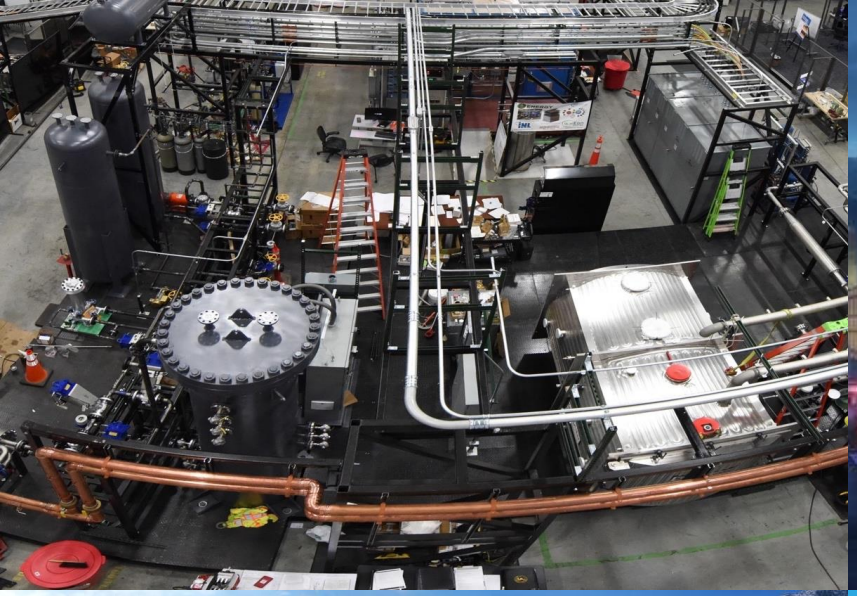

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The Essential Role of Integrated Nuclear-Renewable Energy Systems in Achieving Economy-wide Net-Zero Solutions

Battelle Conference: Innovations in Climate Resilience

March 30, 2022

Idaho National Laboratory

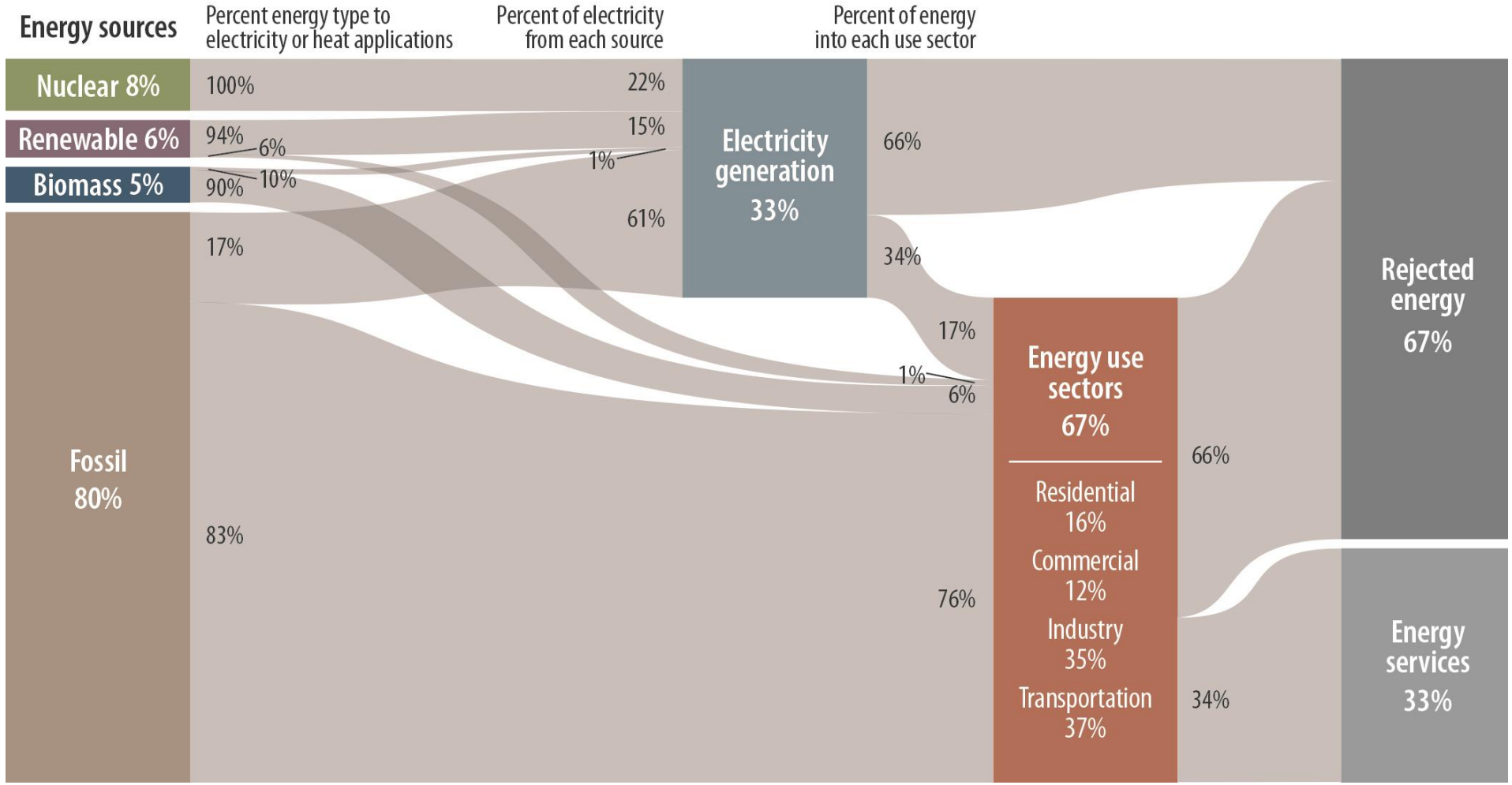
INL/CON-22-66397

Today's electricity grid

- Individual generators contribute to meeting grid demand, managed by an independent grid operator
- Individual thermal energy resources typically support industrial demand
- Transportation mostly relies on fossil fuels (with growing, yet limited, electrification)

Achieving net-zero emissions will require us to consider the role(s) of <u>all</u> clean energy generation options—and we must look to non-emitting sources of <u>heat</u> in addition to electricity.

2018 energy sources and consumers, U.S.



Forsberg and Bragg-Sitton, Maximizing Clean Energy Use: Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat and Hydrogen Demand, *The Bridge*, National Academy of Engineering, 50(3), p. 24-31, 2020. Available at https://www.nae.edu/239120/Fall-Issue-of-The-Bridge-on-Nuclear-Energy-Revisited.

Decarbonizing electricity is only part of the challenge

Electricity accounts for only 17% of total energy use in the U.S. across all "Energy use sectors," with the remaining 83% used in the form of heat.

Adapted from LLNL (2020), https://flowcharts.llnl.gov/

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

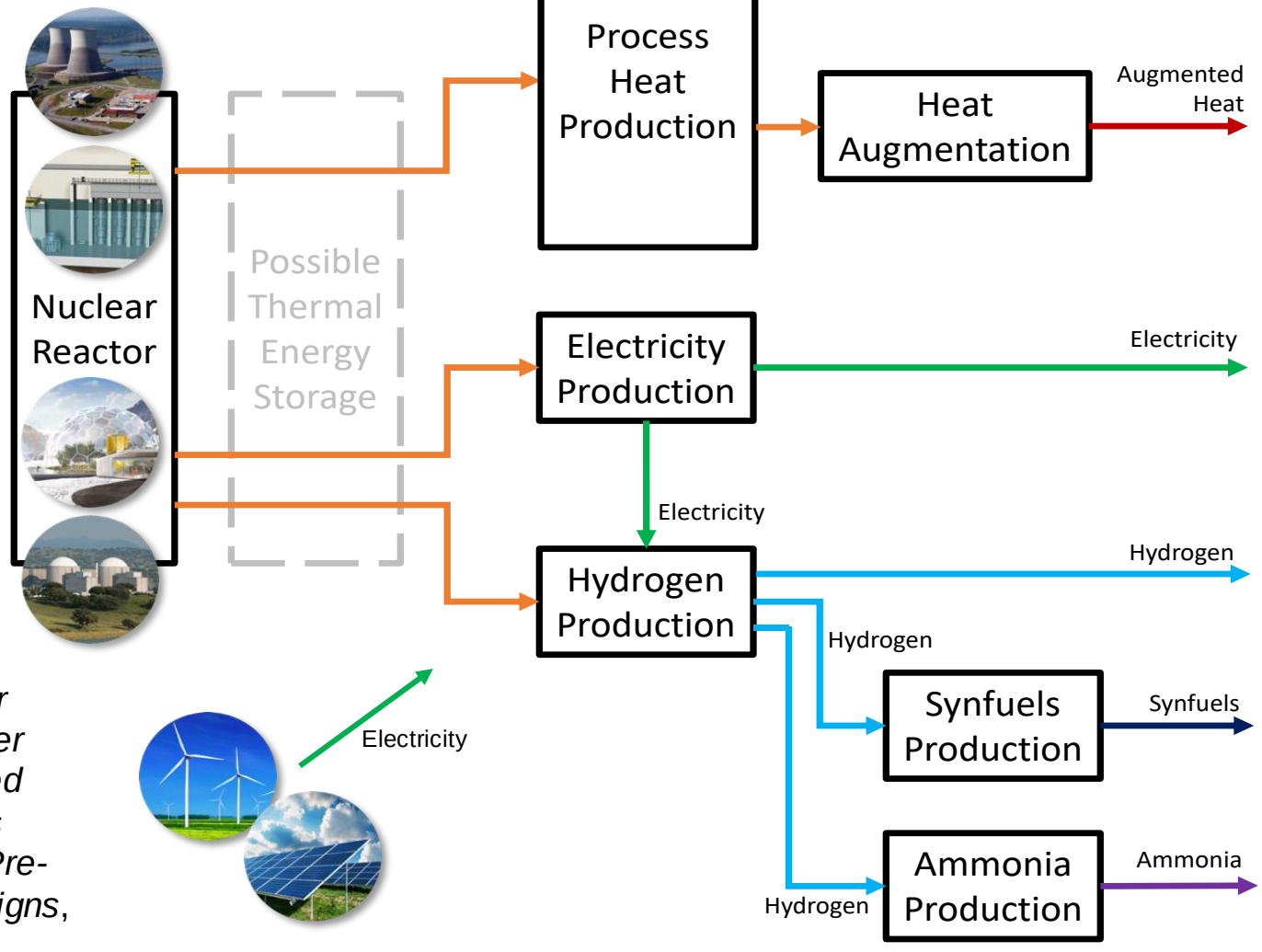
Industry

Electricity

Hydrogen for vehicles and industry

Potential nuclear-driven IES opportunities

Examples not exhaustive



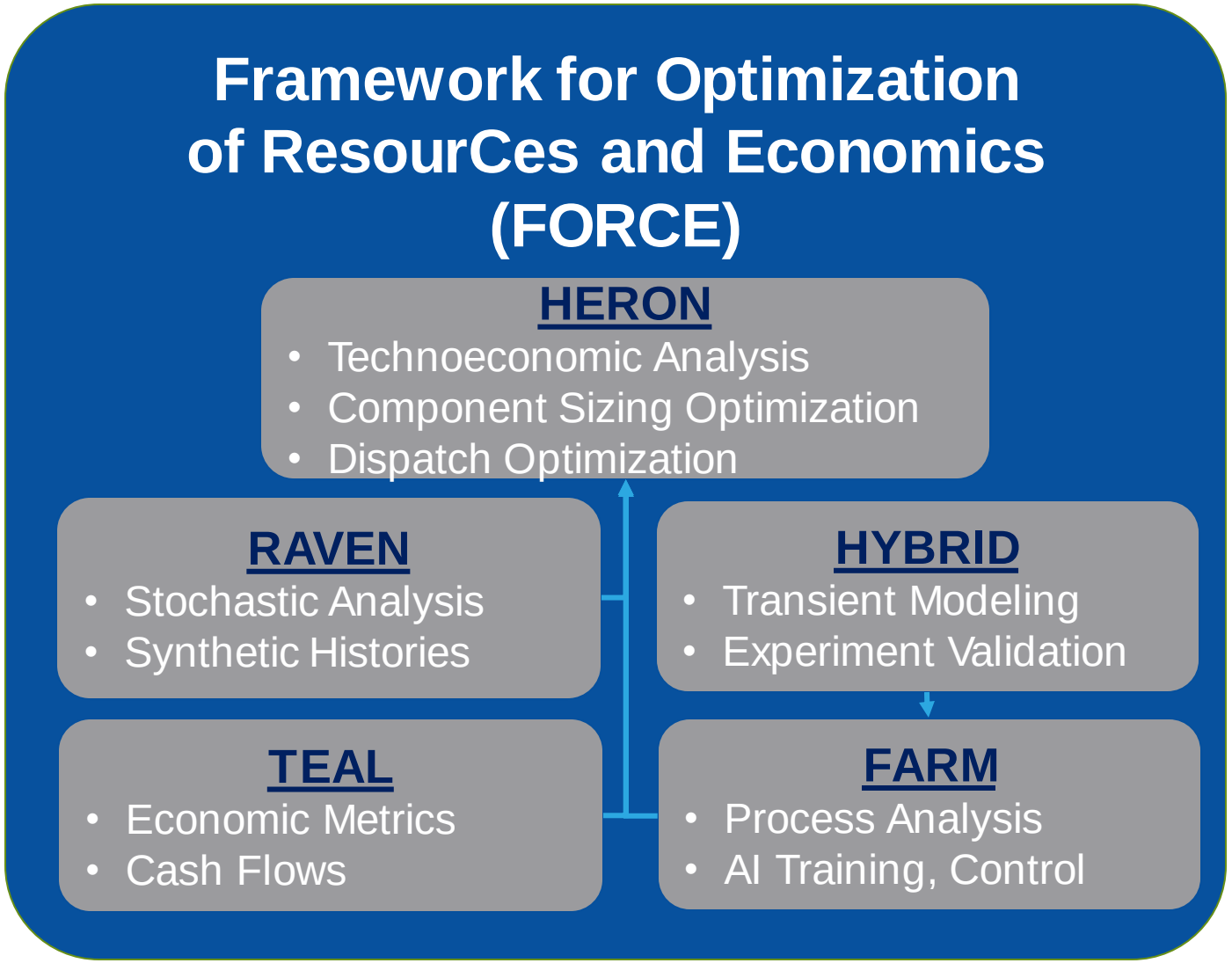
Source: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, April 2021

- Petroleum Refining
- Chemicals Manufacturing
- Cement and Lime Production
- Primary Metals Manufacturing
- Food Production
- Pulp and Paper Manufacturing
- Transportation (Hydrogen, Synfuels, Elec.)
- Mining
- Carbon Conversion
- Desalination
- Electricity and Other Energy Systems

Other options may include methanol, synthetic methane

Integrated energy systems analysis and optimization

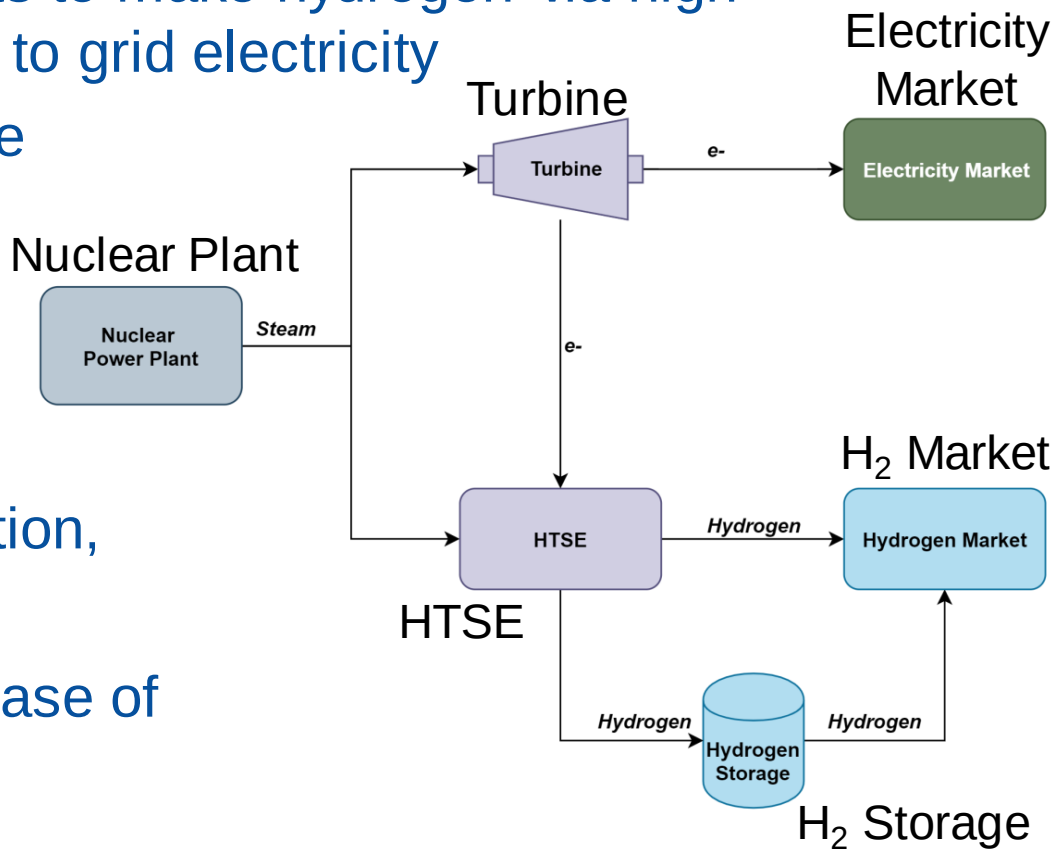
- **Technoeconomic assessment**
  - Portfolio Optimization
  - Dispatch Optimization
  - Process Model Simulation
  - Economic Analysis
  - Supervisory Control
  - Stochastic Analysis
  - Workflow Automation



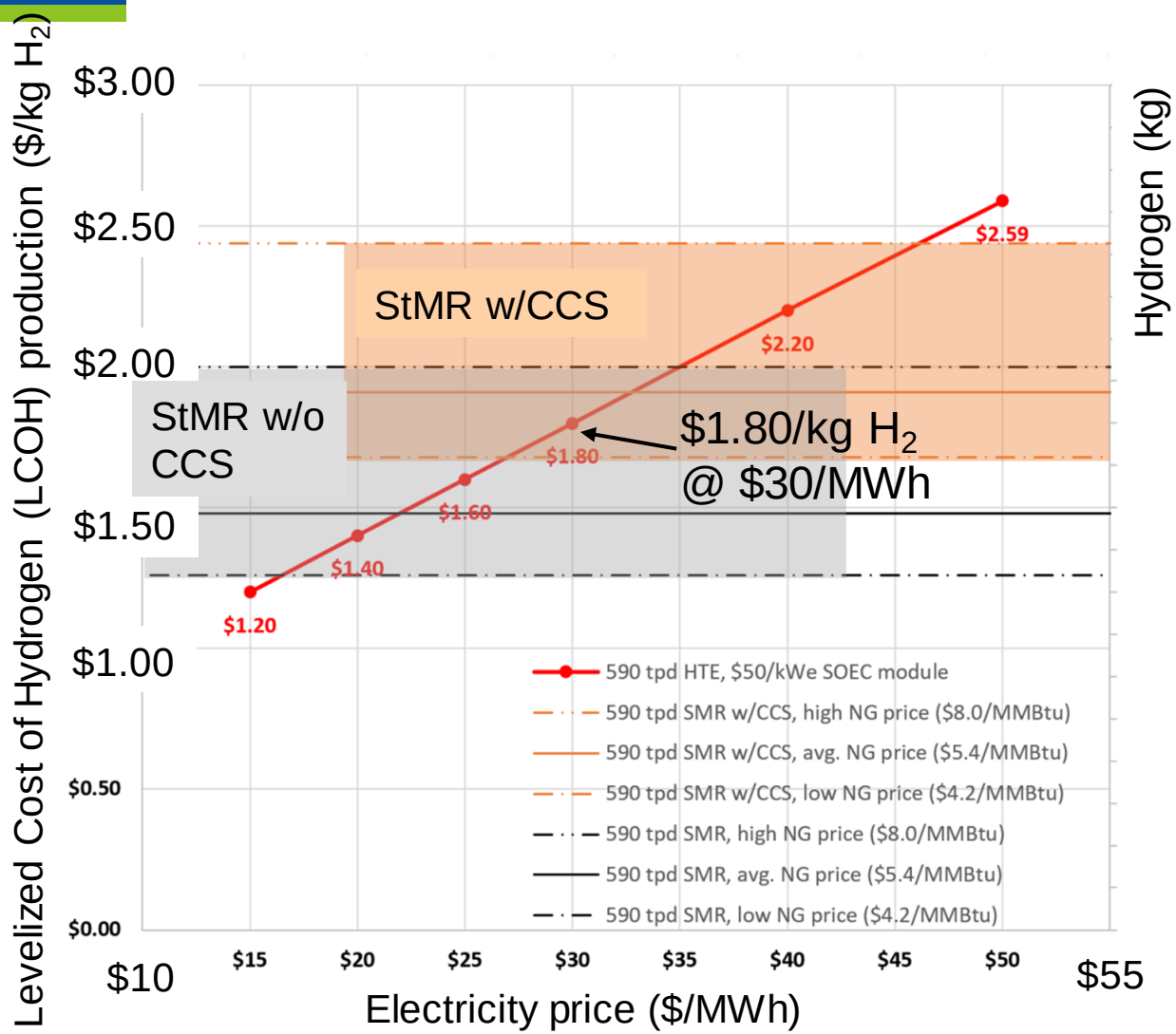
For more information and to access opensource tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.

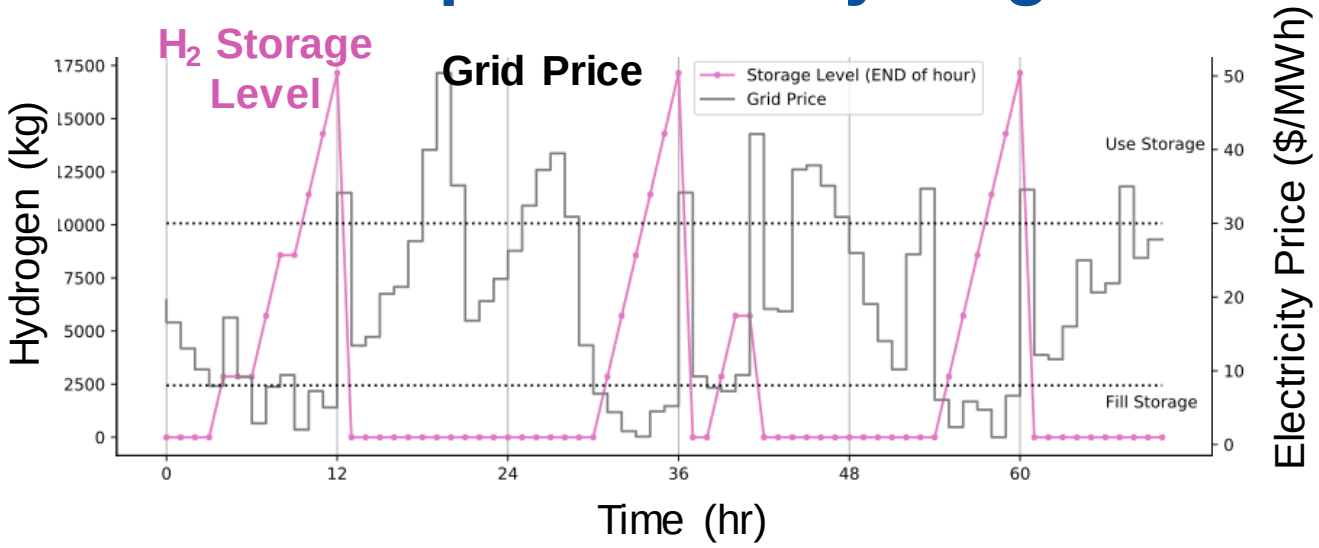
Example: Disruptive potential of nuclear produced hydrogen

- Collaboration between INL, ANL, NREL, 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



Example: Disruptive potential of nuclear produced hydrogen





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.

- **Outcome:** Award from the DOE EERE Hydrogen & Fuel Cell Technologies Office with joint Nuclear Energy funding for follow-on work and demonstration at Exelon Nine-Mile Point plant.
- **Full report:** Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest (INL/EXT-19-55395)

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 NPP (~150 kWe HTSE)
- APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~15-20 MWe LTE/PEM)
- FuelCell Energy: Demonstration at INL (250 kWe)

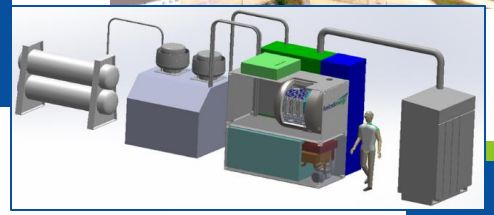
Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

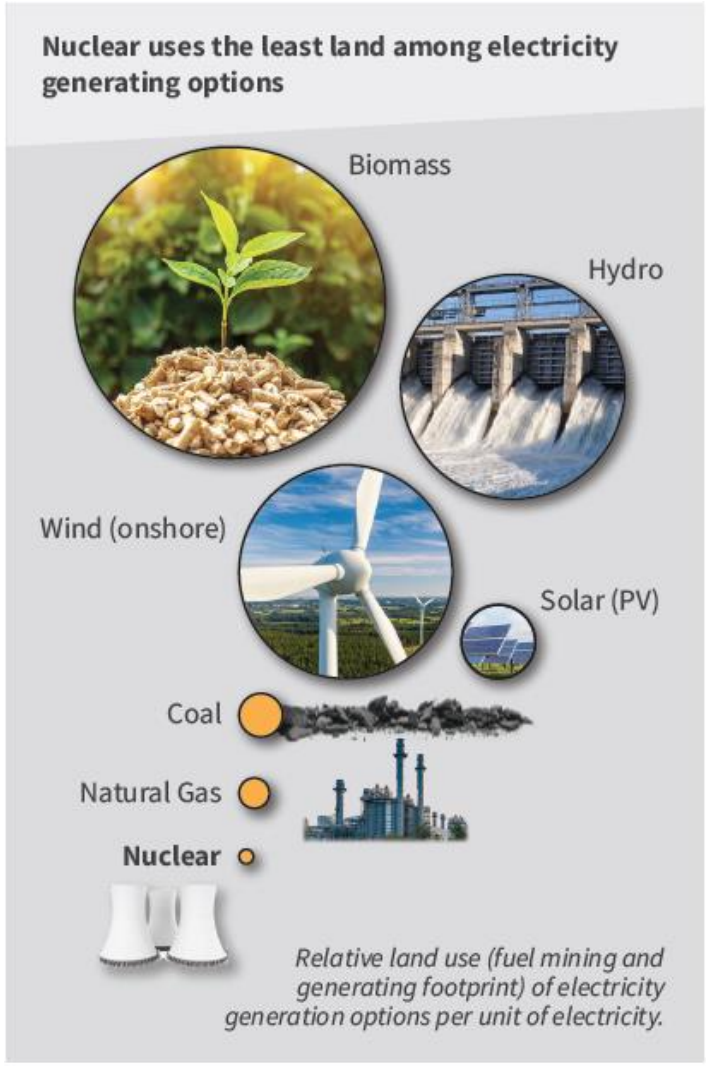
Thermal & Electrical Integration at Prairie Island NPP HTSE/SOEC

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

FuelCell Energy at INL, SOEC



The new nuclear paradigm: Supporting deployment flexibility

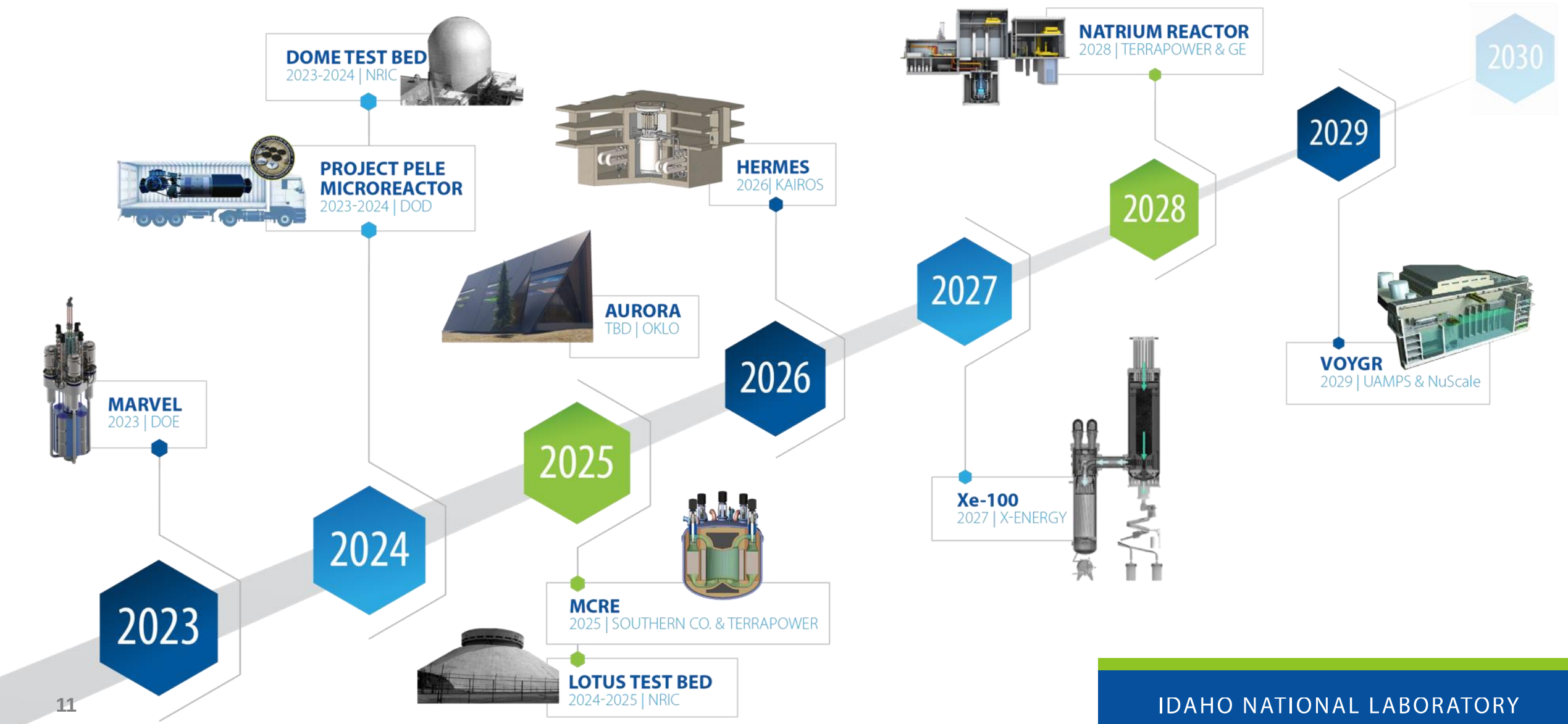


Source: https://world-nuclear.org/information-library/energy-and-the-environment/nuclear-energy-and-sustainable-development.aspx

The advent of microreactors and small modular reactors will allow deployment of nuclear energy to provide reliable energy where it is needed—with a small footprint that allows for siting very near the intended use.

Images courtesy of GAIN and Third Way, inspired by the *Nuclear Energy Reimagined* concept led by INL. Learn more about these and other energy park concepts at thirdway.org/blog/nuclear-reimagined

Accelerating advanced reactor demonstration & deployment



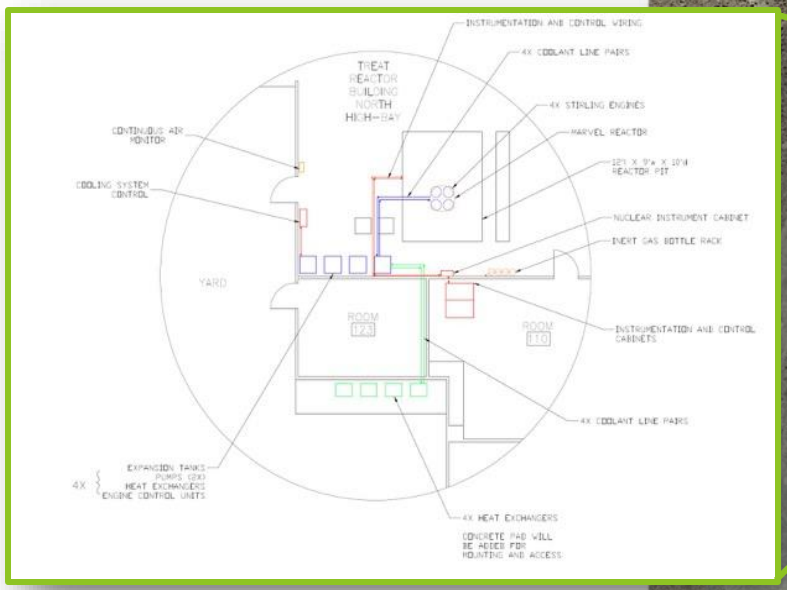
Microreactor integration with a microgrid

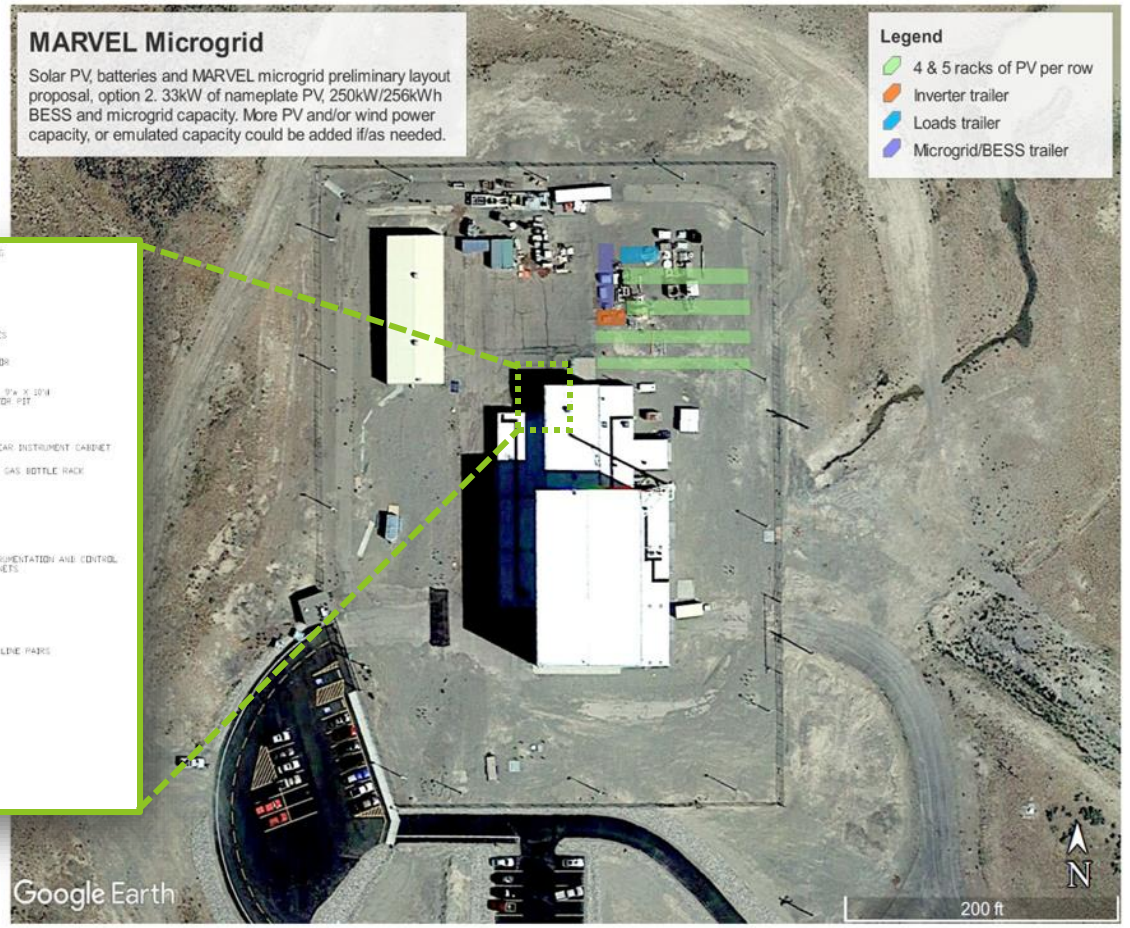
MARVEL

Microreactor Applications Research Validation and Evaluation (MARVEL) Objective:

Operational reactor that produces combined heat and power (CHP) to a functional microgrid

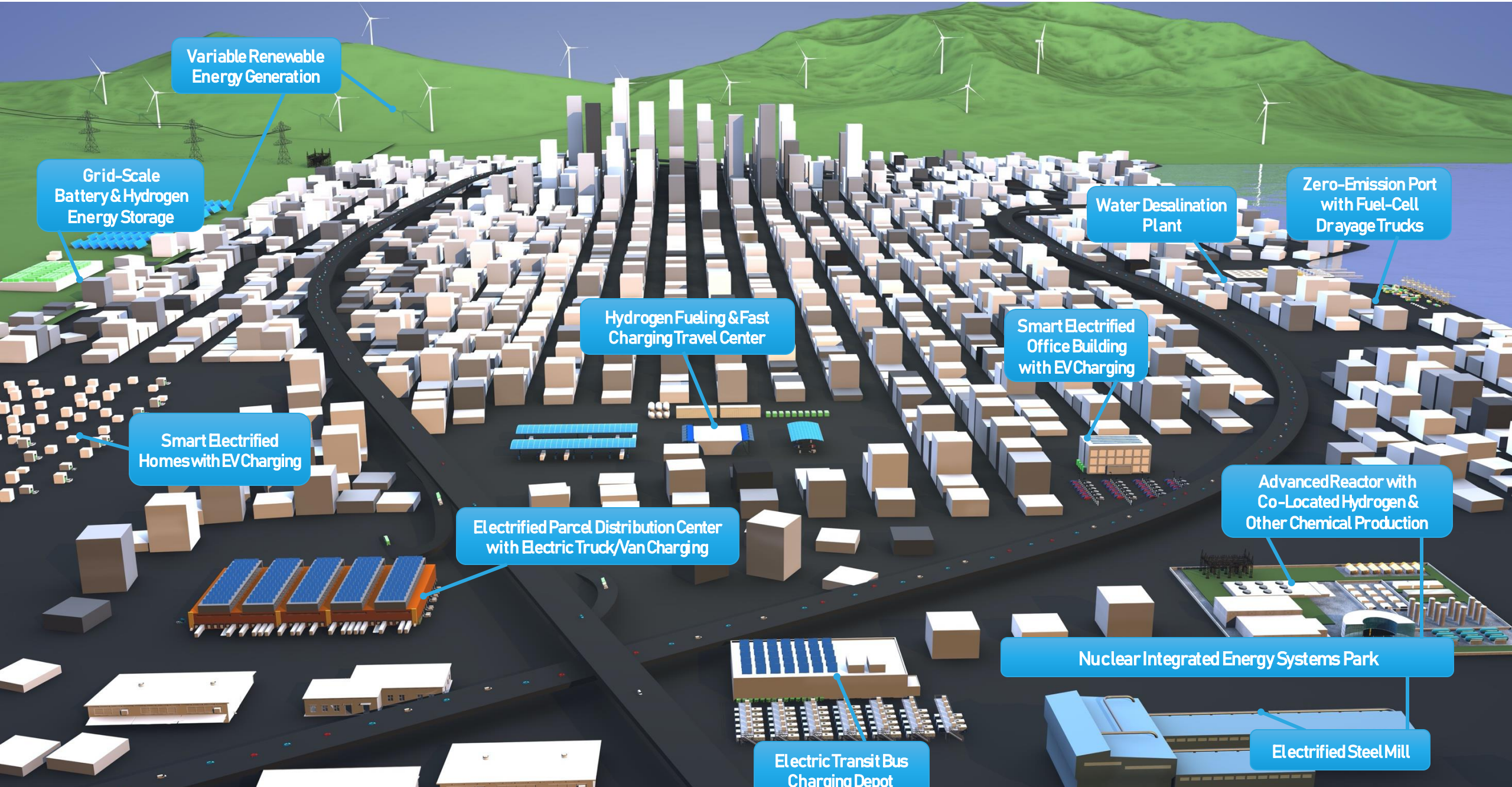
Demonstrate nuclear microgrid operations and provide opportunity to demonstrate operation with coupled energy users, such as hydrogen production and desalination.





MARVEL Construction: Dec 2022
MARVEL Criticality: Dec 2023

Distributed energy systems for a net-zero future



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  - Infographic: https://www.energy.gov/ne/downloads/infographic-advanced-reactor-demonstration-program
  - News release: https://www.powermag.com/final-doe-advanced-reactor-demonstration-awards-announced/
  - More info: https://www.energy.gov/ne/articles/5-advanced-reactor-designs-watch-2030