INL/CON-23-72868-Revision-0

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

May 2023

Changing the World's Energy Future

Shannon M Bragg-Sitton

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

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May 2023

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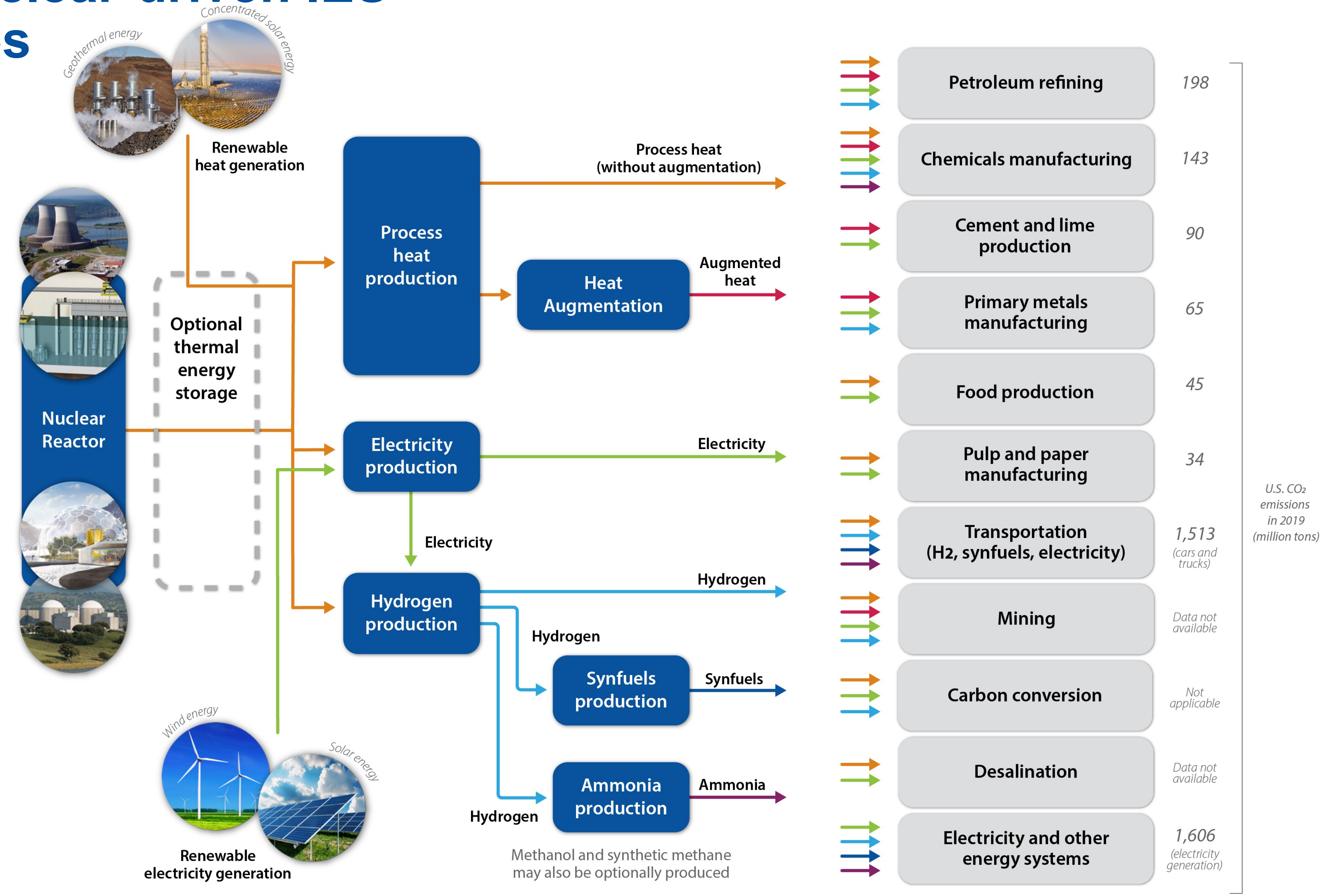
Integrated Energy Systems: Extending Nuclear Energy to Non-Grid Applications

DOE ARPA-E Nuclear Heat Workshop, Houston, TX

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.

U.S. DOE Next Generation Nuclear Plant program—key takeaways

- Cases examined for high temperature gas-cooled reactor utilization (2011)
  - Power generation
  - Hydrogen generation using natural gas
  - Methanol to synthetic gasoline using natural gas
  - Synthetic diesel (liquid) production using natural gas or coal
  - Ammonia production using Natural Gas or Coal
  - SAGD for oil recovery
  - Coal to Natural Gas Production
- High temperature heat, electricity, and hydrogen provided by an HTGR with high temperature steam electrolysis (HTSE) offers many opportunities for integration of nuclear energy in industrial applications
- Results are highly sensitive to economic assumptions and cost inputs
- Cases should be re-evaluated in light of current technology costs, energy markets, and assumptions

INL/EXT-09-16942
Revision 3

Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications

September 2011

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

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INL/EXT-11-23008

Integration of High Temperature Gas-Cooled Reactors into Selected Industrial Process Applications

August 2011

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

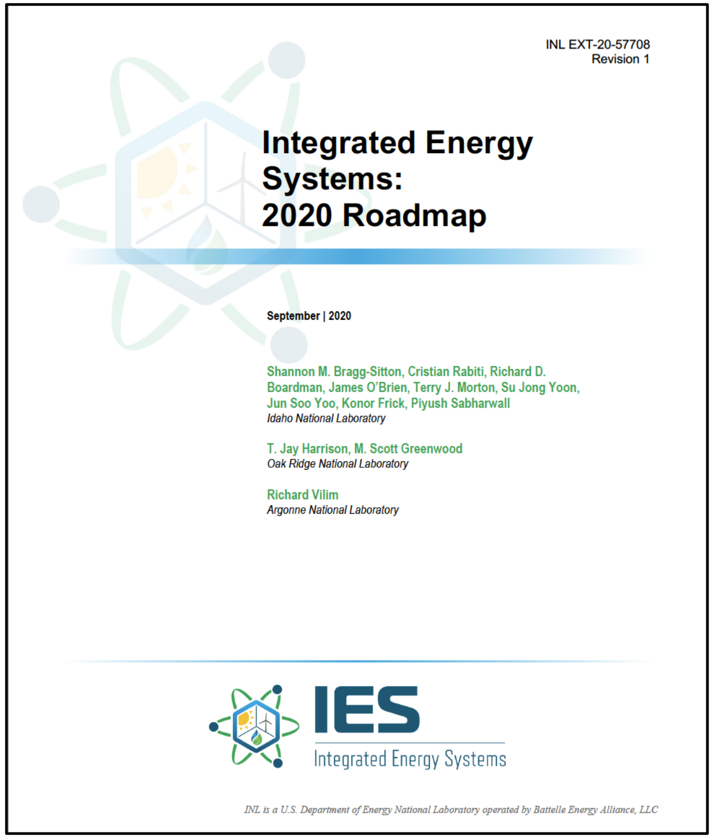
INL Idaho National Laboratory

Report available for download at OSTI.gov: https://doi.org/10.2172/1032079

Also see https://doi.org/10.2172/1481779

Future clean energy systems – transforming the energy paradigm

Current DOE-NE R&D programs for multi-output integrated energy systems


INL EXT-20-57708
Revision 1

Integrated Energy Systems:
2020 Roadmap

September | 2020

Shannon M. Bragg-Sitton, Cristian Rabiti, Richard D. Boardman, James O'Brien, Terry J. Morton, Su Jong Yoon, Jun Soo Yoo, Konor Frick, Piyush Sabharwall
Idaho National Laboratory

T. Jay Harrison, M. Scott Greenwood
Oak Ridge National Laboratory

Richard Vilim
Argonne National Laboratory

IES
Integrated Energy Systems

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

Crosscutting Technology Development
Integrated Energy Systems

IES
Integrated Energy Systems

VISION

A robust and economically viable fleet of light-water and advanced nuclear reactors available to support US clean baseload electricity needs, while also operating flexibly to support a broad range of non-electric products and grid services.

Flexible simulation ecosystem for system design, analysis, technical and economic optimization
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Experimental demonstration for technology development and model validation
-----
Greenfield system design and advanced reactor applications

Reduce risk for commercial LWR-IES deployment

Energy dispatch design and implementation

Technical and economic analysis, near-term markets

Safety assessment and licensing considerations

Timeline for Nuclear IES Deployment

Current fleet **NOW**—Advanced Reactors **5-15 years**


INL/EXT-20-59585
Revision 0

Light Water Reactor Sustainability Program

Flexible Plant Operation and Generation
Technical Program Plan for FY 2021

September 2020

U.S. Department of Energy
Office of Nuclear Energy

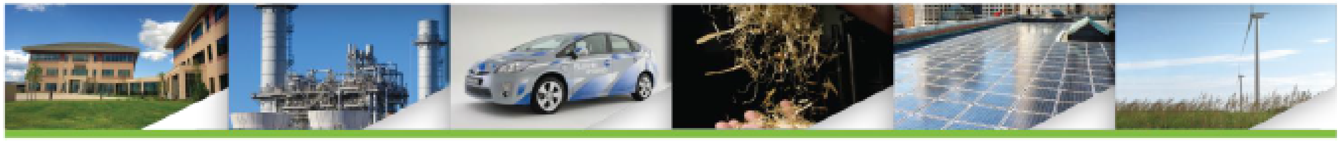
Flexible Plant Operations & Generation Pathway

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Evaluating the options: Heat market study (2016)

JISEA Joint Institute for Strategic Energy Analysis

NREL/TP--6A50-66763
INL/EXT--16-39680



Idaho National Laboratory

Generation and Use of Thermal Energy in the United States Industrial Sector and Opportunities to Reduce its Carbon Emissions

Colin McMillan[1], Richard Boardman[2], Michael McKellar[2], Piyush Sabharwall[2], Mark Ruth[1], and Shannon Bragg-Sitton[2]

[1] National Renewable Energy Laboratory
[2] Idaho National Laboratory

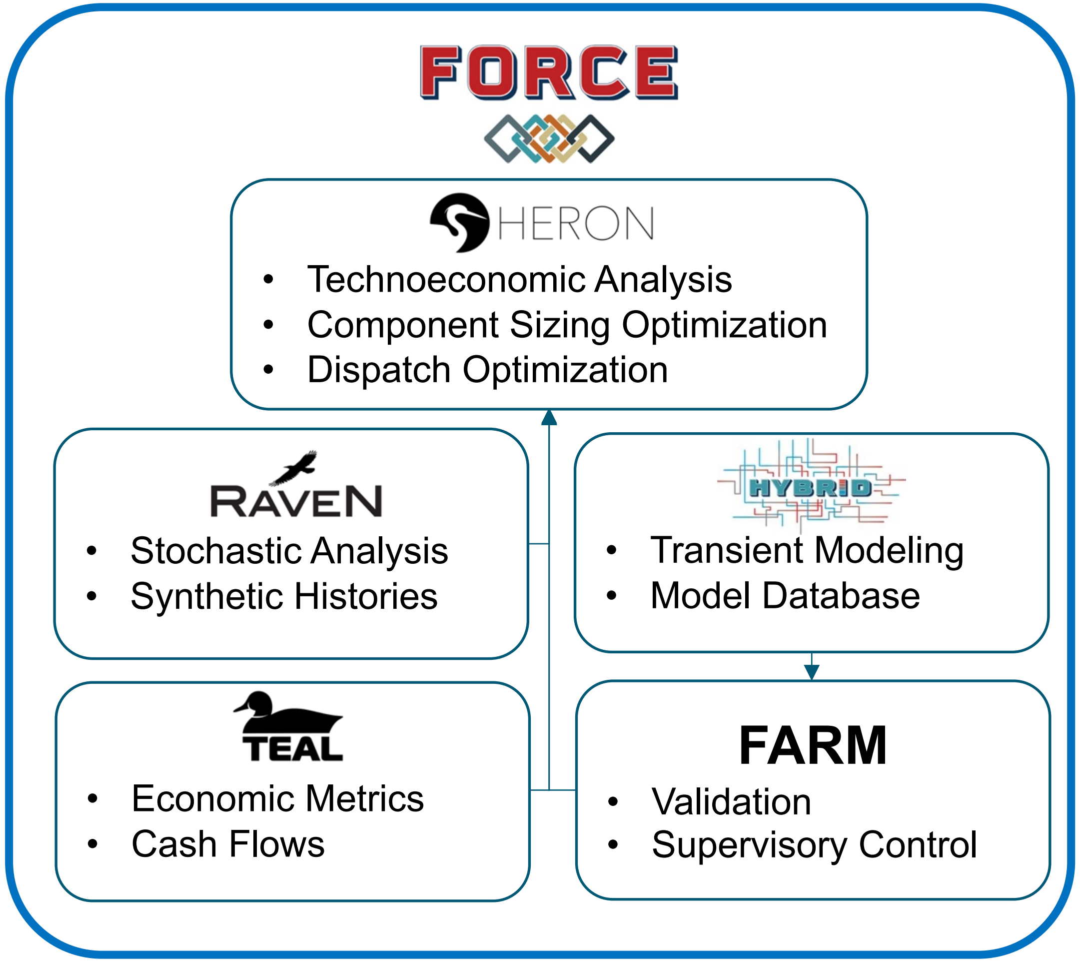
Key conclusions:

- Less than 0.5% of all U.S. manufacturing facilities were responsible for nearly 25% of industrial GHG emissions
- SMR technologies are expected to be well-matched to the scale of demand of oil refineries, pulp/paper manufacturing, methanol, fertilizer plants, among others
- Heat recuperation and temperature boosting are important thermal energy management concepts that may benefit lower temperature energy sources
- Hybrid thermal/electricity generation may help balance hourly, daily, and/or seasonal electrical cycles

http://www.osti.gov/scitech/biblio/1334495-generation-use-thermal-energy-industrial-sector-opportunities-reduce-its-carbon-emissions

IES analysis and optimization tool suite

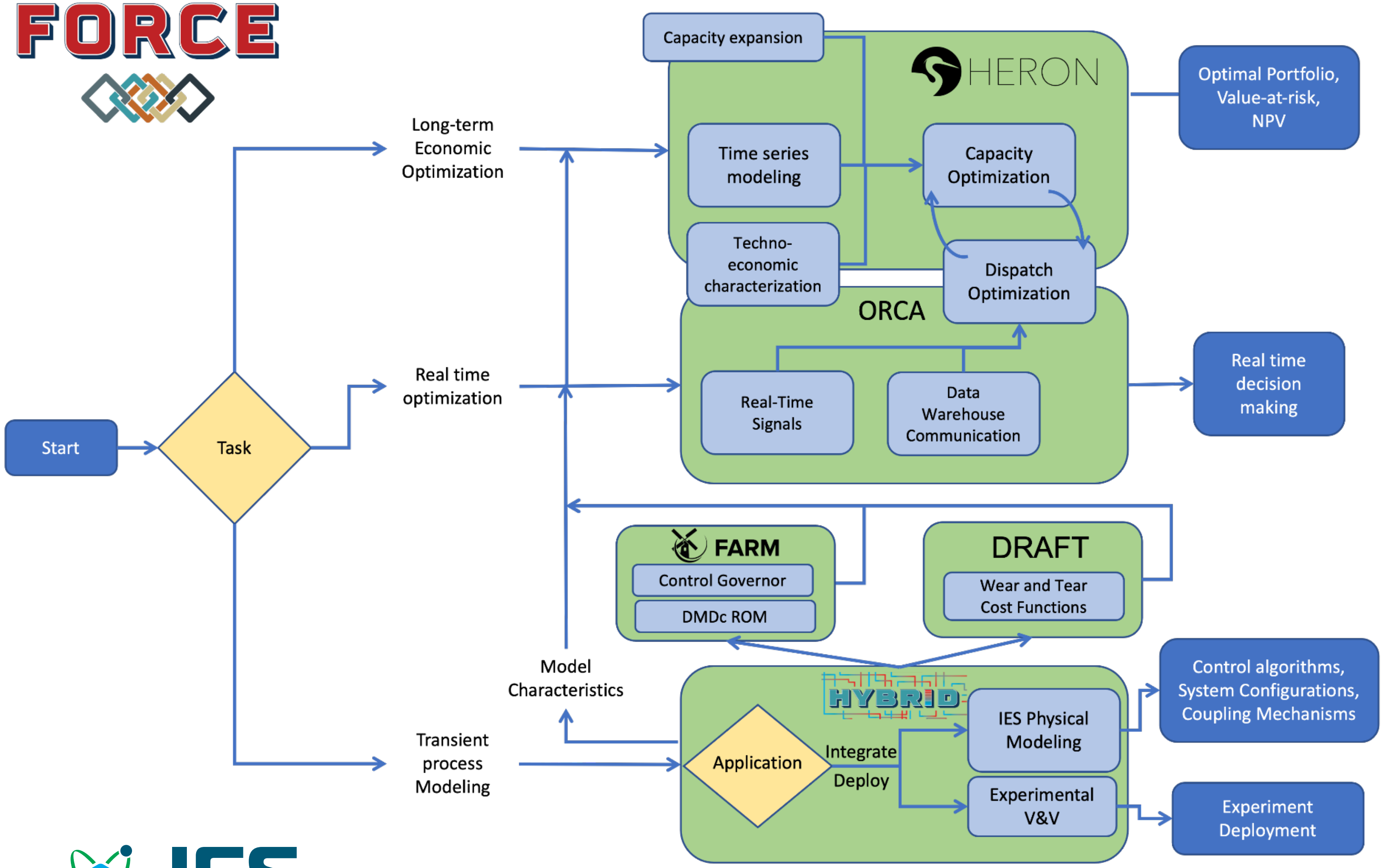
- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Physical process, integration modeling and safety analysis
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - Stochastic analysis, multiple commodities
  - Energy storage,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

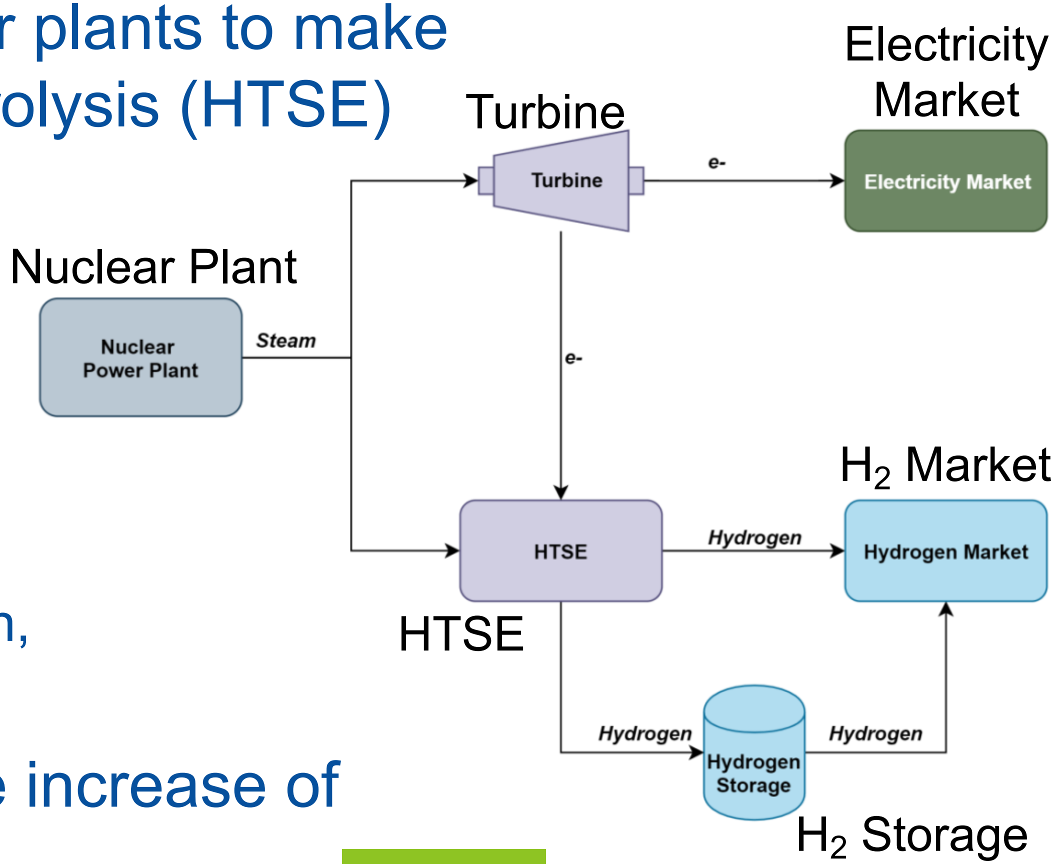
IES Integrated Energy Systems

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

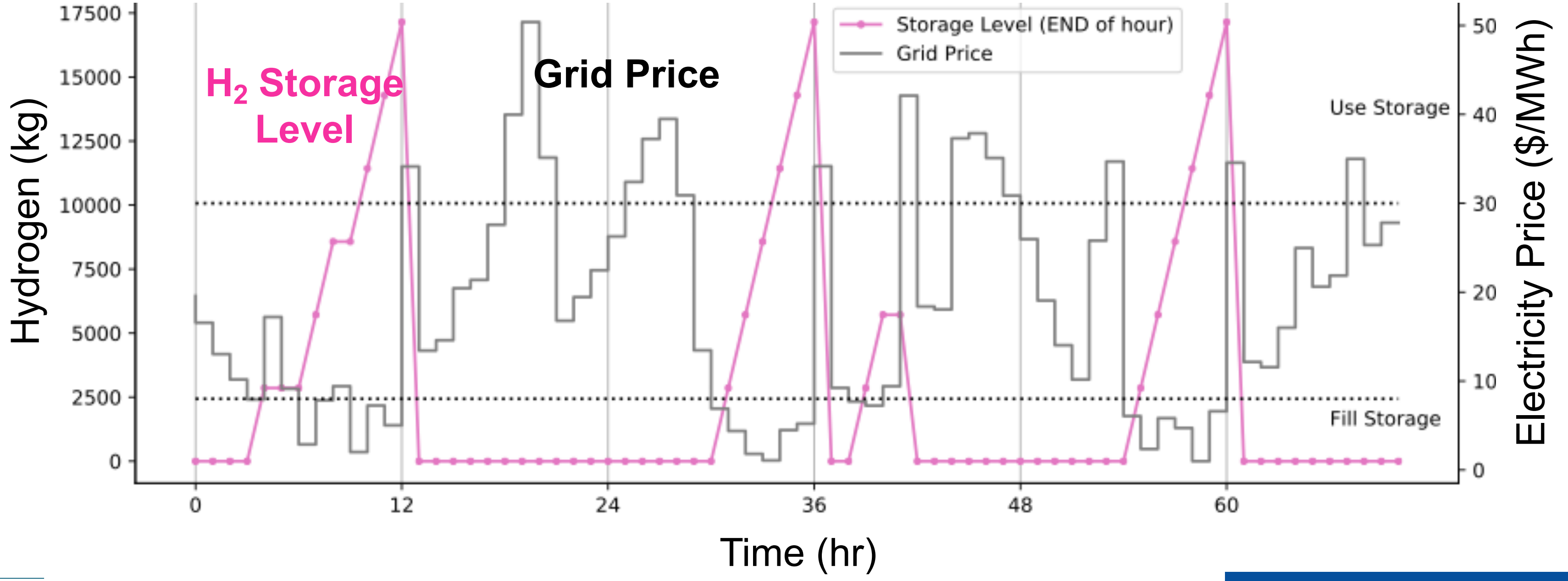
Example: Disruptive potential of nuclear produced hydrogen

- 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)



Nuclear Synthetic Fuels Production

IES Integrated Energy Systems

- 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
- FY23 ongoing
  - Evaluate alternative processes for synfuel production.
  - Develop models, use cases, and dynamically evaluate the Methanol-to-Diesel (MTD) process.

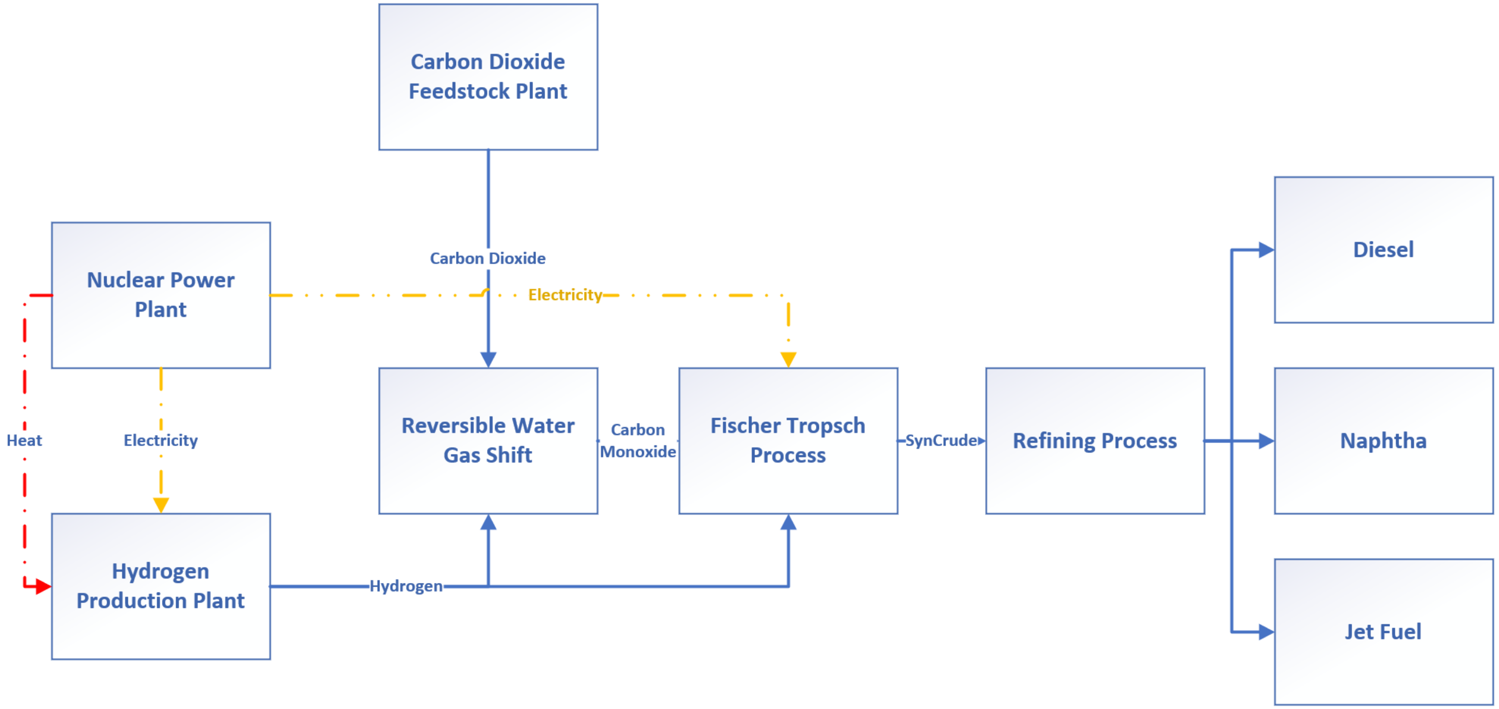
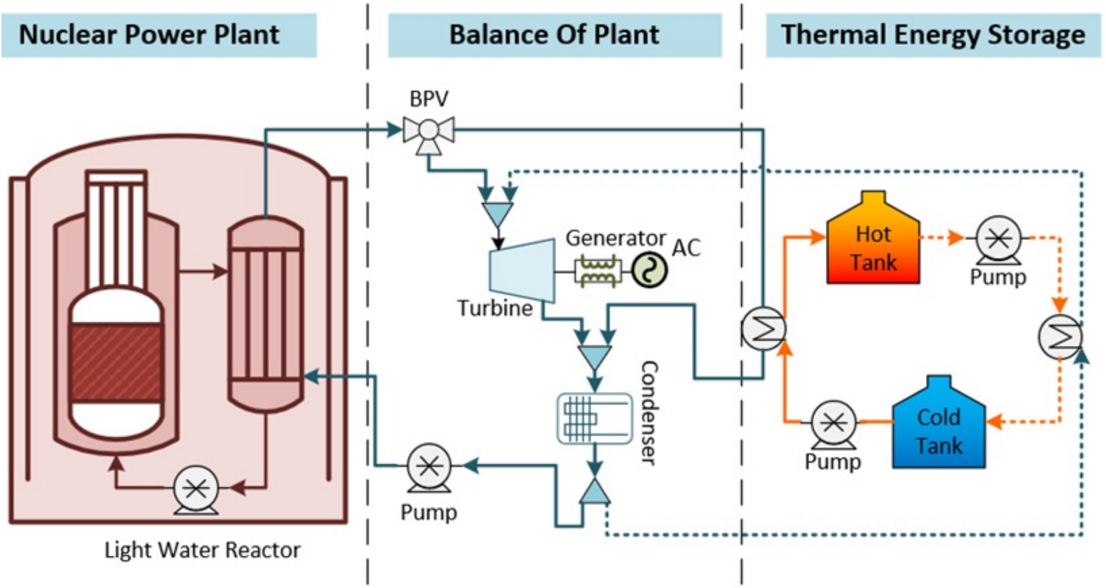


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

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?
  - TES enables NPPs to respond nimbly to market variability and to participate in restructured markets.
  - TES systems store nuclear energy in its original form (heat), allowing for a much more flexible use on the back end, providing electricity and/or heat.
- Optimized system architecture to support the 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

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 form 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 due to variety of non-fuel pathways for further processing. Polymers chosen as the final product. Polypropylene was found to have the highest market potential of olefin-based polymers, with an annual market of 1.87 billion with expected annual growth of 3.2%. Demand is expected to increase due to growing demand of lightweight vehicles.
  - **Formic acid:** Ideal product for carbon dioxide utilization because it can be synthesized directly using hydrogen from electrolysis. The process would consume 2 tons of CO_2 per ton formic acid and has a growing market due to its use as a livestock food preservative and growing interest in its use as a hydrogen carrier. The global market size is currently $878.7 million annually with expected annual growth of 4.94%.
  - **Activated carbon**: Coal char from pyrolysis is converted to activated carbon. While activated carbon does not have a strong market potential, it is highly effective for mercury removal from the syngas. The main barrier to use is its cost, so making it in-house could make it more economical.

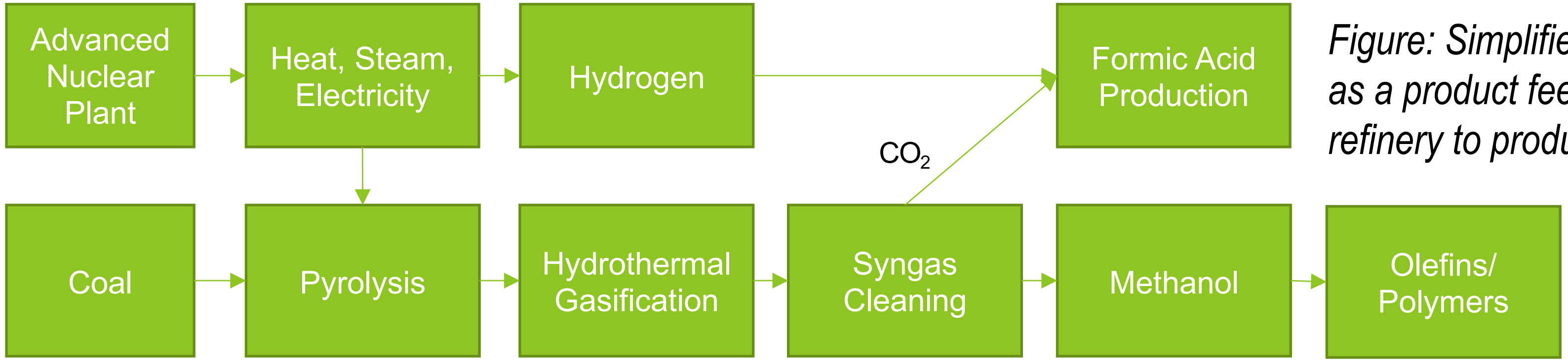


Figure: Simplified flowsheet for the carbon refinery design, using coal as a product feedstock and an advanced nuclear plant to power the refinery to produce hydrogen, formic acid, methanol and polymers.

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

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

Joint EERE-NE H_2 production demonstration projects

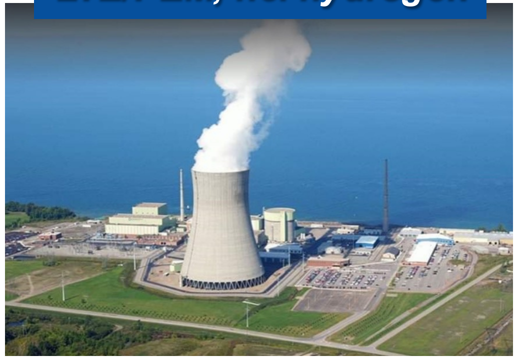
Multiple projects have been announced for demonstration of hydrogen production at nuclear power plants

- 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

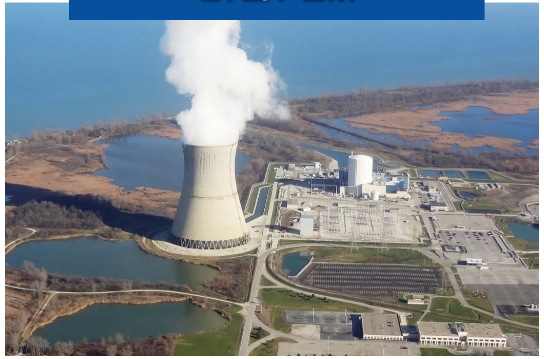
H2@Scale U.S. Department of Energy

LWRS LIGHT WATER REACTOR SUSTAINABILITY

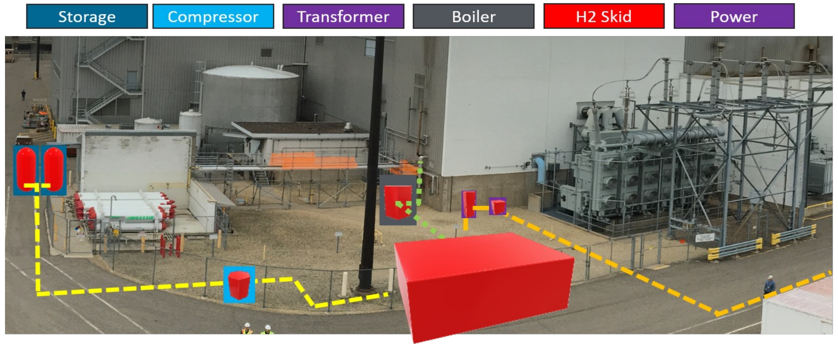
Nine Mile Point Nuclear Power Plant LTE/PEM, nel hydrogen



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

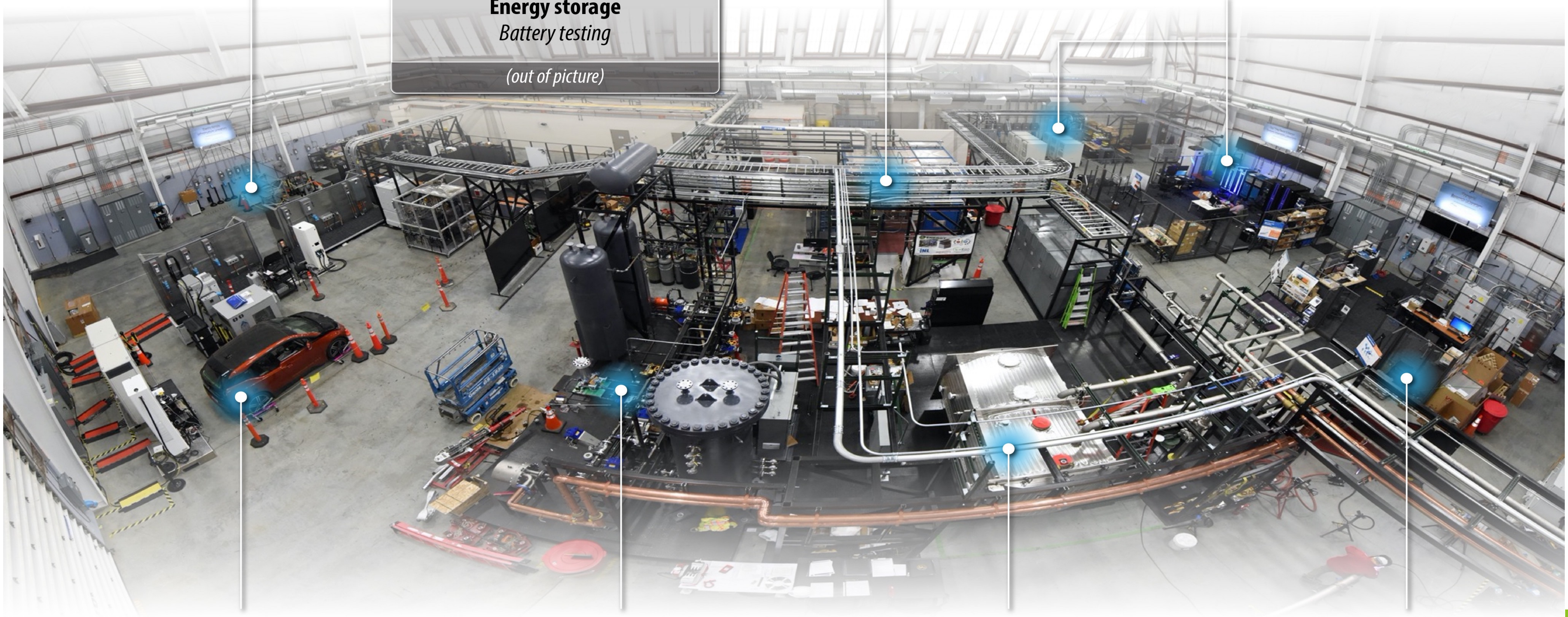
Constellation Starts Production at Nation's First One Megawatt Demonstration Scale Nuclear-Powered Clean Hydrogen Facility

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.

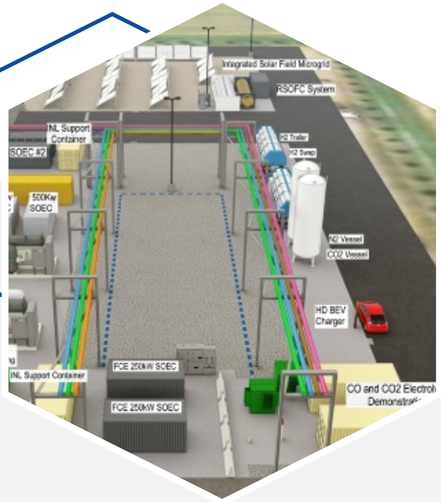
Photos courtesy Constellation, https://www.ans.org/news/article-4810/constellation-starts-hydrogen-production-at-nine-mile-point/

Dynamic Energy Transport and Integration Laboratory (DETAIL)



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

25 kWe High Temperature Electrolysis Stacks V&V



100-500kWe 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:

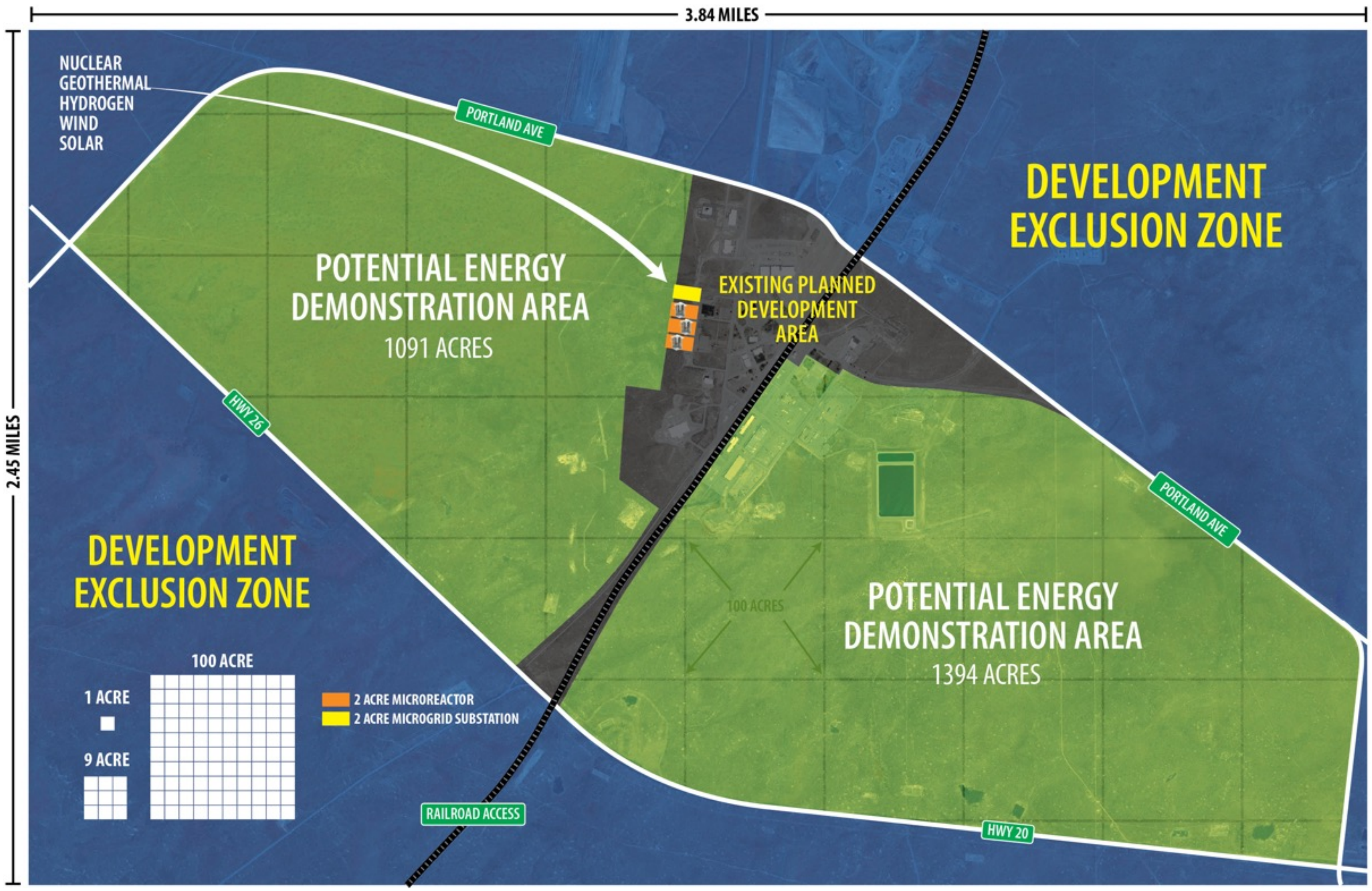
- Hydrogen production at nuclear power plants
- Industry-embedded hydrogen production and use

INL Central Facilities Area

Home of the new Energy Technology Proving Ground (ETPG)

- INL has committed to becoming a net-zero campus by 2031
- Attributes of a small city or county
- 890 sq mi
- >5800 employees
- >50 MWe purchased in FY2020
- >300 DOE-owned buildings
- Existing microgrid
- 3 fire stations, 1 museum, medical facilities, …
- >40 miles primary roads

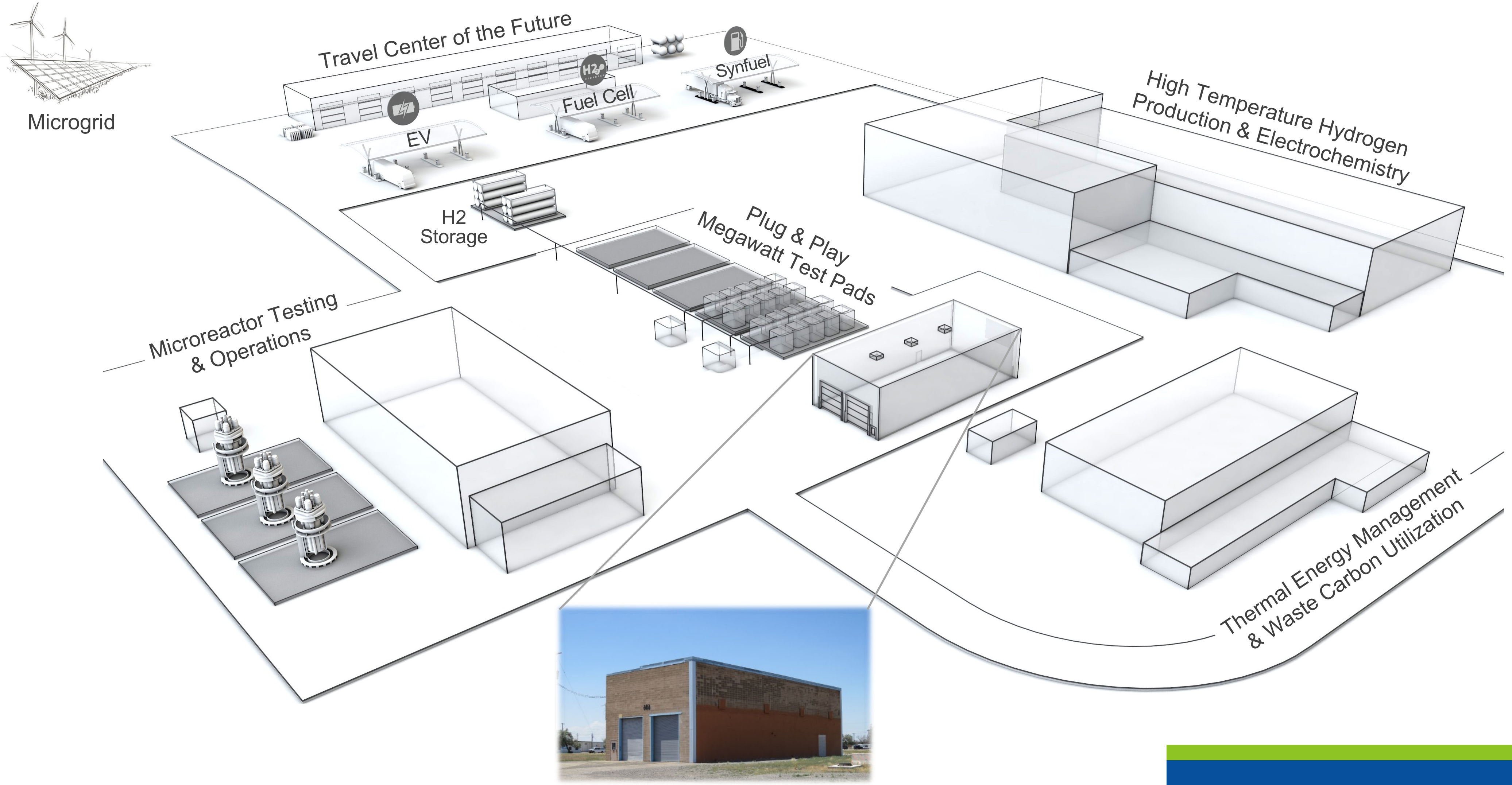
CFA region



CFA region with notional layout options

- ~2500 acres of land available for growth
- Leverages existing infrastructure (highbay) and INL investment in necessary infrastructure upgrades
- 15 MWe to be available from existing substation and transmission upgrades
- Supports testing and demonstration of energy users and thermal island well in advance of micro reactor installation

INL Energy Technology Proving Ground



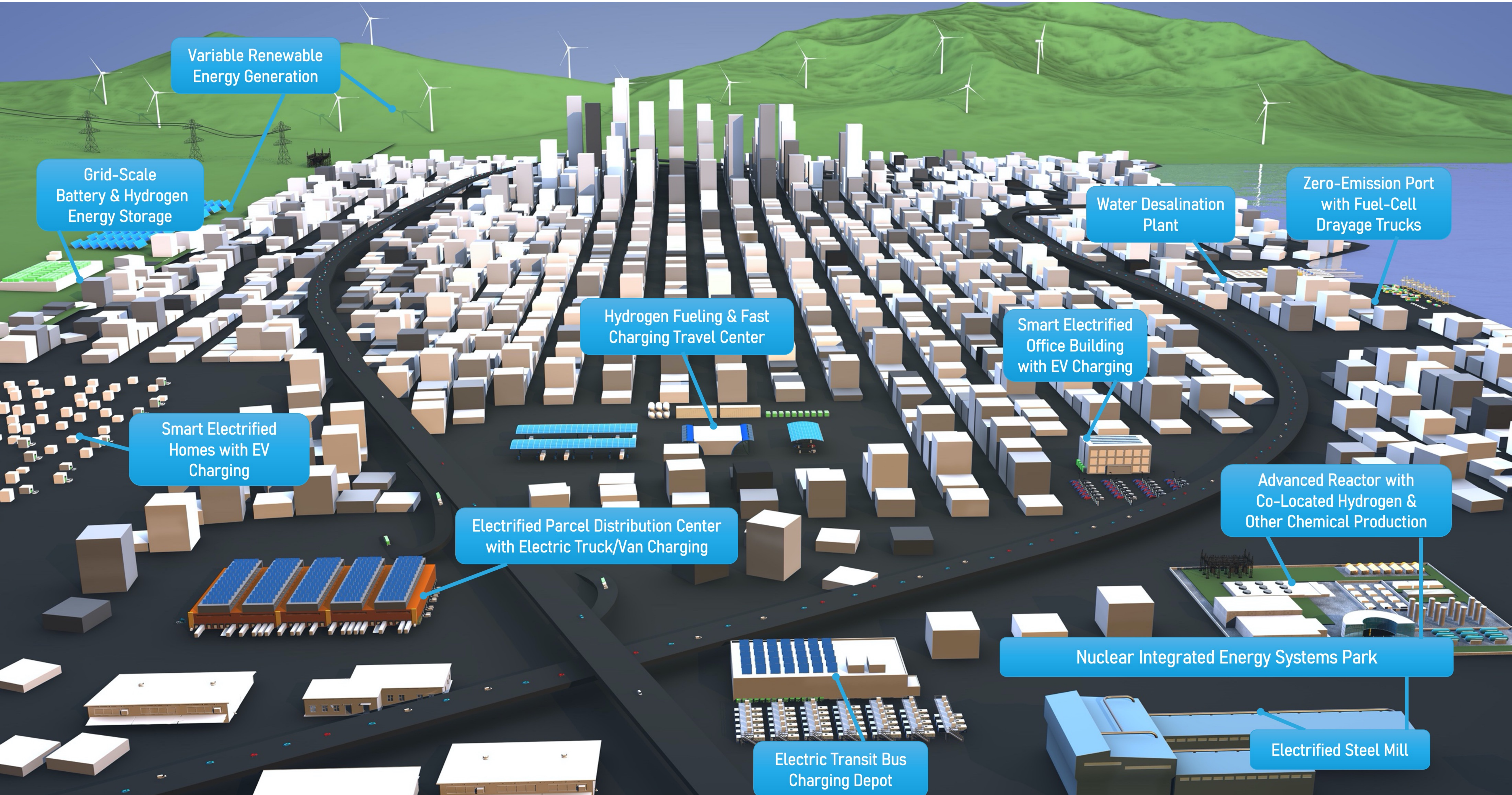
Proving Ground multi-scale research program areas

- 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

Energy production, capture and utilization

- The CFA 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

A vision for a net-zero future



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- DOE-NE LWRS, Flexible Plant Operations & Generation reports: https://lwrs.inl.gov/SitePages/GroupedReports-sorted.aspx?ReportCategory=Flexible%20Plant%20Operation%20and%20Generation

INL

Idaho National Laboratory

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