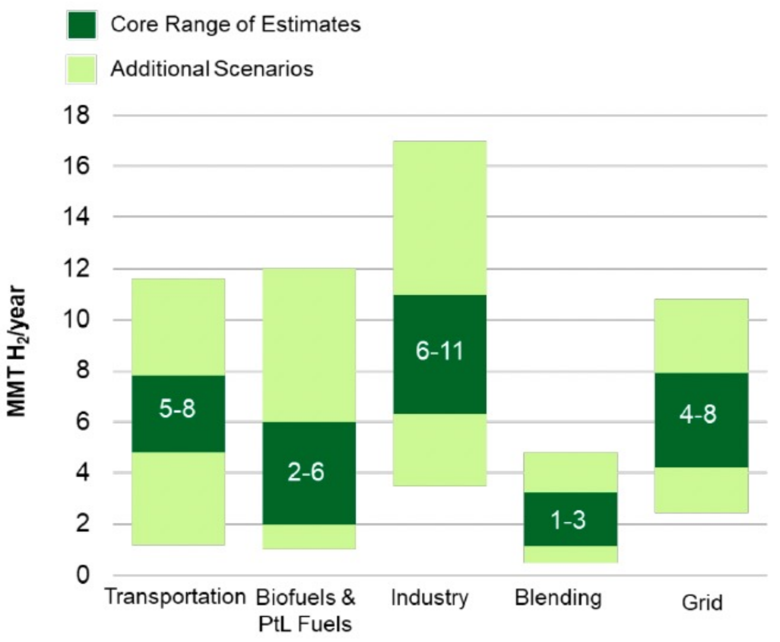
Opportunities for Clean Hydrogen Across Applications



Clean Hydrogen Use Scenarios

- Catalyze clean H_2 use in existing industries (ammonia, refineries), initiate new use (e.g., sustainable aviation fuels (SAFs), steel, potential exports)
- Scale up for heavy-duty transport, industry, and energy storage
- Market expansion across sectors for strategic, high-impact uses

Range of Potential Demand for Clean Hydrogen by 2050



- **Core range: ~ 18–36 MMT H_2**
- **Higher range: ~ 36–56 MMT H_2**

Refs: 1. NREL MDHD analysis using TEMPO model; 2. Analysis of biofuel pathways from NREL; 3. Synfuels analysis based off H2@Scale ; 4. Steel and ammonia demand estimates based off DOE Industrial Decarbonization Roadmap and H2@Scale. Methanol demands based off IRENA and IEA estimates; 5. Preliminary Analysis, NREL 100% Clean Grid Study; 6. DOE Solar Futures Study; 7. Princeton Net Zero America Study

U.S. Opportunity:
10MMT/yr by 2030, 20 MMT/yr by 2040, 50 MMT/yr by 2050

Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023

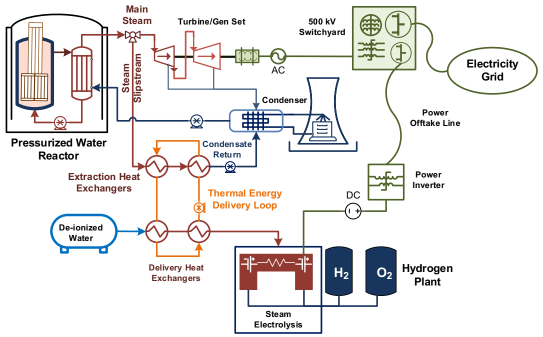
Hydrogen technology development and commercialization


Cell Fabrication and Stack Manufacturing



Modular Systems / Balance of Plant

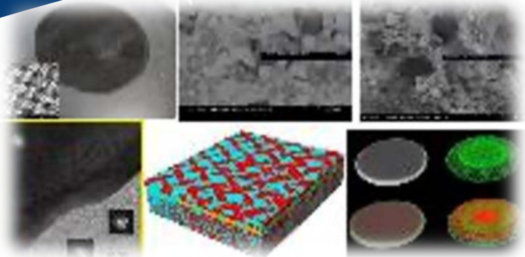
Pilot Plant and Commercial Scale Demonstration



Commercial Demonstrations


High Throughput Materials Testing

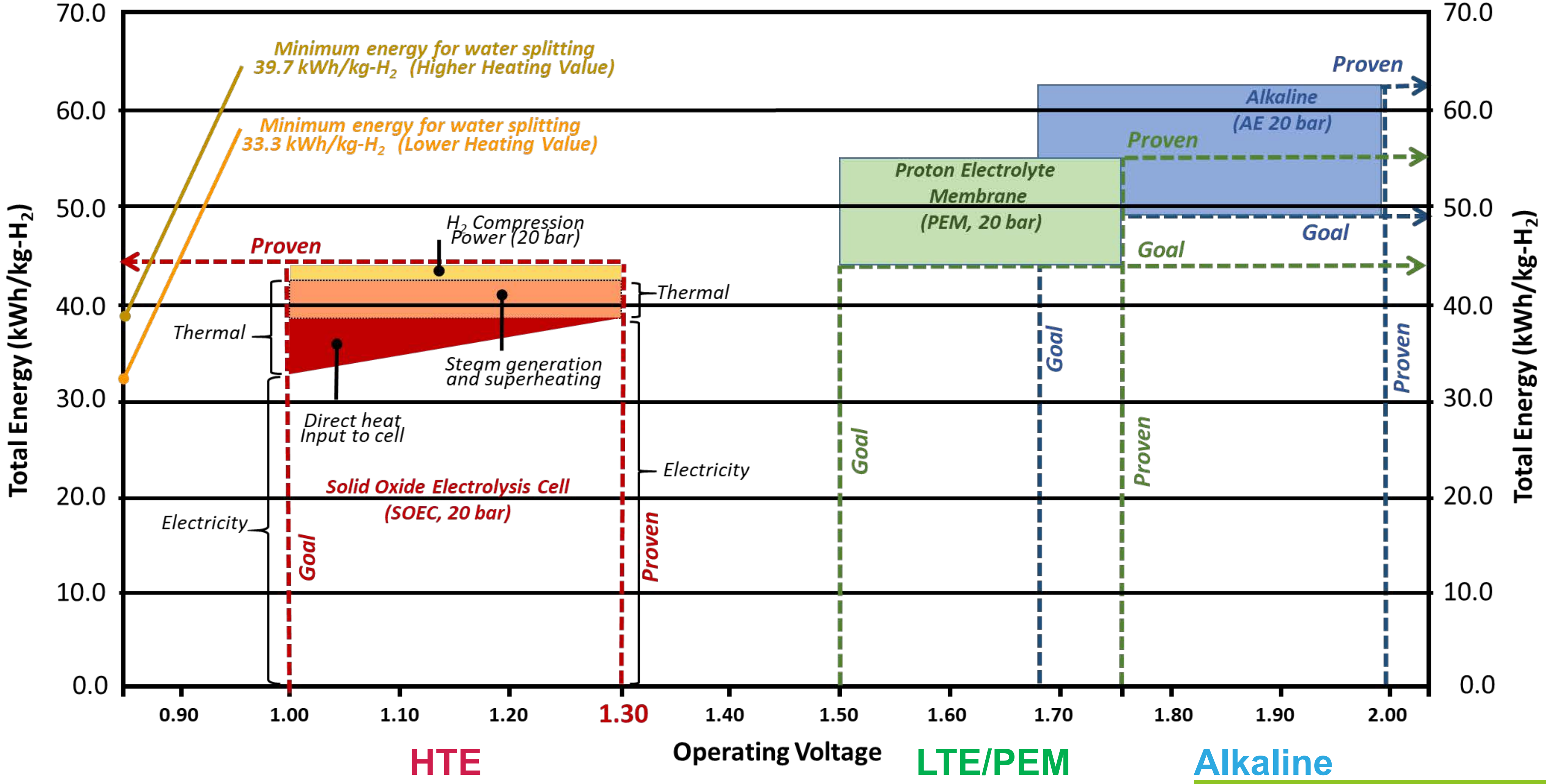

Materials Preparation


Electrode Engineering & Diagnosis

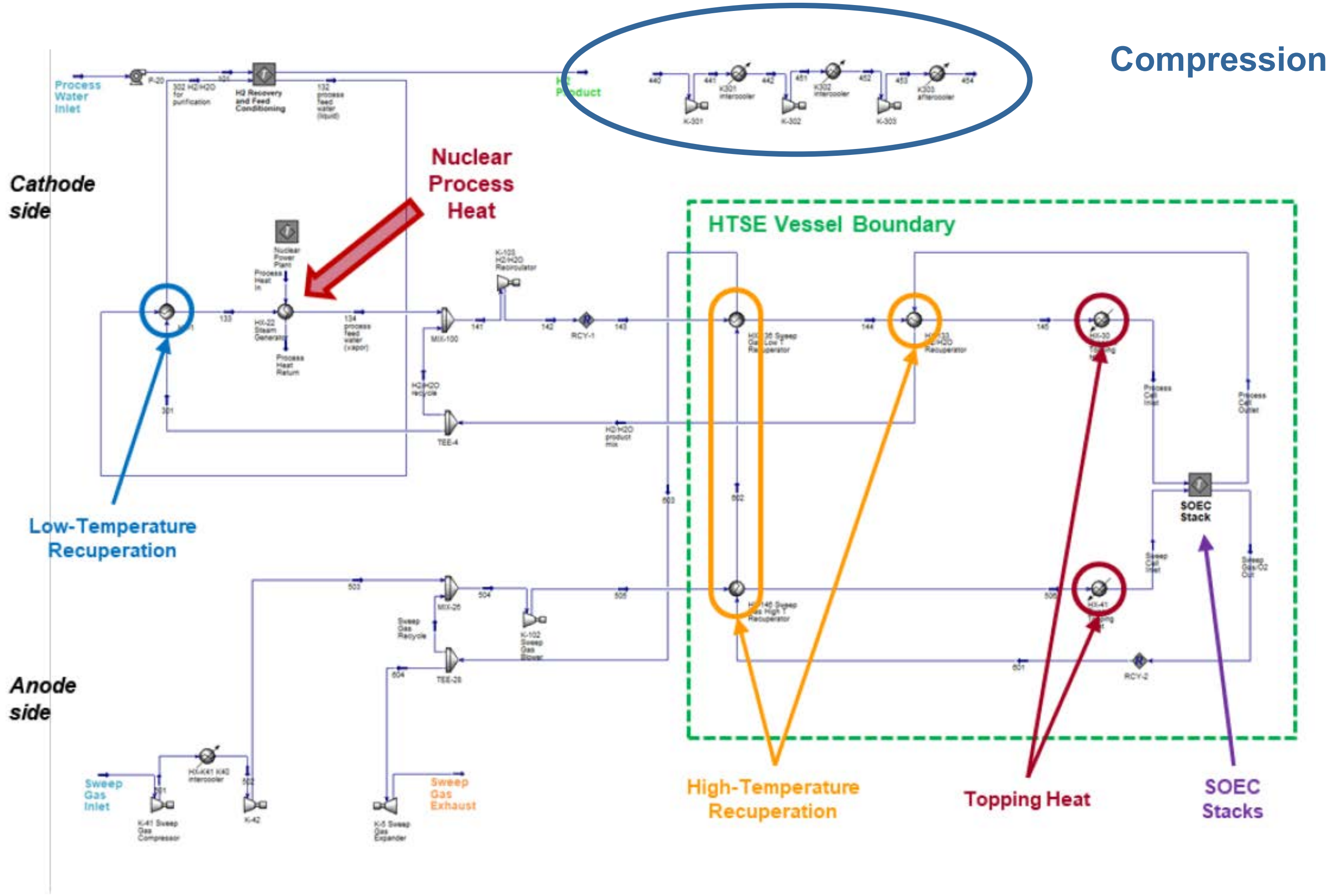

Commercial Stack Testing

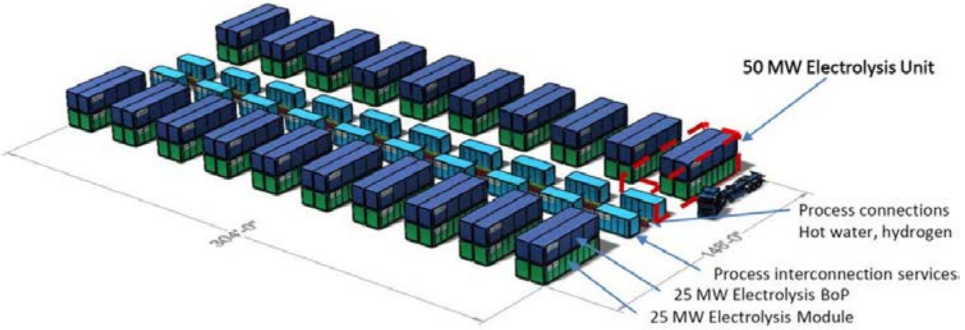
Materials Development and Testing

Energy requirements for hydrogen production



High temperature steam electrolysis heat recuperation





- HTE integration only requires a low-grade heat source to produce low temperature steam (150 ^{o}C)

  → LWR provides an excellent heat source

- Current electrolysis module R&D Focus—Demonstration of standard containerized modules with internal heat recuperation

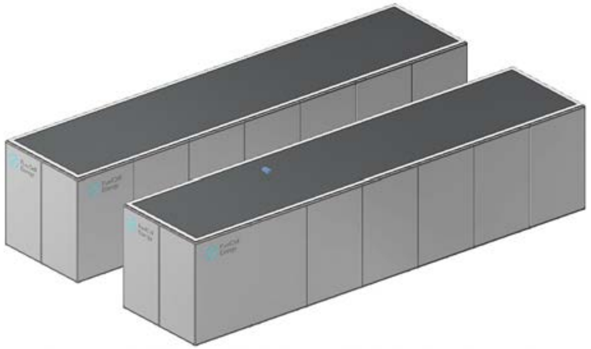
Accelerating technology commercialization

- INL R&D enables commercial developers to operate and V&V fully integrated HTE electrolysis module performance
- Stack module testing
  - **Today:** Bloom Energy >100 kW_{eDC} SOEC stack module is in test under a CRADA supported project
    - > 5,000 hours of stable and transient testing
  - **Early 2024:** INL will commence performance testing of two factory-assembled modular 250 kW_{eDC} SOEC Systems
- 50 kW rSOEC system and 50 kW “open” test architecture currently being installed
- H_2 compression and fueling station to be installed, late 2023

INL HTE Support Facility:
- *CE+T America Power Converters*
- *Chromalox steam generator*

Bloom Energy 100 kWe HTE Stack Module

INL operators monitoring the Bloom Energy HTE stack module performance



FuelCell Energy 250 kW_{eDC} HTE module Installation and operation early 2024

25 kW_{eDC} commercial stack testing module

Pilot plant hydrogen production demonstration projects

Constellation: Nine-Mile Point Plant

- H_2 production beginning in 2023
- 1 MW_{eDC} 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

Nuclear-based hydrogen production has commenced!

Press release:
https://www.constellationenergy.com/newsroom/2023/Constellation-Starts-Production-at-Nations-First-One-Megawatt-Demonstration-Scale-Nuclear-Powered-Clean-Hydrogen-Facility.html

Constellation Starts Production at Nation's First One Megawatt Demonstration Scale Nuclear-Powered Clean Hydrogen Facility

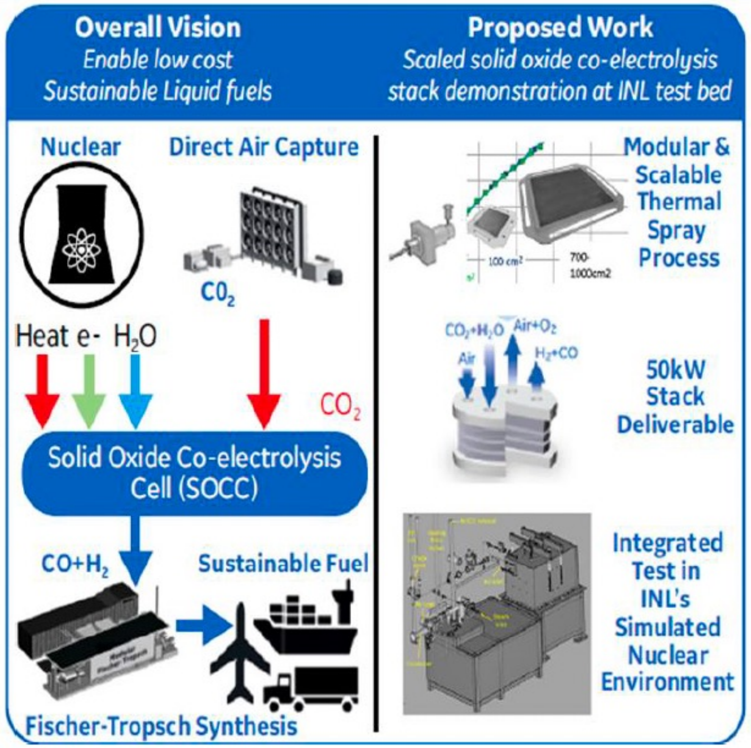
State-of-the-art facility will demonstrate the value of producing hydrogen with carbon-free nuclear energy to help address the climate crisis

OSWEGO, NY (Mar. 7, 2023) — Hydrogen production has commenced at the nation's first 1 MW demonstration scale, nuclear-powered clean hydrogen production facility at Constellation's Nine Mile Point Nuclear Plant in Oswego, New York, an advancement that will help demonstrate the potential for hydrogen to power a clean economy.

Photos courtesy Constellation, https://www.ans.org/news/article-4810/constellation-starts-hydrogen-production-at-nine-mile-point/

New nuclear-H2 integration projects (cross-DOE collaboration)

GE Research – Scaled Solid Oxide Co-Electrolysis for Low-Cost Syngas Synthesis from Nuclear Energy



Goals:

Complete engineering design/testing for **production of synthetic jet fuel using nuclear energy from existing light water reactors & Solid Oxide Co-Electrolysis**

- Complete TEA
- Manufacture of scaled solid oxide cells
- Integration & testing of 50kW stack at INL

Potential Impact: Nuclear to H_2 + CO to Synthetic Aviation Fuel

Westinghouse – FEEDs for Integrating Commercial Electrolysis H_2 Production with Selected LWRs

Goals:

Complete Front-End Engineering Designs (FEEDs) development for **nuclear-coupled SOEC H_2 production** at specific U.S. LWR plants

- Designs will be developed for **both pressurized water reactor (PWR) & boiling water reactor (BWR)**
- Licensing impact assessments will be completed
- TEA & LCA for markets under consideration

Westinghouse

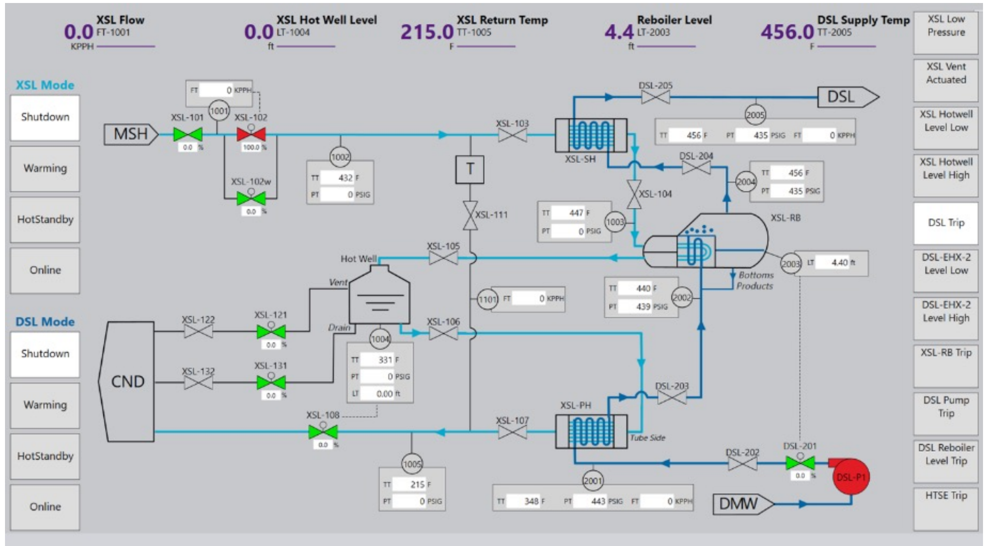
Sub-Recipient/FFRDC	INL Idaho National Laboratory
Utility Support	aps (1), energy harbor (1), Xcel Energy (1)
Industry Support	Bloomenergy (1), FAUSKE & Associates, LLC (2)
Academia Support	The University of Toledo (3)

Potential Impact: Higher system efficiencies / lower cost through thermal integration of SOEC with nuclear plant

Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023

Progress in flexible thermal and electrical power dispatch

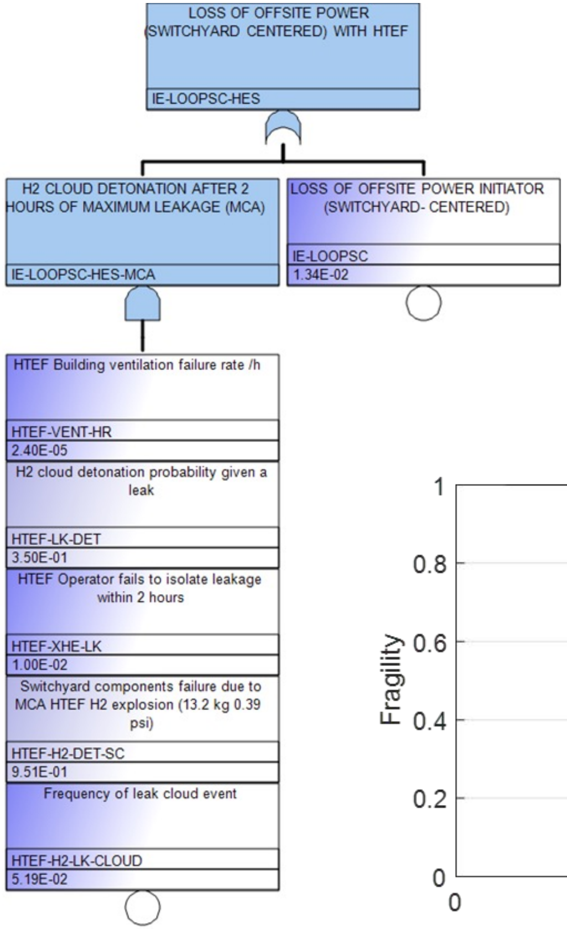
- The INL Human Systems Simulation Laboratory was used to test concepts for dispatching thermal and electrical power from nuclear reactors to a hydrogen electrolysis plant
  - Two formerly licensed operators tested 15 scenarios
  - A modified full-scope generic PWR was used to emulate the nuclear power 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



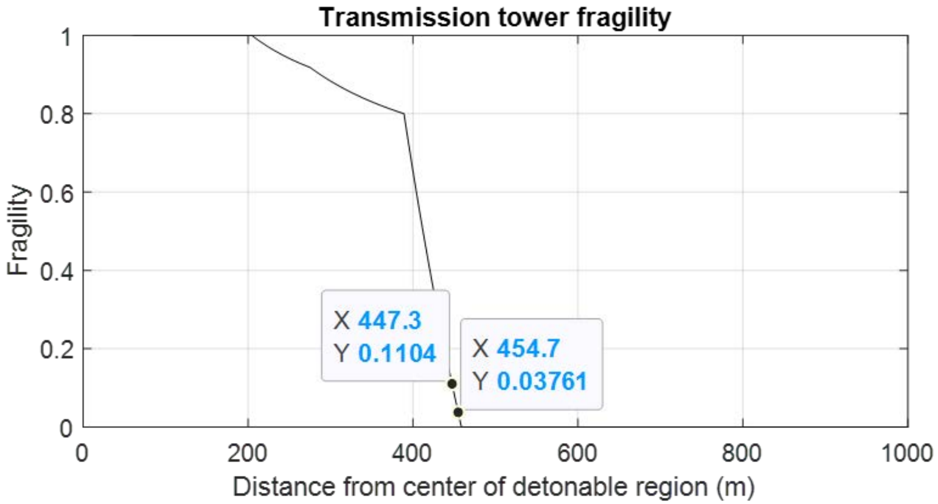
Report: *Multi-Facility Coordinated Thermal Power Dispatch Plan*, September 2022, INL/RPT-22-69493.
Available for download at the LWRS reports page.

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
  - Suggests 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

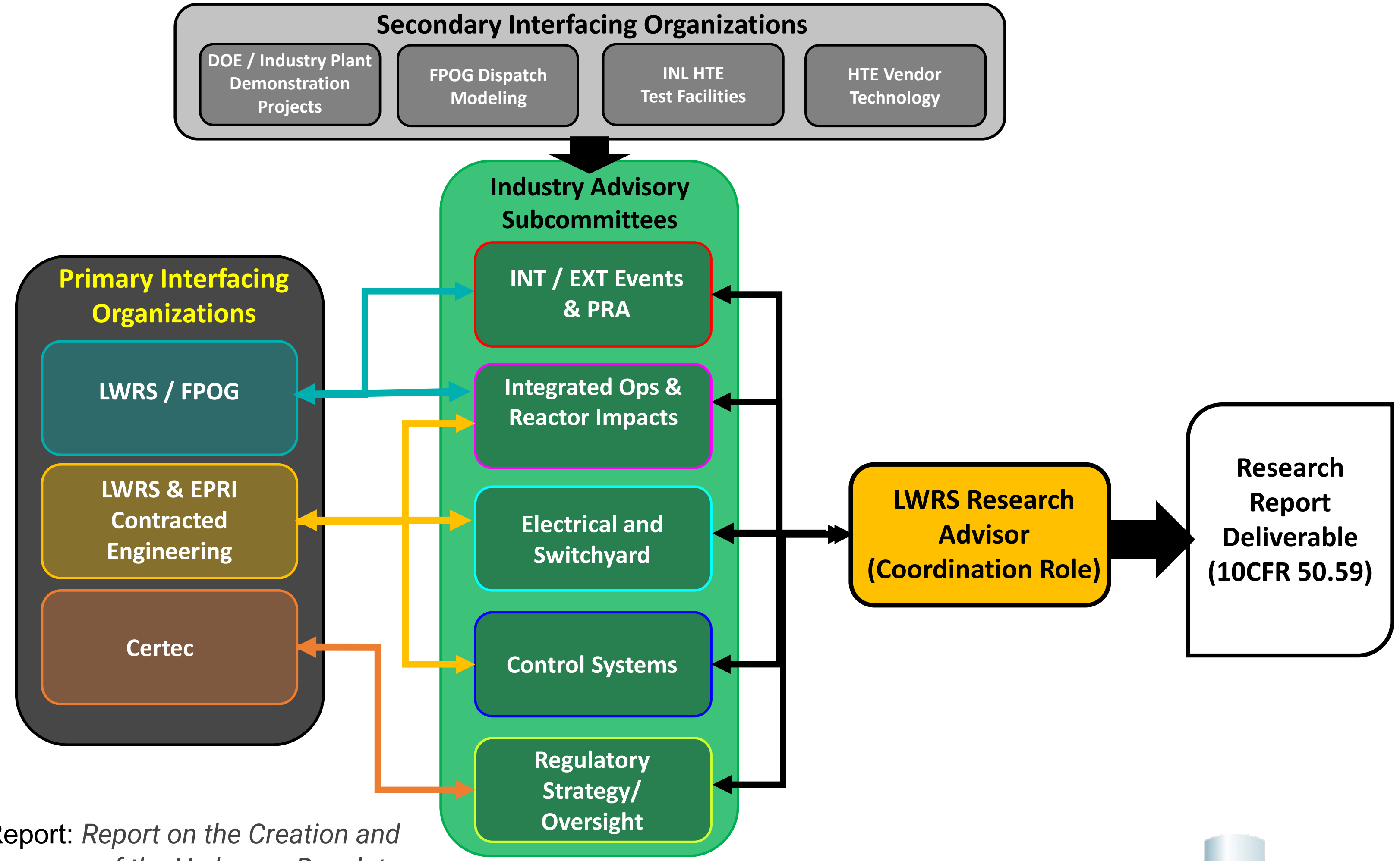


Calvert Cliffs NPP critical external structures. Image from the USNRC



Report: *Probabilistic Risk Assessment of a Light-Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant*, November 2022, https://doi.org/10.2172/1903606.

Hydrogen Regulator Research & Review Group (H3RG)



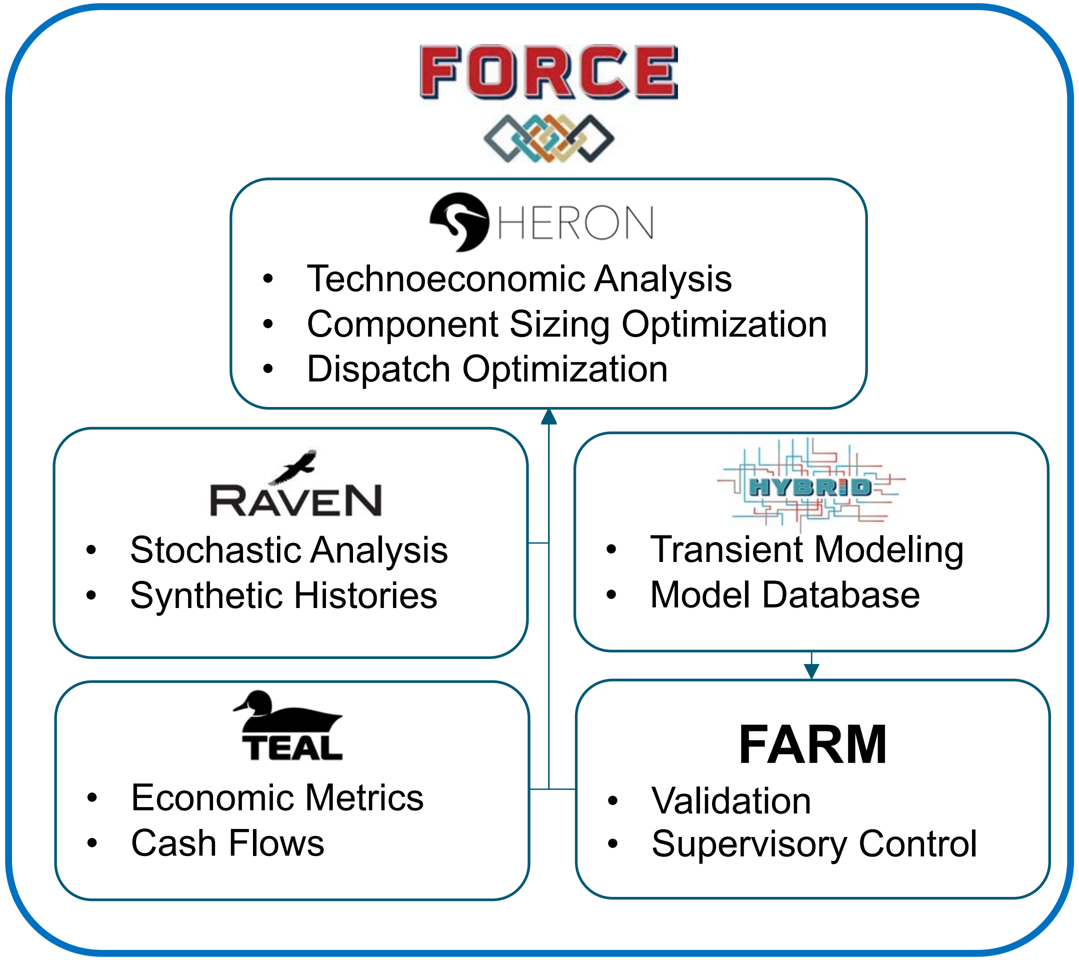
Purpose: H3RG Formation and Structured Approach

- 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

Report: *Report on the Creation and Progress of the Hydrogen Regulatory Research Review Group*, August 2023, INL/RPT-22-66844 Rev 2. Available for download at the LWRS reports page.

IES analysis and optimization tool suite

- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Physical process, integration modeling and safety analysis
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - Stochastic analysis, multiple commodities
  - Energy storage, various markets
  - Real-time optimization and control



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

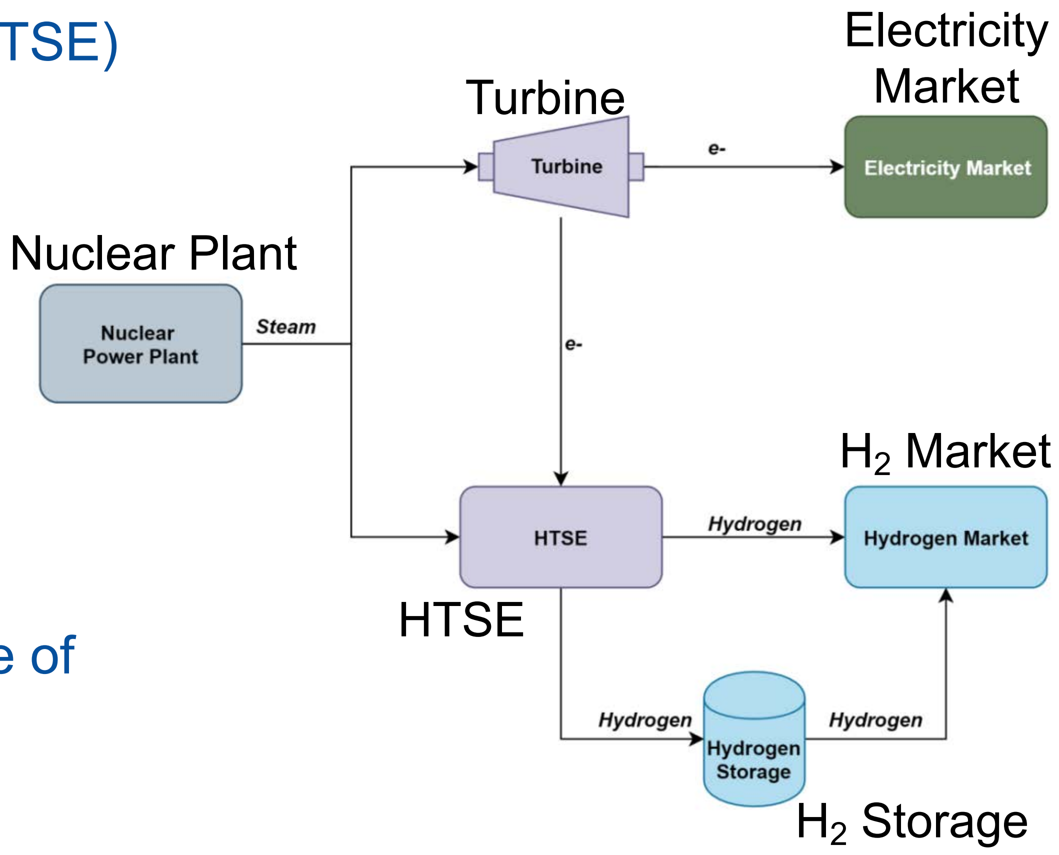
Recorded training modules can be viewed at https://ies.inl.gov/SitePages/FORCE%20training%202023.aspx.

A variety of detailed dynamic models are available for use

- Reactor technologies
  - 4-loop PWR
  - Small modular IPWR
  - Small modular natural circulation IPWR
  - High temperature gas-cooled reactor
  - Sodium fast reactor
  - Molten-salt cooled reactor (in development)
- Energy storage
  - Solid media thermal energy storage (TES)
  - 2-tank TES
  - Thermocline TES
  - Latent heat TES
  - Compressed air
  - Li-ion battery
- Energy use technologies
  - Reverse osmosis desalination
  - High T steam electrolysis (HTSE) for H_2 prod
  - HTSE “experimental”
  - Single-stage balance of plant
  - Two-stage balance of plant
  - Stage-by-stage balance of plant
  - Synthetic fuel production (F-T; methanol pathway in development)
  - Carbon conversion (in development)
- Other
  - Steam manifold
  - Switchyard
  - Electric grid
  - Natural gas turbine

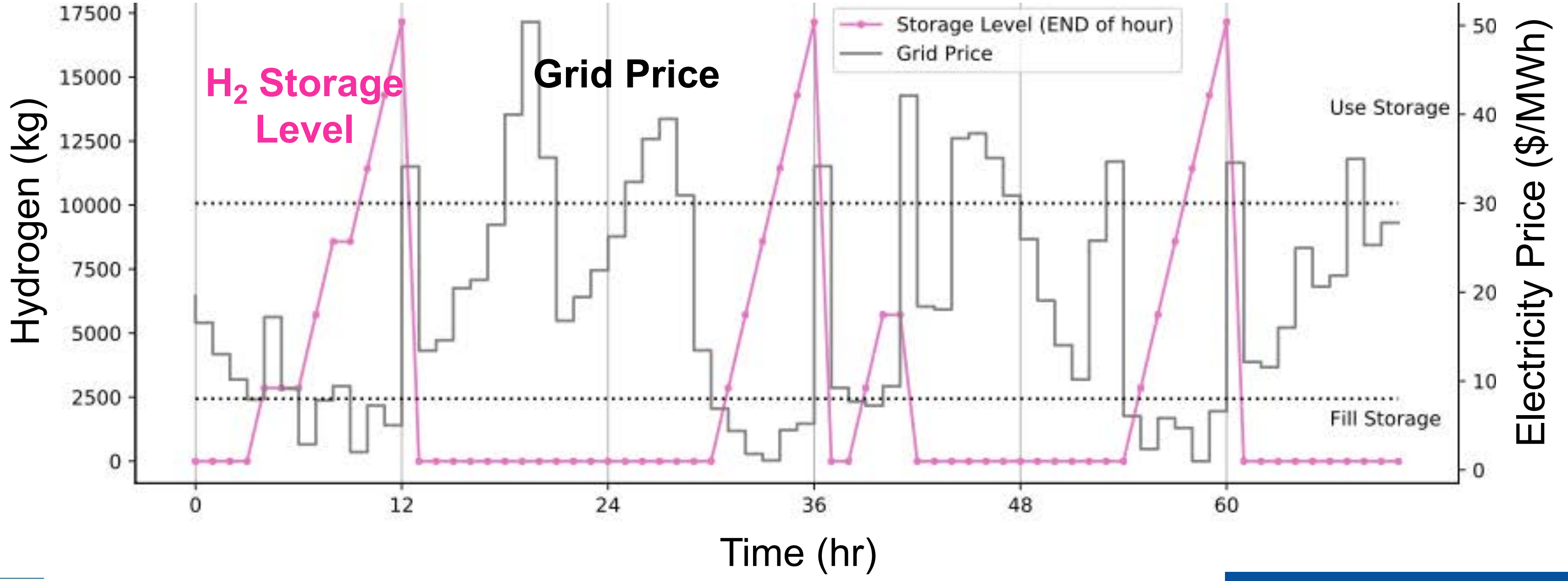
Example: Disruptive potential of nuclear produced hydrogen

- 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



Flexible hydrogen production

- 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)



IES Integrated Energy Systems

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) in the production of synthetic fuel production using F-T process
- Next steps
  - Evaluate alternative processes for synfuel production
  - Develop models, use cases, and dynamically evaluate the Methanol-to-Diesel (MTD) process

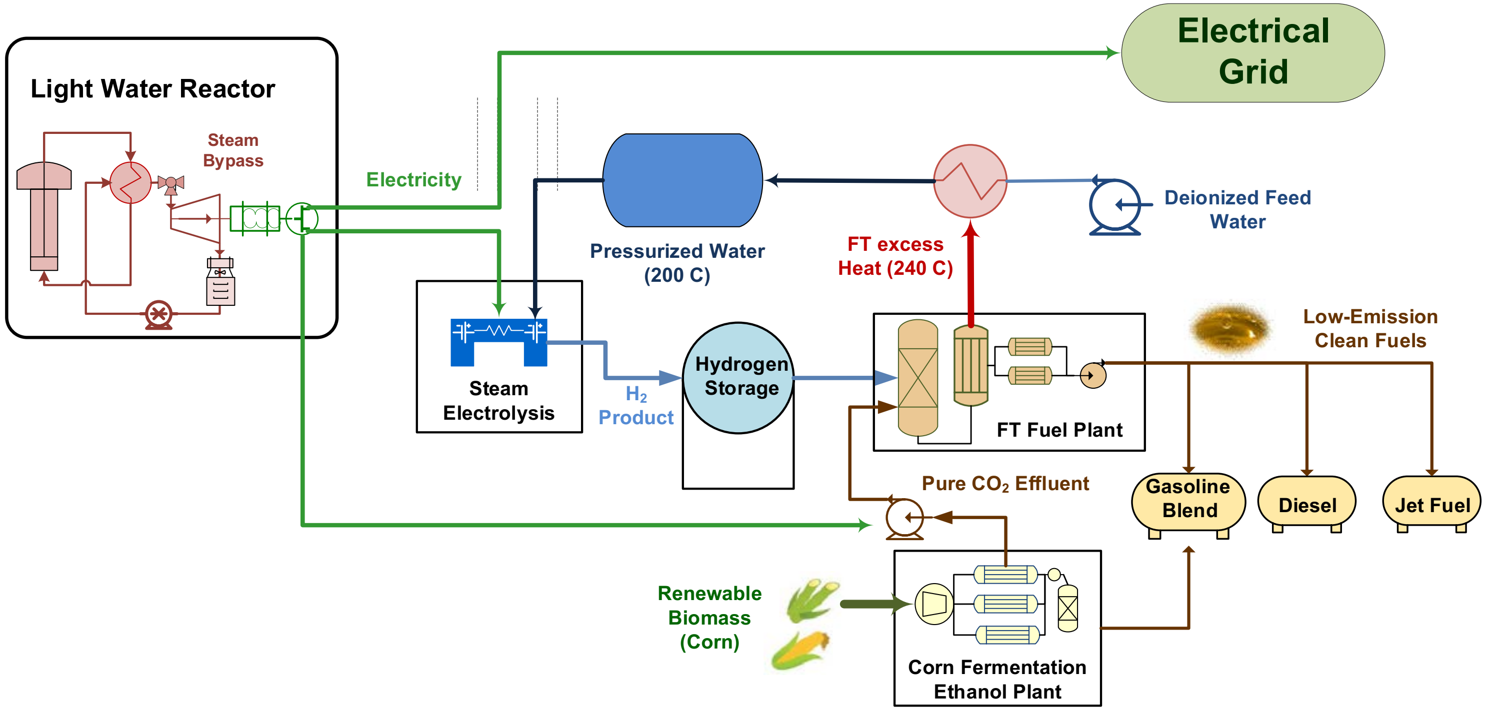
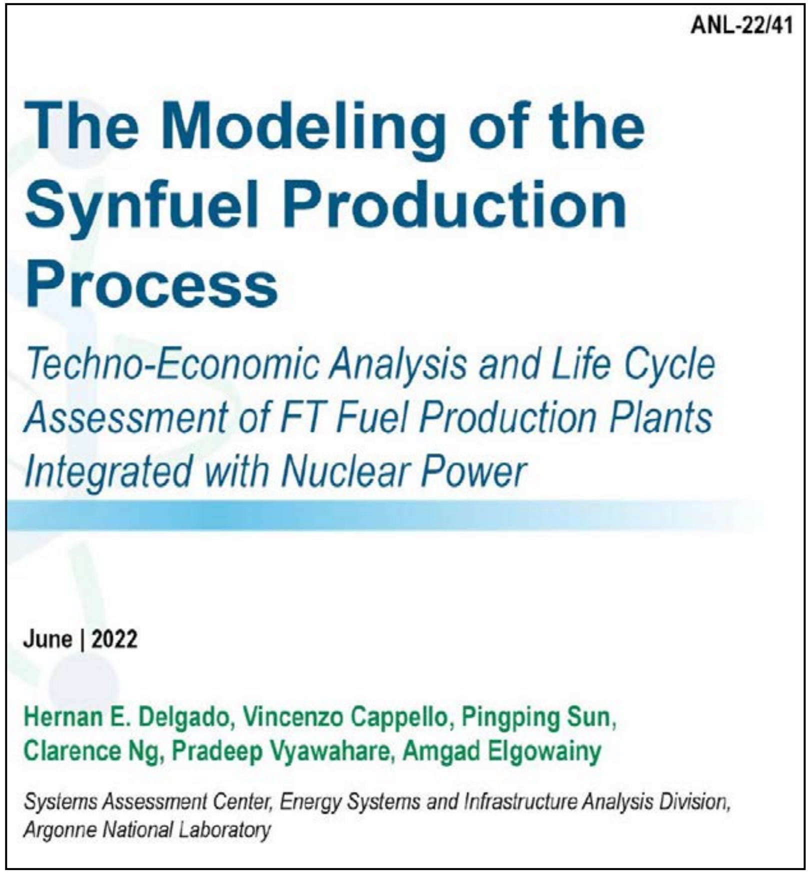


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

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

1 GWe LWR, 10,000 bbl/day FT liquids


ANL-22/41

The Modeling of the Synfuel Production Process

Techno-Economic Analysis and Life Cycle Assessment of FT Fuel Production Plants Integrated with Nuclear Power

June | 2022

Hernan E. Delgado, Vincenzo Cappello, Pingping Sun, Clarence Ng, Pradeep Vyawahare, Amgad Elgowainy

Systems Assessment Center, Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory

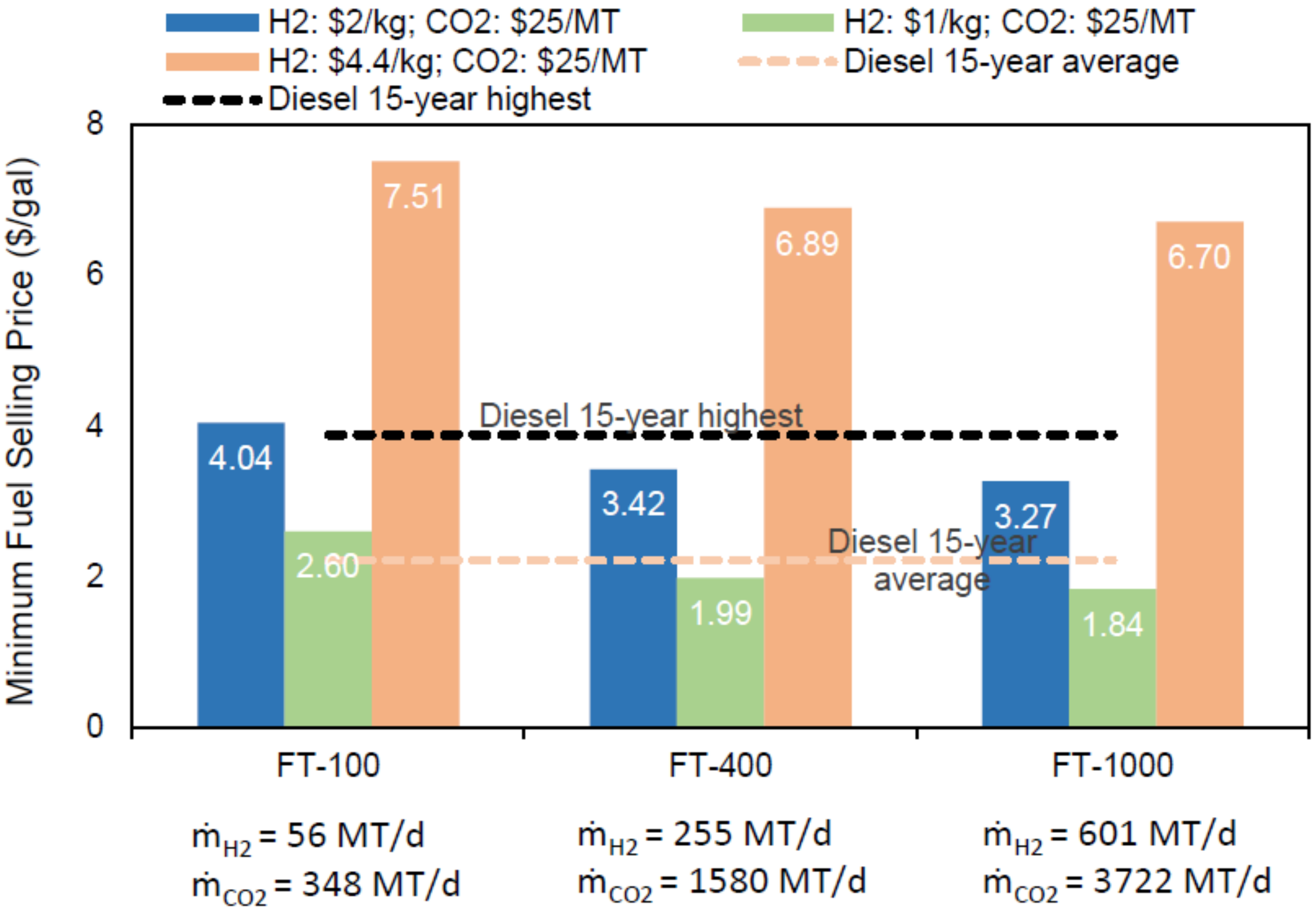
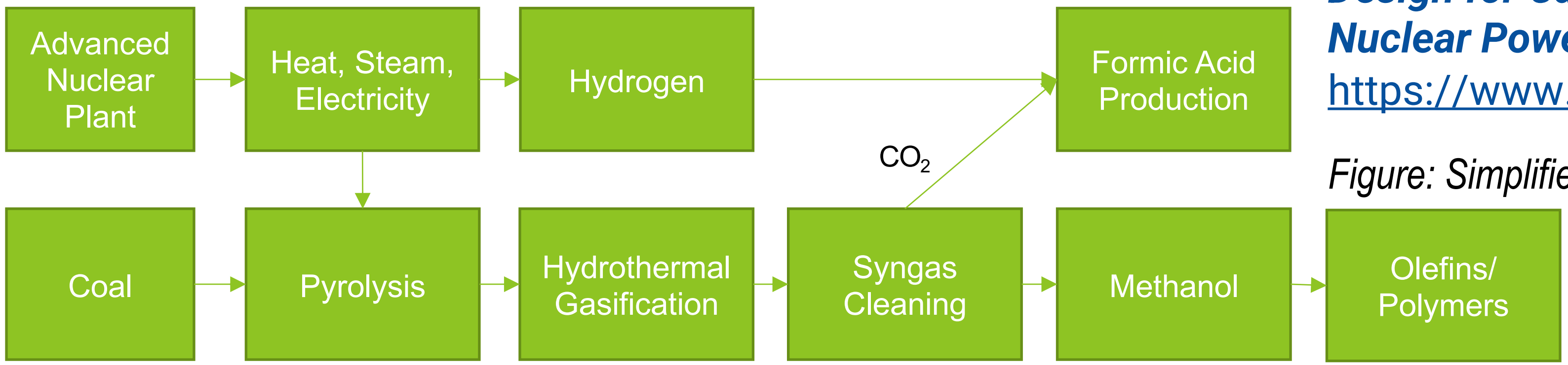


Figure I. Production cost of FT fuel at different plant scales and H_2 prices.

Carbon conversion pathways aim to preserve coal economies in Appalachia

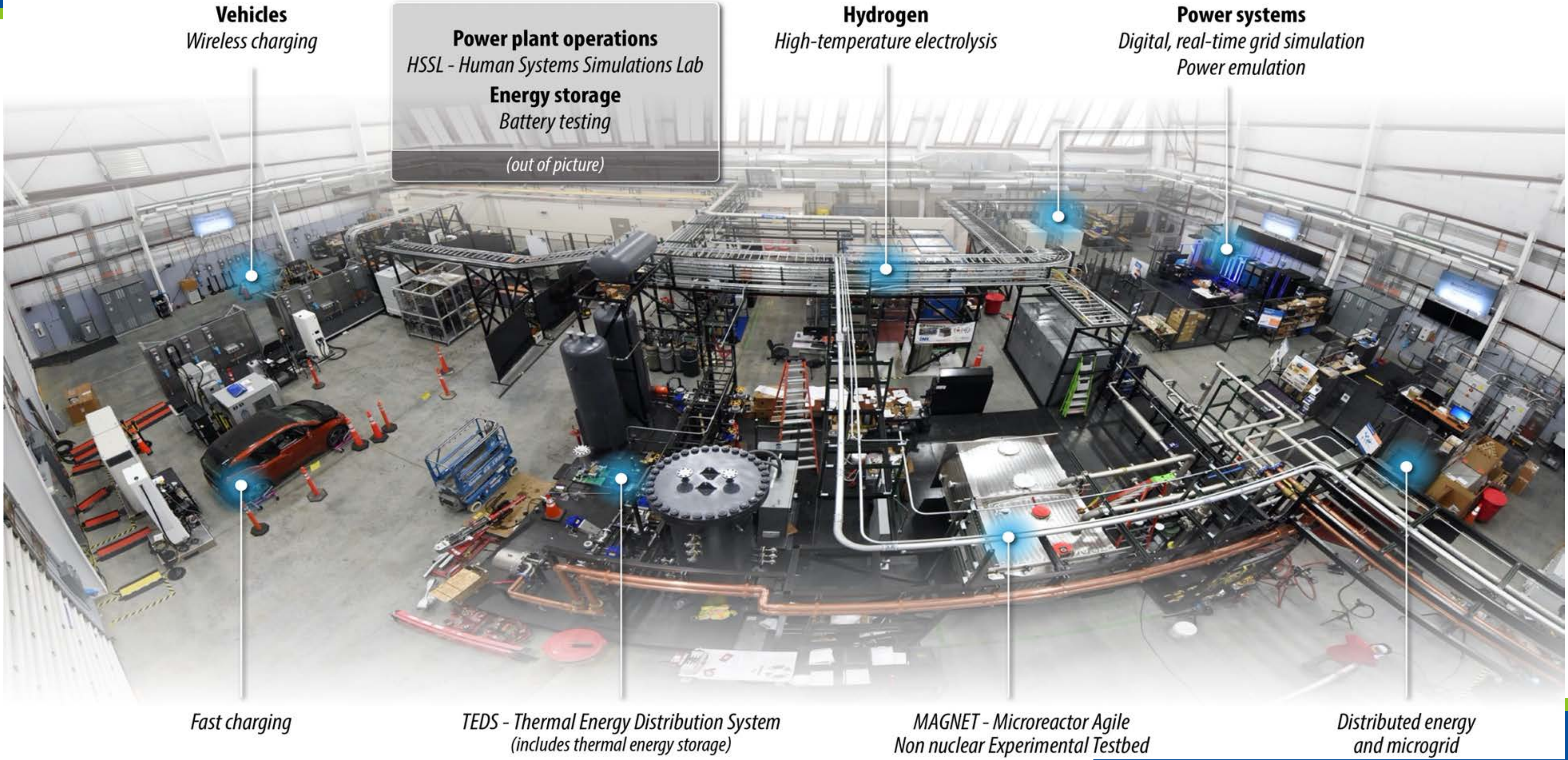
- "Carbon refinery" converts coal via pyrolysis and gasification to syngas for higher value product pathways w/carbon capture
- Focuses on synthesis of non-fuel products from coal utilizing an advanced reactor for heat and steam eliminates carbon output
- Design is optimized to maximize revenues from product streams
- Analyzed main product pathways:
  - **Methanol:** Main product pathway. Polymers chosen as the final product (e.g., polypropylene).
  - **Formic acid:** Ideal product for CO_2 utilization (livestock food preservative and potential hydrogen carrier); can be synthesized directly using hydrogen from electrolysis.
  - **Activated carbon**: Coal char from pyrolysis is converted to activated carbon (used for mercury removal from syngas).



Design for Carbon Conversion Product Pathways with Nuclear Power Plant Integration, 2022, https://www.osti.gov/biblio/1963875

Figure: Simplified flowsheet for the carbon refinery design.

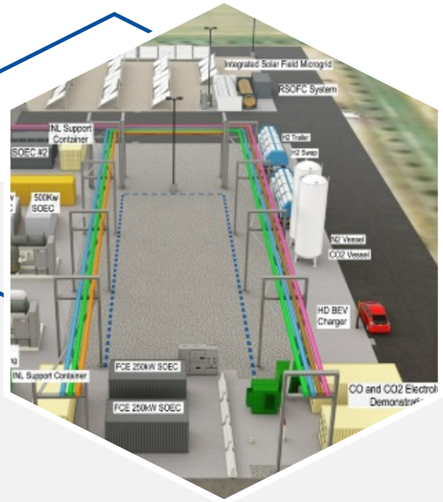
Dynamic Energy Transport and Integration Laboratory (DETAIL)



At-scale demonstrations, > 1 MWe systems

Example: Hydrogen production via HTSE

25 kWe High Temperature Electrolysis Stacks V&V



100-500 kWe Modular High Temperature Electrolysis Pilot Plant Demonstration

"The GAP"

2-10 MWe Modular HTE Units

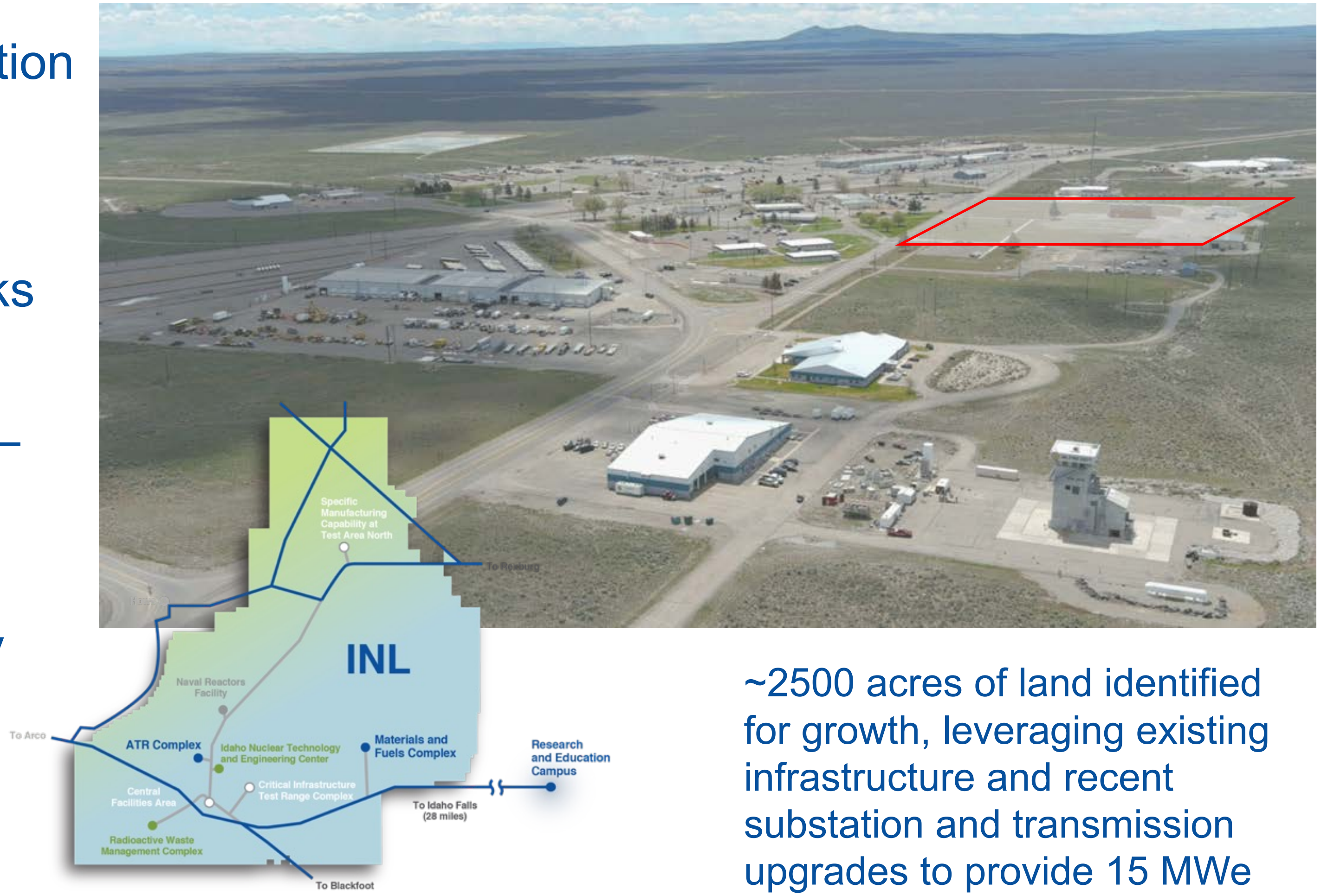
- Integrated proof of operation system
- Hydrogen supply for user technology demonstrations
- Accelerates high temp H2 production pathway to commercialization

Wide Commercial Deployment:

- Hydrogen production at nuclear power plants
- Industry-embedded hydrogen production and use

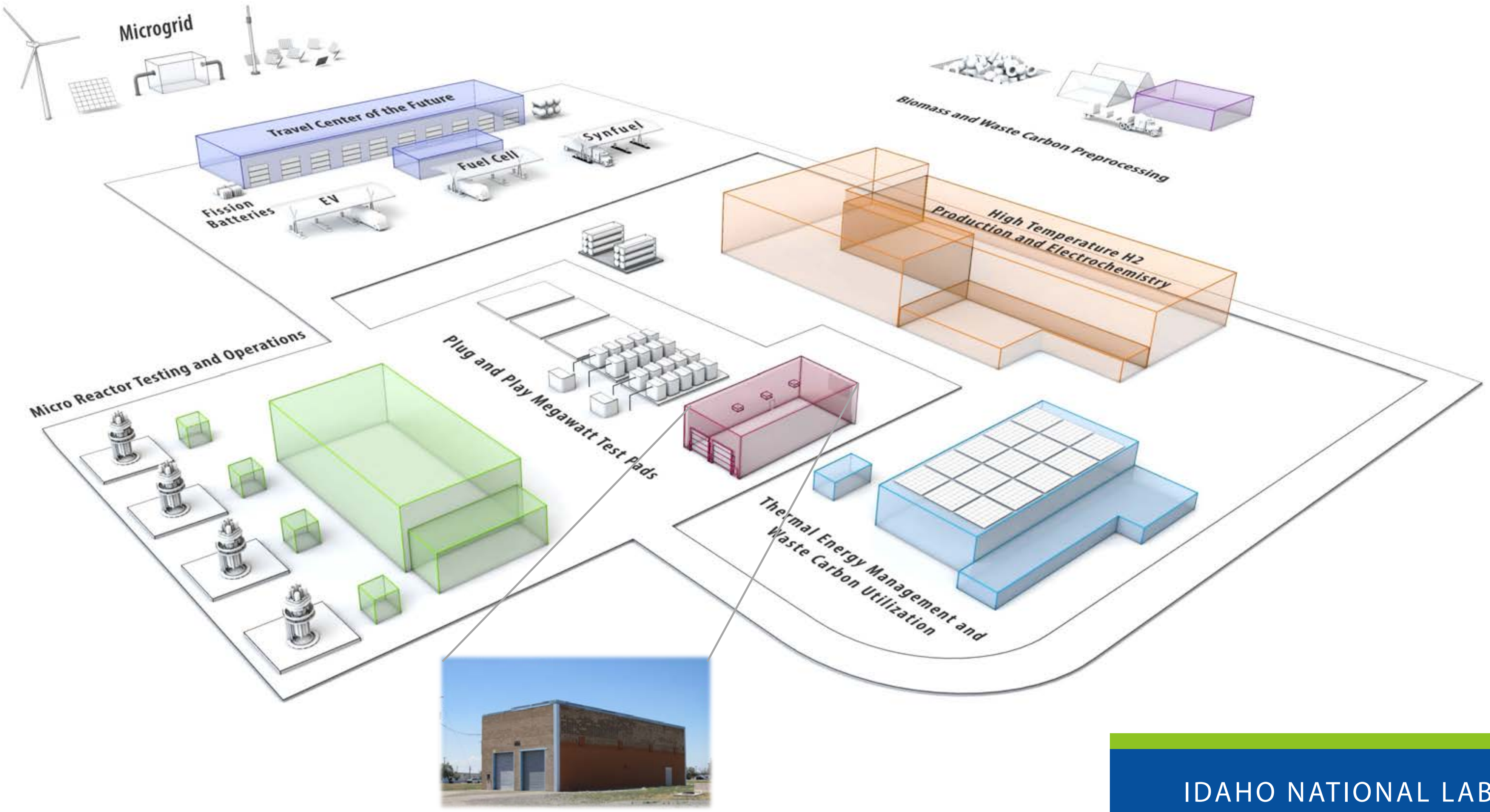
Proposed INL Energy Technology Proving Ground (ETPG)—Multi-scale research program areas

- High Temperature Hydrogen Production
- Thermal Energy Management
- High Temperature Electrochemistry
- Biomass & Waste Carbon Feedstocks
- Transportation & Electric Storage
- Distributed Clean Energy Systems — Microgrid
- Microreactor Testing & Operations
- Digital Engineering & Cyber Security
- Real-Time Power & Energy Analysis



~2500 acres of land identified for growth, leveraging existing infrastructure and recent substation and transmission upgrades to provide 15 MWe

Proposed INL Energy Technology Proving Ground—facilities



Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Additional references

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