INL/MIS-23-74069-Revision-0



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

#### July 2023

nanging the World's Energy Future

Shannon M Bragg-Sitton



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

#### DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/MIS-23-74069-Revision-0

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

Shannon M Bragg-Sitton

July 2023

Idaho National Laboratory Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the U.S. Department of Energy Under DOE Idaho Operations Office Contract DE-AC07-05ID14517

### 27 July 2023

Shannon Bragg-Sitton, PhD Director, Integrated Energy & Storage Systems, INL

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

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



## 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, <u>National Reactor</u> <u>Innovation Center</u> (NRIC) Integrated <u>Energy Systems</u> <u>Demonstration Pre-</u> <u>Conceptual Designs</u>, April 2021



2019 U.S.  $CO_2$  emissions (million tons)

# 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 <u>Summary Report</u> 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 <u>Summary Report</u> 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**

Integrated Energy Systems



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?

## 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<sub>2</sub> 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  $\rightarrow$  hydrogen is more profitable Nuc
  - High grid pricing  $\rightarrow$  grid is more profitable
  - H<sub>2</sub> storage provides flexibility in plant operations, ensures that all demands are met
  - H<sub>2</sub> 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**



- Synthetic fuels production linked to nuclear plant capacity
- Fischer-Tropsch TEA
  - LWRs
  - Different locations
  - Different CO<sub>2</sub> 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, <u>https://www.osti.gov/biblio/1984196</u>

# 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<sub>2</sub> 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).



# 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



### 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

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

## Joint DOE-industry H<sub>2</sub> 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





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, <u>https://www.ans.org/news/article-</u> 4810/constellation-starts-hydrogen-production-at-nine-mile-point/





Fast charging

TEDS - Thermal Energy Distribution System (includes thermal energy storage) MAGNET - Microreactor Agile Non nuclear Experimental Testbed Distributed energy and microgrid

## 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<sub>eDC</sub> 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





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



# 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.

### WWW.INL.GOV

## **Additional references**

- <u>Summary Report</u> from the Generation-IV International Forum (GIF) Nonelectric Applications of Nuclear Heat (NEANH) Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies, July 2022.
- GIF NEANH, *Non-electric applications of nuclear workshop*, October 2022, <u>https://www.gen-4.org/gif/jcms/c\_206303/non-electric-applications-of-nuclear-workshop-in-collaboration-with-ifnec</u>.
- Bragg-Sitton, S.M., and Boardman, R., "Introduction to Non-electric Applications of Nuclear Energy," *Encyclopedia of Nuclear Energy*, Section 12: Non-electric applications of terrestrial nuclear reactors, Vol. 3, p. 1-7, 2021.
- IAEA Nuclear Energy Series, Nuclear Renewable Hybrid Energy Systems, No. NR-T-1.24, Vienna, 2022, <u>https://www-pub.iaea.org/MTCD/Publications/PDF/PUB2041\_web.pdf</u>.
- DOE-NE IES program reports: <u>https://ies.inl.gov/SitePages/Reports.aspx</u>
- DOE-NE LWRS, Flexible Plant Operations & Generation reports: <a href="https://lwrs.inl.gov/SitePages/GroupedReports-sorted.aspx?ReportCategory=Flexible%20Plant%20Operation%20and%20Generation">https://lwrs.inl.gov/SitePages/GroupedReports-sorted.aspx?ReportCategory=Flexible%20Plant%20Operation%20and%20Generation</a>
- NEI, Advanced Nuclear Energy, accessed August 2023

## **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