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Integrated Energy Systems: Extending Nuclear Energy to Non-Grid Applications

July 2023

Changing the World's Energy Future

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Idaho National Laboratory

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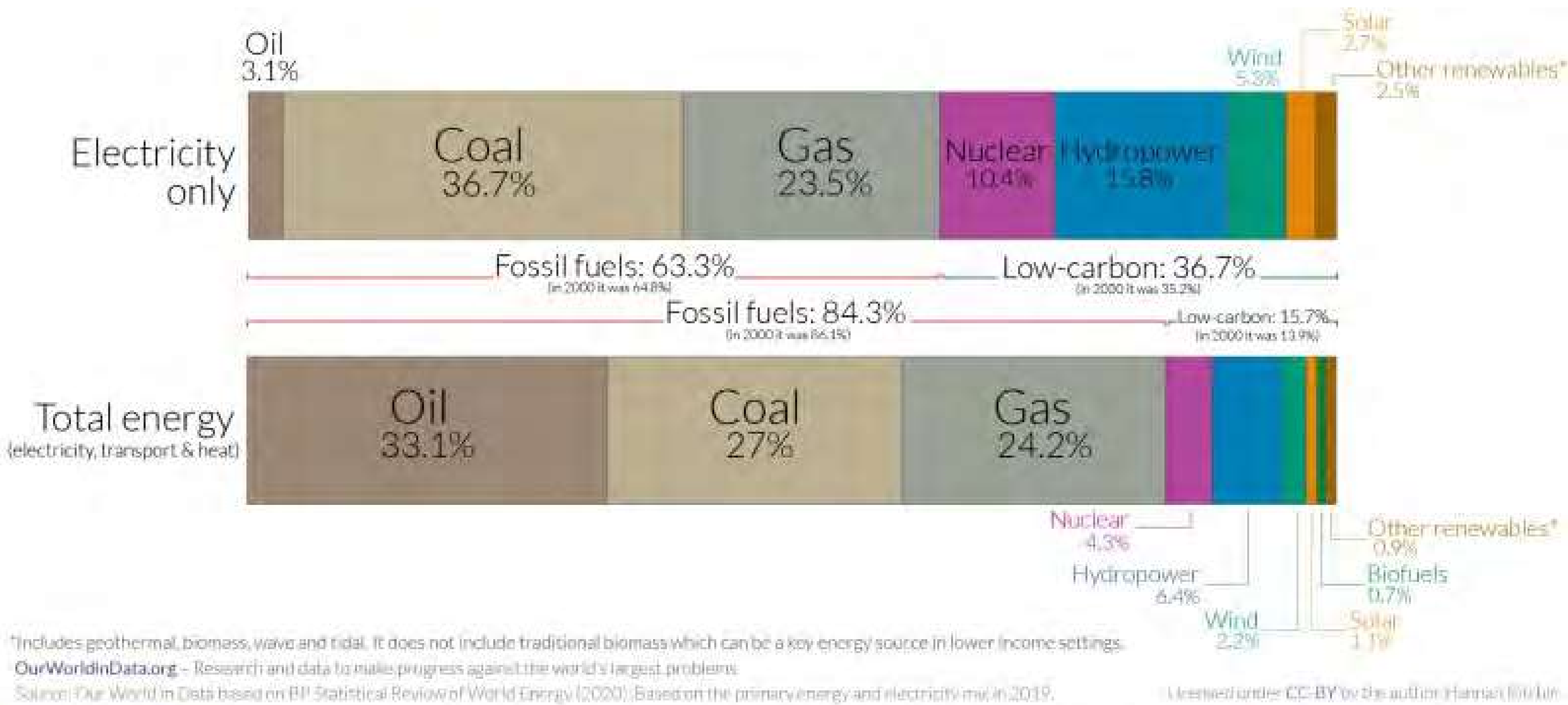
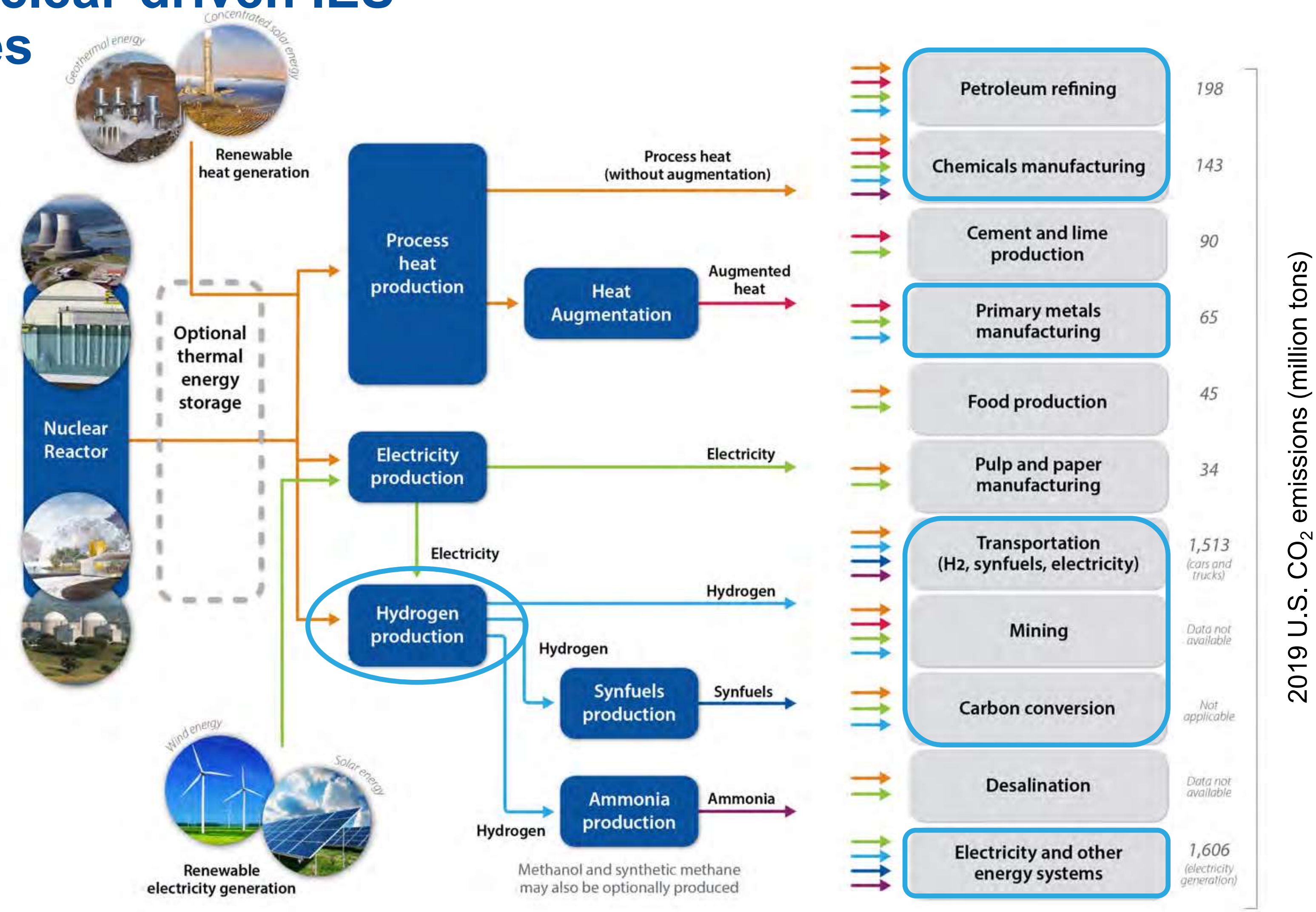
Integrated Energy Systems: Extending Nuclear Energy to Non-Grid Applications

The global challenge: Decarbonizing electricity and total energy sources (2019)



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

Past experience in *operational* nuclear cogeneration, as summarized by Gen-IV International Forum signatory countries

- UK Calder Hall Magnox (heat supported onsite nuclear fuel plant, shut down in 2003)
- Norway Halden BWR (steam for the Saugbrugs paper factory, shut down in 2018)
- Switzerland Gösgen PWR (transport of steam over 2 km to a cardboard factory)
- Canada Bruce A CANDU (district and industrial heating, cogeneration stopped in 1997)
- Germany Stade PWR (salt refinery, nuclear plant shut down in 2003)
- Switzerland Beznau (district heating)
- Various Eastern European countries (district heating)
- >200 reactor-years operating experience with seawater desalination (mostly Japan, India, Kazakhstan; MSF, MED, RO technologies)

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

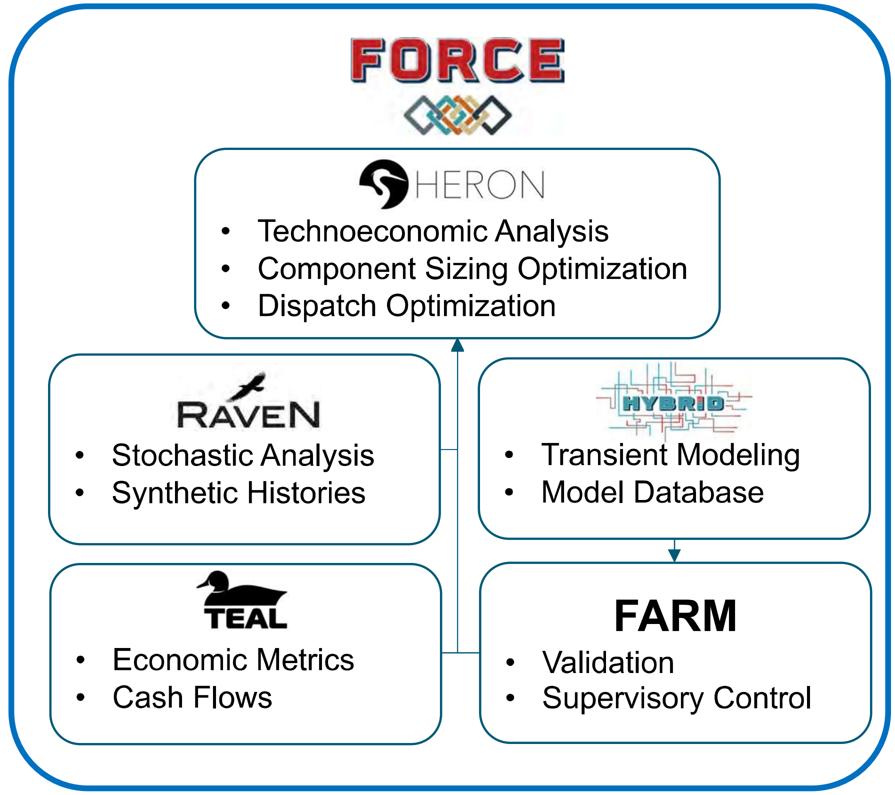
Past experience in *operational* nuclear cogeneration, reflections and lessons learned

- If possible, it is important to consider heat applications at the design phase of nuclear energy systems to avoid potentially costly retrofitting of a system exclusively designed for electricity production.
- Precedent has been established for safe, reliable operation of nuclear cogeneration systems.
- Nuclear standards and regulations have evolved since many of these systems operated and must be reviewed as a part of current efforts.

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

IES analysis and optimization tool suite

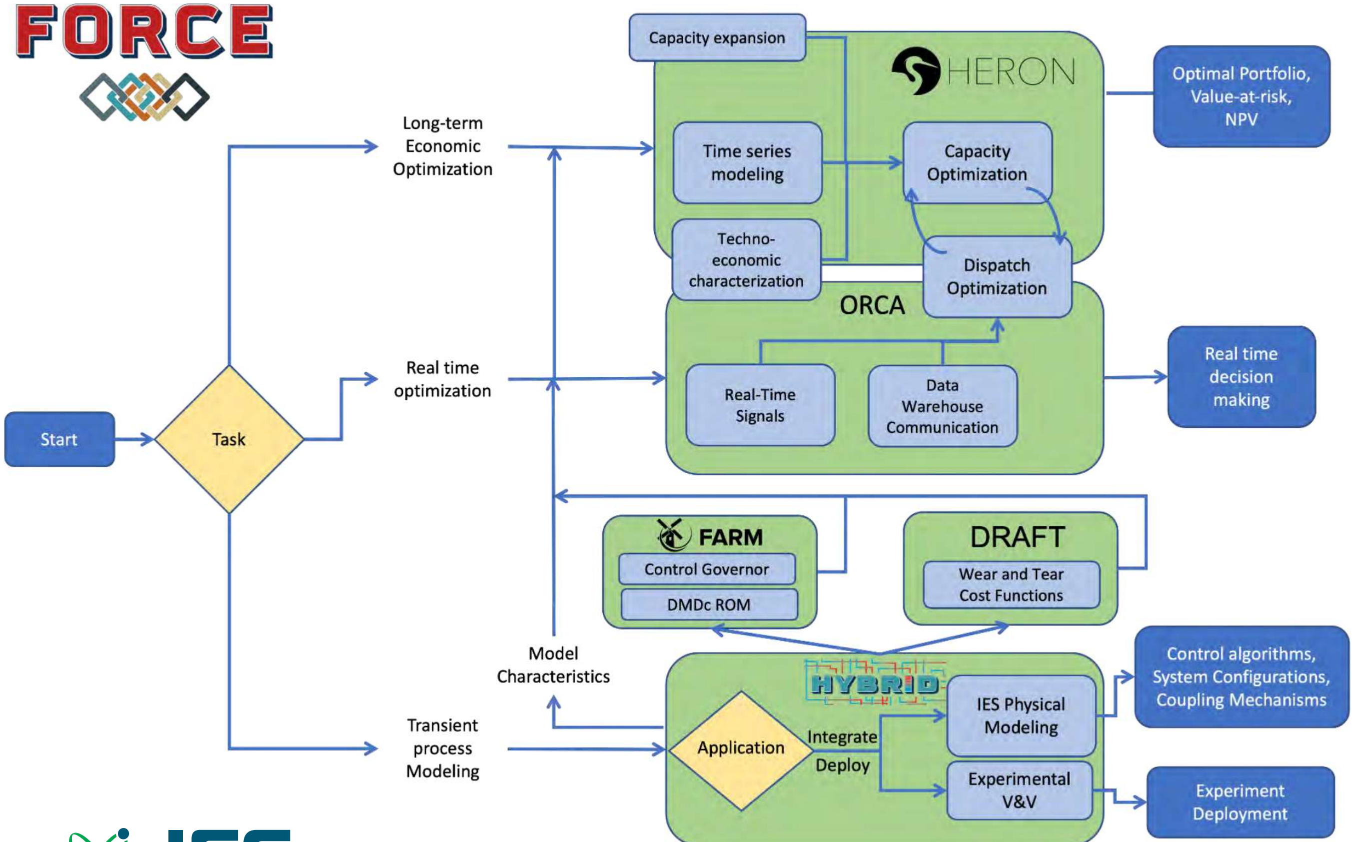
- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Physical process, integration modeling and safety analysis
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - Stochastic analysis, multiple commodities
  - Energy storage, 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_2022.aspx.

Software Map

FORCE



How should each system be sized?

- Technical limitations
- Optimal economics
- Cross-market interaction

How will integrated systems be dispatched?

- What is optimal dispatch?

How are IES dispatched in real time?

- Can we respond to market activity?

What are heat and chemical balances for IES?

- How will IES handle transient operations?

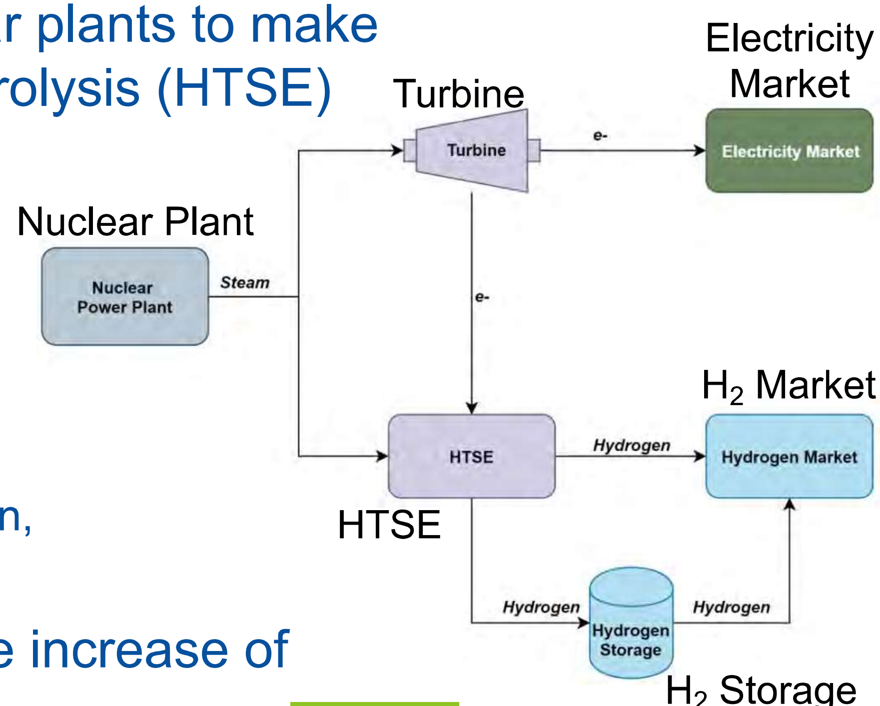
IES Integrated Energy Systems

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 and methanol pathways in development)
  - Carbon conversion (in development)
- Other
  - Steam manifold
  - Switchyard
  - Electric grid
  - Natural gas turbine

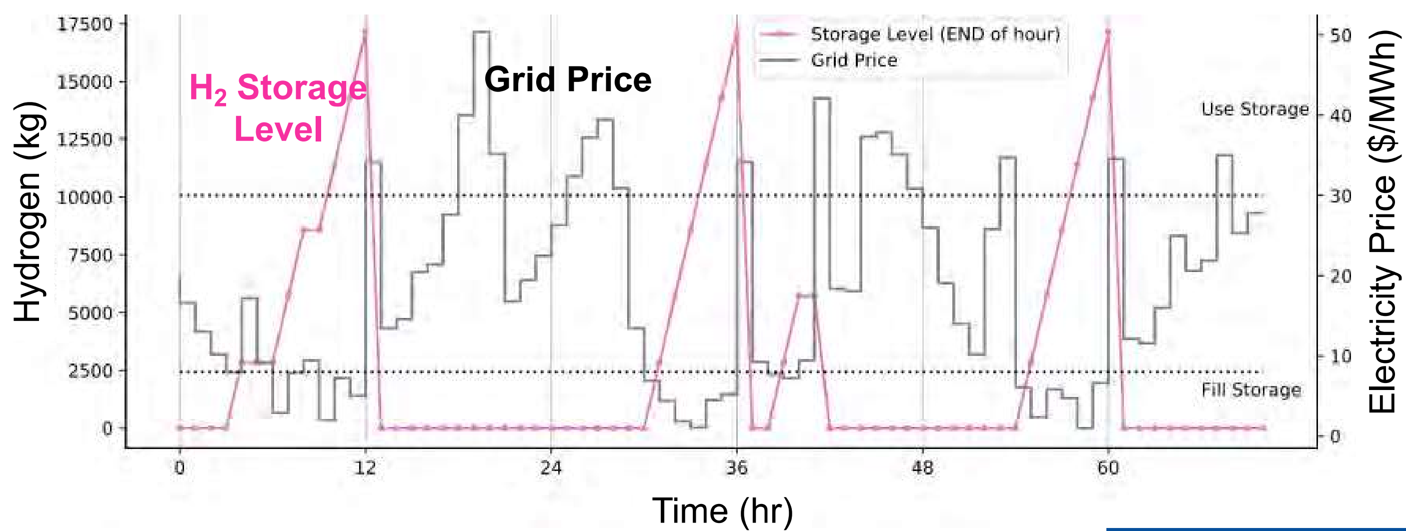
Example: Disruptive potential of nuclear produced hydrogen

- 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.

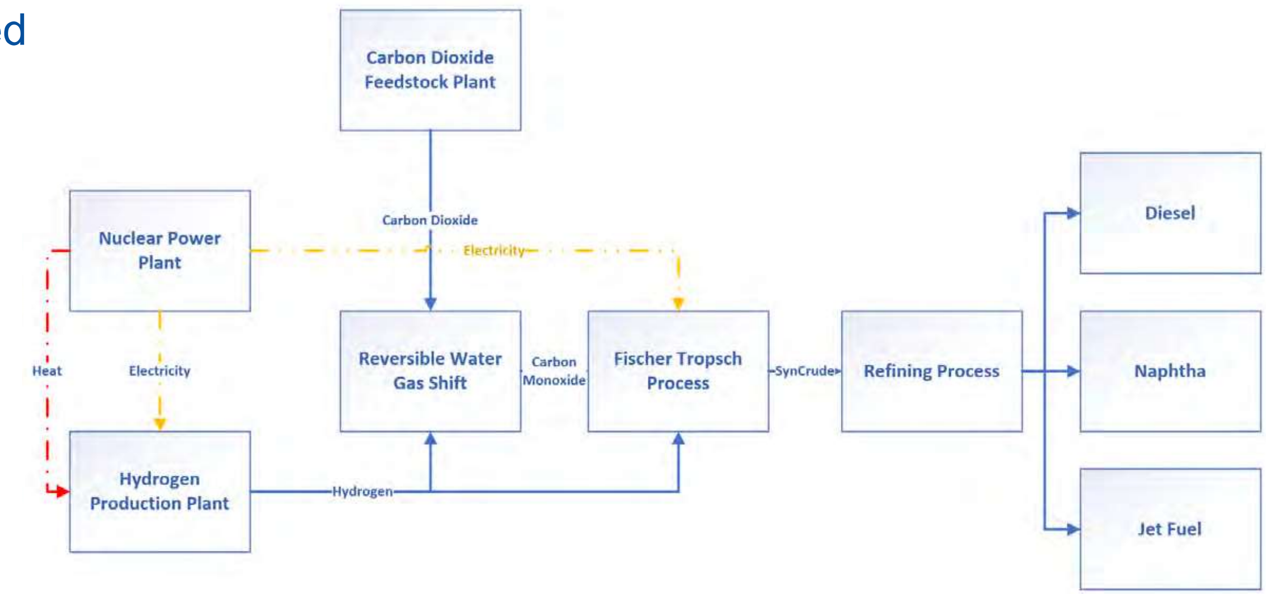
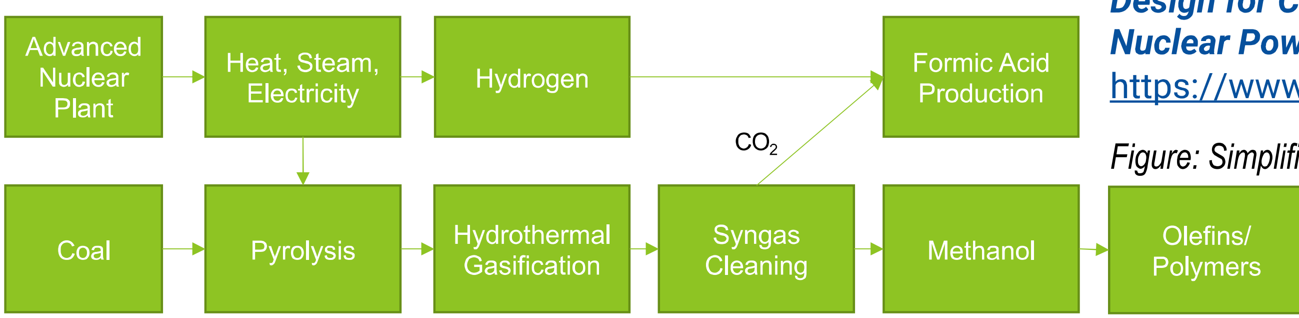


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

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

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).

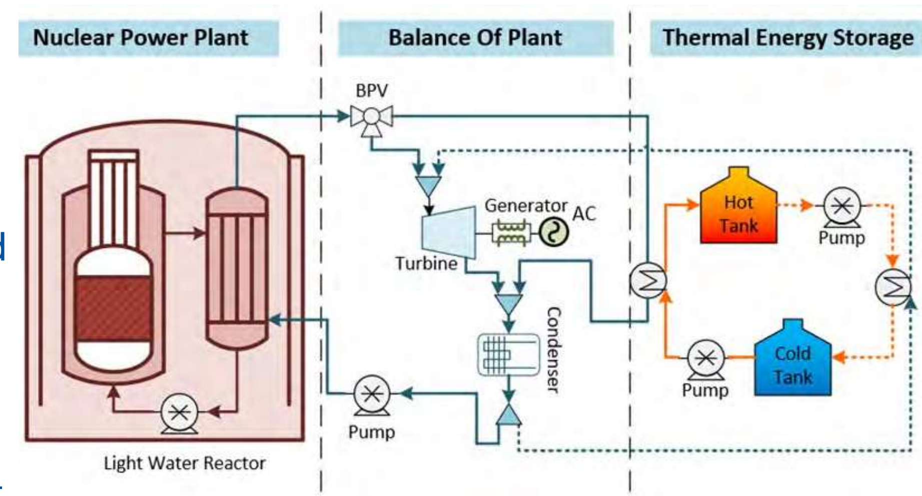


Design for Carbon Conversion Product Pathways with Nuclear Power Plant Integration, 2022, https://www.osti.gov/biblio/1963875

Figure: Simplified flowsheet for the carbon refinery design.

Thermal Energy Storage: Multilevel Analysis and Design of Coupling Advanced Nuclear Reactors

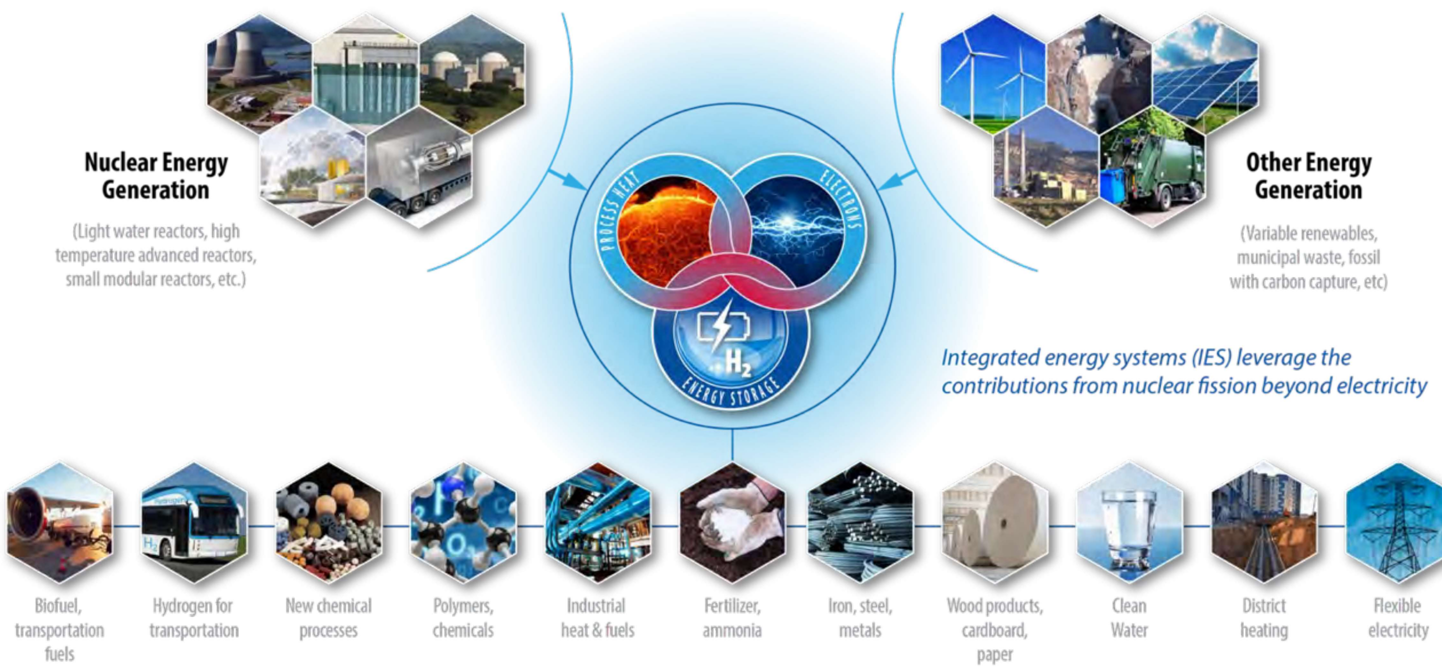
- Explored design and techniques of how advanced nuclear reactors can operate in a more competitive energy market than the current nuclear power plants (NPPs) are facing.
- Why thermal energy storage (TES) coupling?
  - Enables NPPs to respond to market variability and to participate in restructured markets.
  - Store nuclear energy in its original form (heat), allowing for a more flexible use on the back end, providing electricity and/or heat.
- Optimized system architecture to support development of flexible electrical generation from advanced NPP.
- Developed transient process models and control schemes that demonstrated that the design and use cases are physically capable to follow the required dynamic operations.
- All developed computational models have been made available to the public through the HYBRID repository.



Example showing a simplified process flow diagrams for one TES-NPP coupling design

Multilevel Analysis, Design, and Modeling of Coupling Advanced Nuclear Reactors and Thermal Energy Storage in an Integrated Energy System, 2022, https://www.osti.gov/biblio/1890160.

Shifting the energy paradigm through research, development, & demonstration



The primary energy currencies for IES are:
Heat, Electricity, Hydrogen & Carbon

Heat

- Demonstrate high efficiency thermal energy use

Electricity

- Enable a sustainable, resilient, and reliable clean energy grid

Hydrogen & Carbon

- Develop novel chemical and industrial processes using low-emission energy

Integration

- Enhance tools and approaches to optimize IES operations

Joint DOE-industry H_2 production demonstration projects

Multiple projects have been announced for demonstration of hydrogen production at nuclear power plants

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant for a commercial, 1-3 MWe, low-temperature (PEM) and high temperature steam electrolysis modules
- Acquaint NPP operators with monitoring and controls procedures and methods for scaleup to large commercial-scale hydrogen plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Evaluate power inverter control response to provide grid contingency (inertia and frequency stability), ramping reserves, and volt/reactive control reserve
- Produce hydrogen for captive use by NPPs and first movers of clean hydrogen

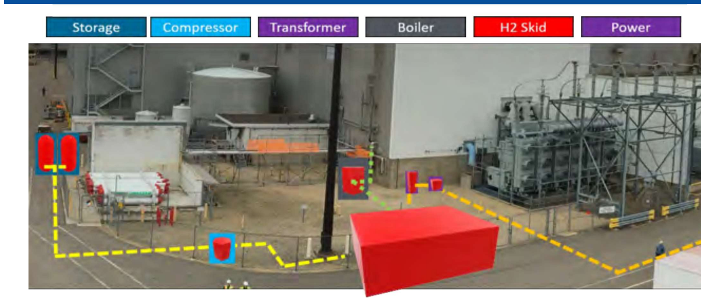
H2@Scale U.S. Department of Energy

LWRS LIGHT WATER REACTOR SUSTAINABILITY

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

Davis-Besse Nuclear Power Plant, LTE/PEM

Thermal & Electrical Integration at Xcel Energy Prairie Island Nuclear Plant



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

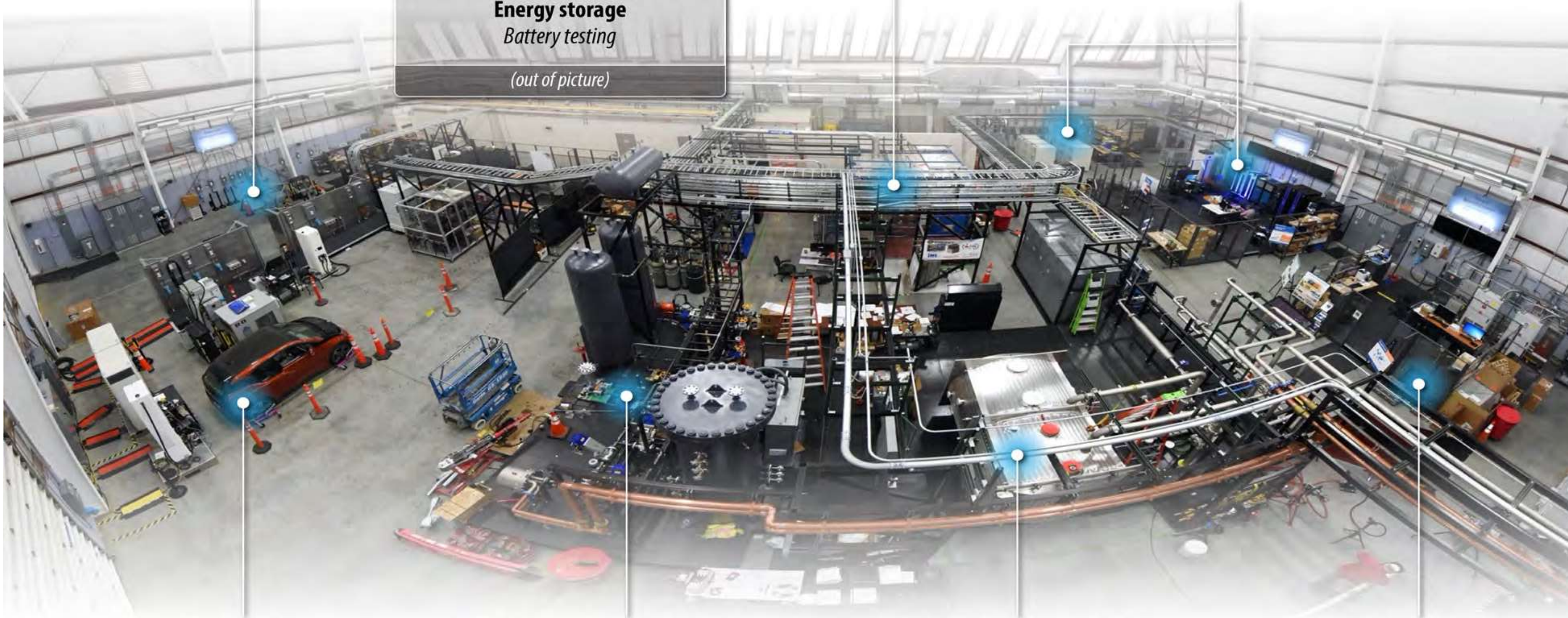
Constellation Starts Production at Nation's First One Megawatt Demonstration Scale Nuclear-Powered Clean Hydrogen Facility

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/

Dynamic Energy Transport and Integration Laboratory (DETAIL)



High temperature electrolysis for hydrogen production

Program Overview

- High temperature electrolysis (HTE) systems produce hydrogen (and oxygen) using heat and electricity with ultra-high efficiency
- INL's 25 kWe HTE Station verifies durability and performance of solid oxide cells that are used to produce hydrogen with high efficiency
- 100 kWe HTE system currently on test (>4500 hrs steady state and transient operation, Bloom Energy)
- 250 kWe HTE to be installed, 2023 (FuelCell Energy)
- 50 kW rSOEC system in preparation
- 50 kW "open" test architecture in preparation
- H2 compression and fueling station to be installed, 2023
- *Working with additional HTSE vendors to test stacks, systems at various scales*

25 kW_{eDC} commercial Stack Testing Module

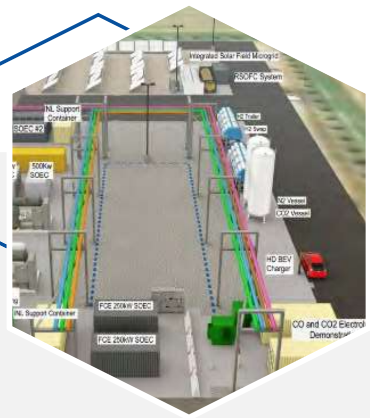
The INL HTE Support Facility:

- *CE+T America Power Converters*
- *Chromalox steam generator*

Bloom Energy 100 kWe HTE Stack Module

At-scale demonstrations, > 1 MW systems, fill the gap

Example, Hydrogen production via HTSE



“ The GAP”

25 kWe High Temperature Electrolysis Stacks V&V

100-500kWe Modular High Temperature Electrolysis Pilot Plant Demonstration

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

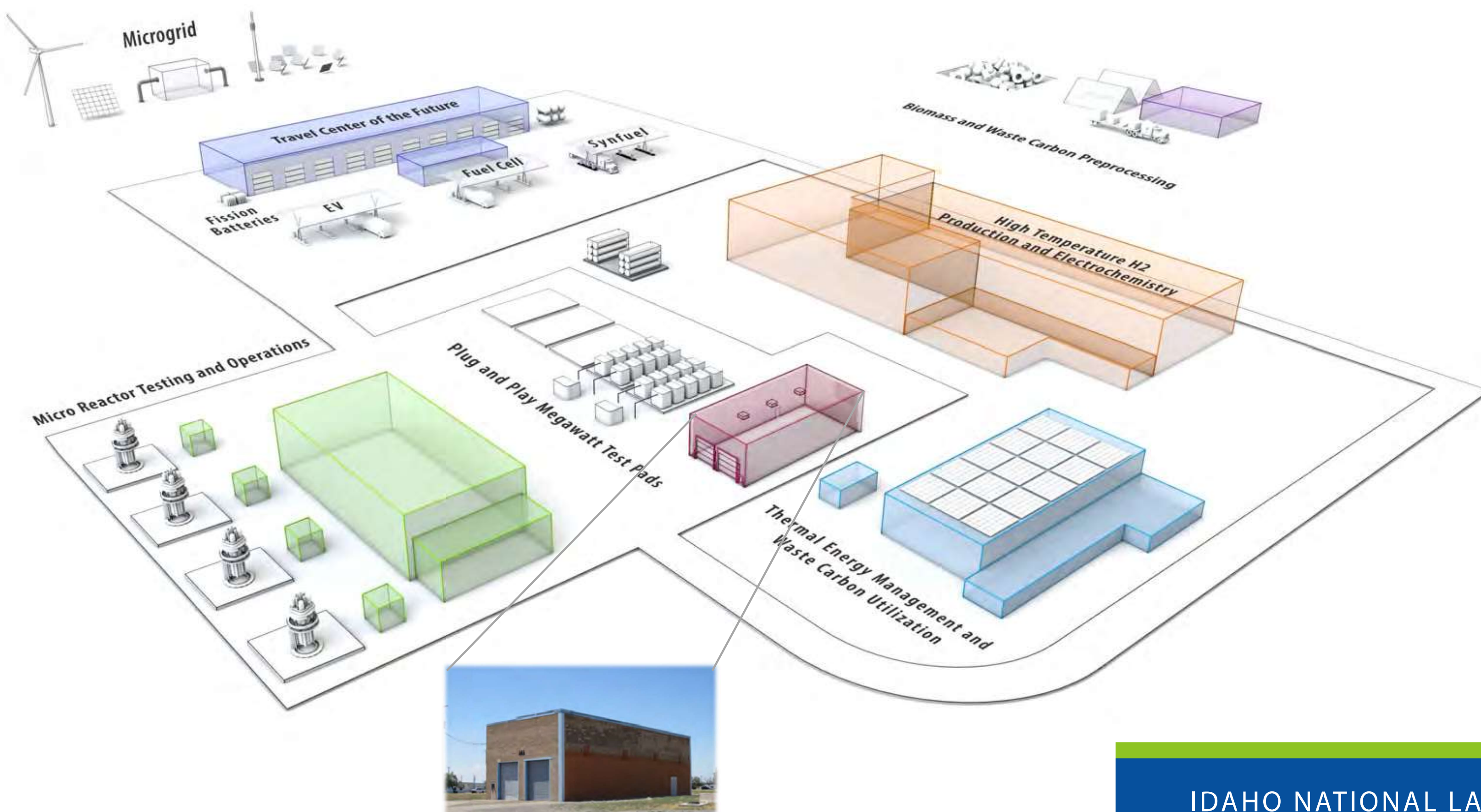
Wide Commercial Deployment:

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

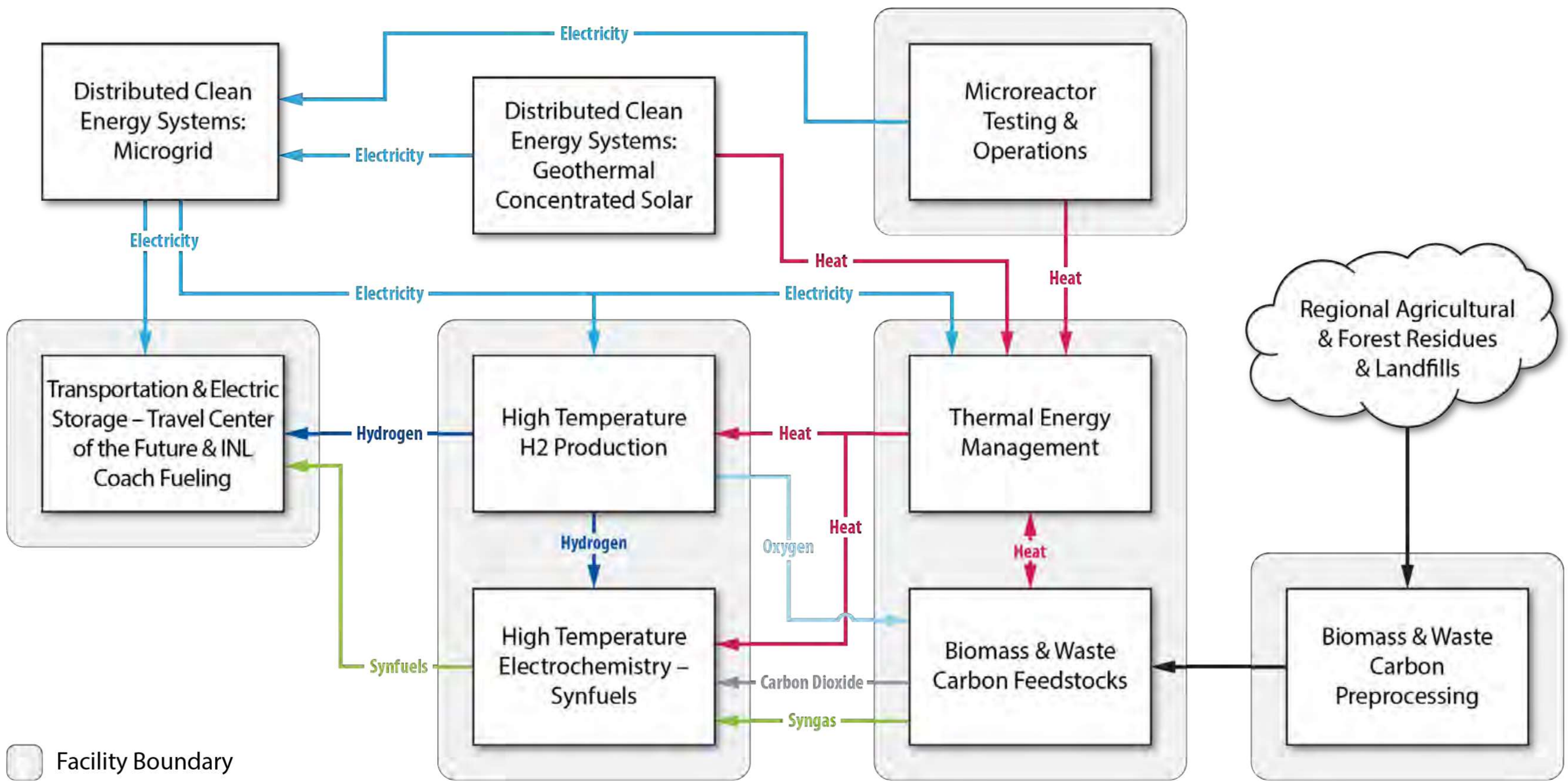
Proposed Energy Technology Proving Ground (ETPG)—Multi-scale research program areas

- 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

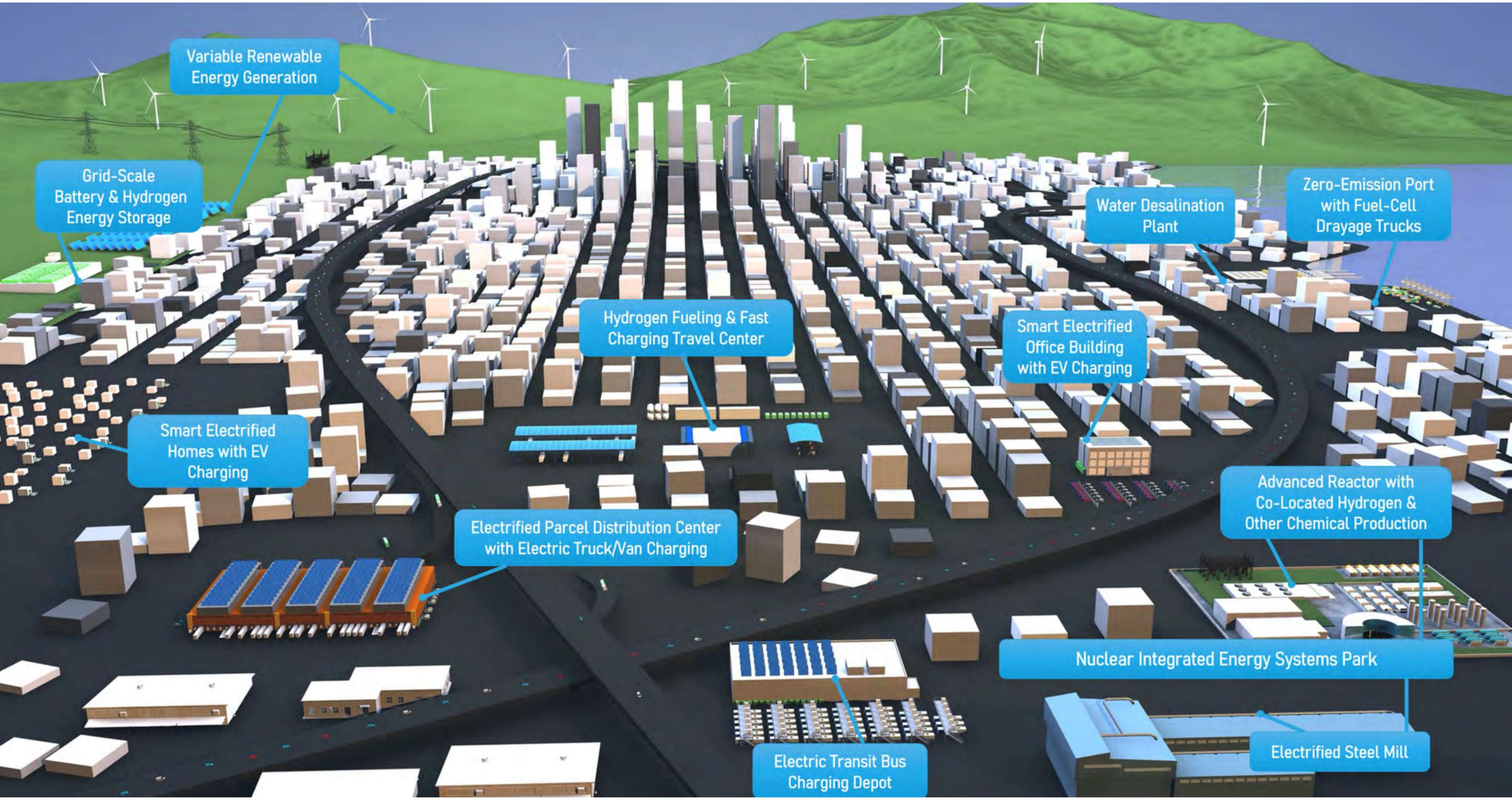
Proposed Energy Technology Proving Ground—planned facilities



Proposed ETPG—Energy flows



A vision for a net-zero future



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Additional references

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Energy production, capture and utilization

- The proposed Energy Technology Proving Ground (ETPG) will be the first to demonstrate a clean energy “community”
- Provides the foundation for future carbon-free infrastructure such as
  - Microreactors for clean industrial thermal and electrical energy uses
  - Microgrid integration of multiple clean energy generators (nuclear, wind, solar, geothermal)
    - Heat for industrial applications and chemical synthesis
    - Electricity for traditional loads and transportation
    - Hydrogen and bio-carbon for transportation, synthetic fuels, and chemical synthesis
- Expect to demonstrate both government-developed and private sector technologies through multiple partnership options