INL/CON-22-66717-Revision-0

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

April 2022

Changing the World's Energy Future

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Idaho National Laboratory

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

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

37th Korea Atomic Power Annual Conference:

Clean Energy for a Net Zero and Hydrogen Economy

April 28, 2022

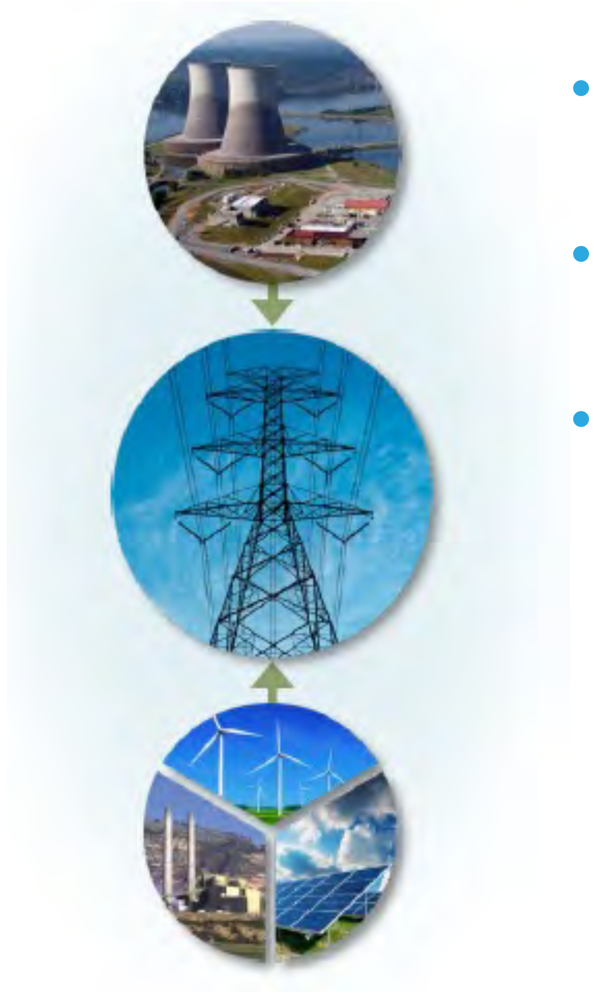
Idaho National Laboratory

From INL/CON-22-66717

Presentation overview

- Energy systems status quo
- New nuclear paradigm: A vision for the future
  - New market opportunities beyond electricity
- Integrated energy systems
  - Concept
  - Design/analysis
  - Opportunity for new markets
- Advancing nuclear and integrated energy systems through demonstration

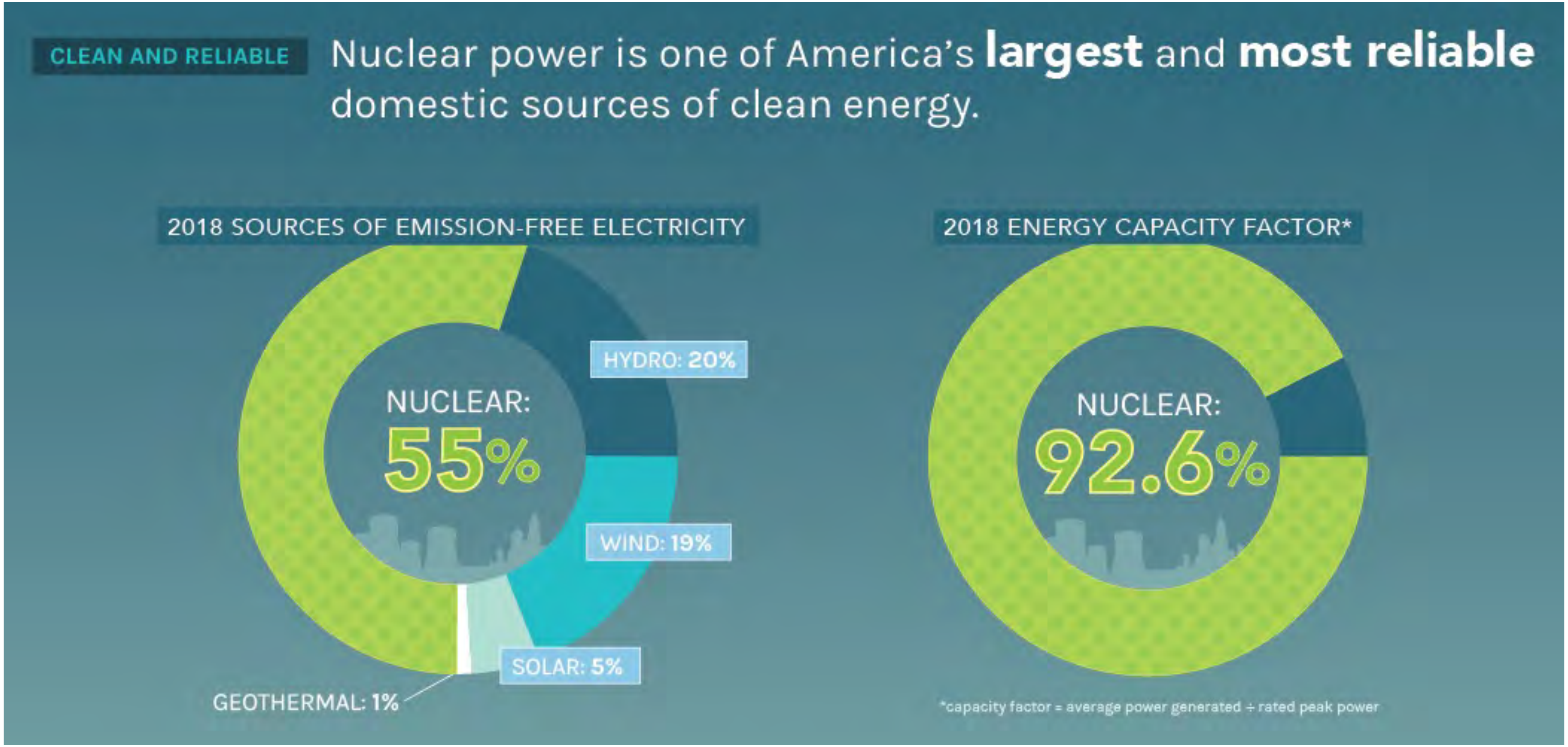
Today's energy systems



- 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)

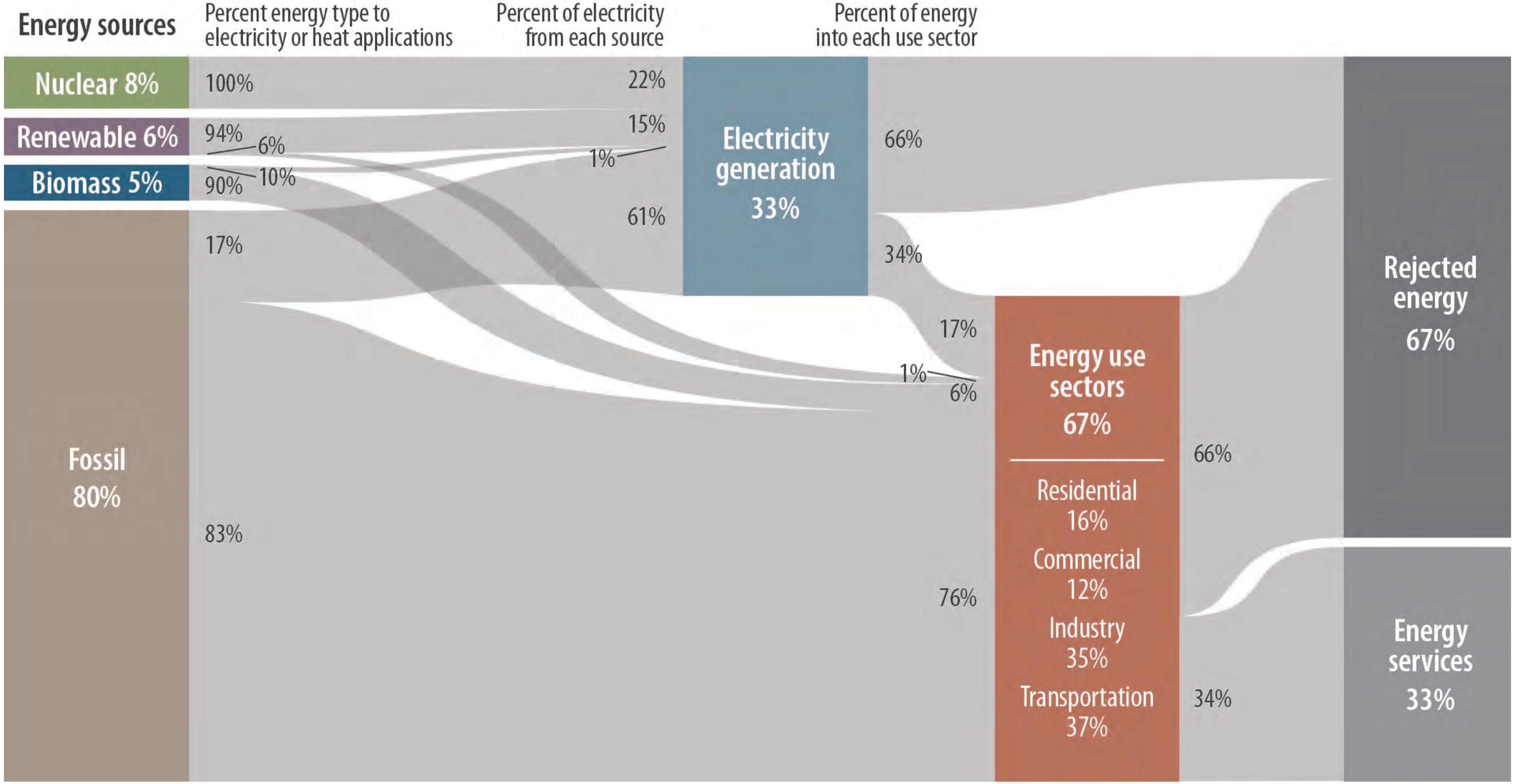
Achieving net-zero emissions will require us to consider the role(s) of all clean energy generation options—and we must look to non-emitting sources of heat in addition to electricity.

The current role of nuclear energy in the U.S.



energy.gov/nuclear

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/

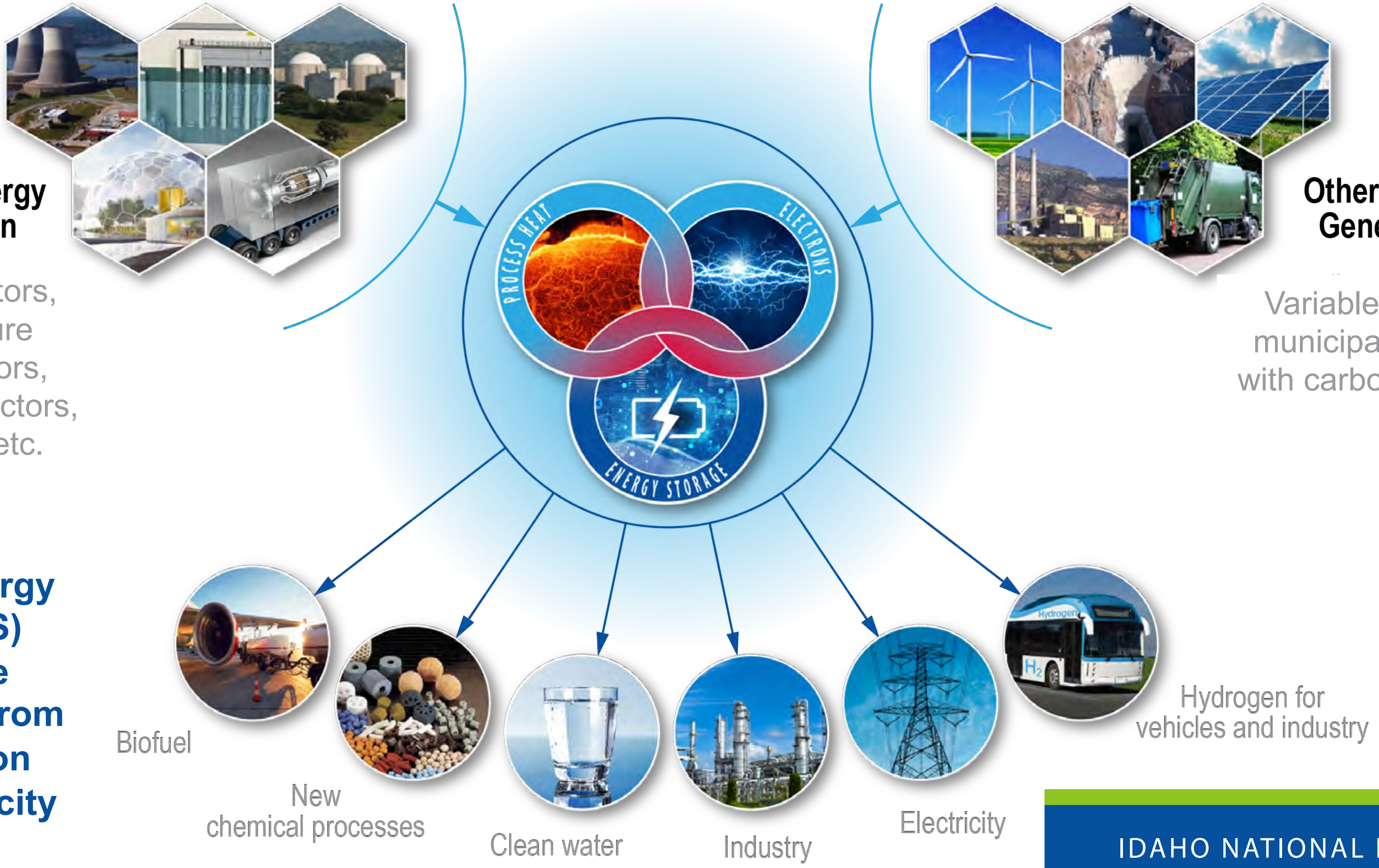
Future clean energy systems – transforming the energy paradigm

Nuclear Energy Generation

Light water reactors, high temperature advanced reactors, small modular reactors, microreactors, etc.

Other Energy Generation

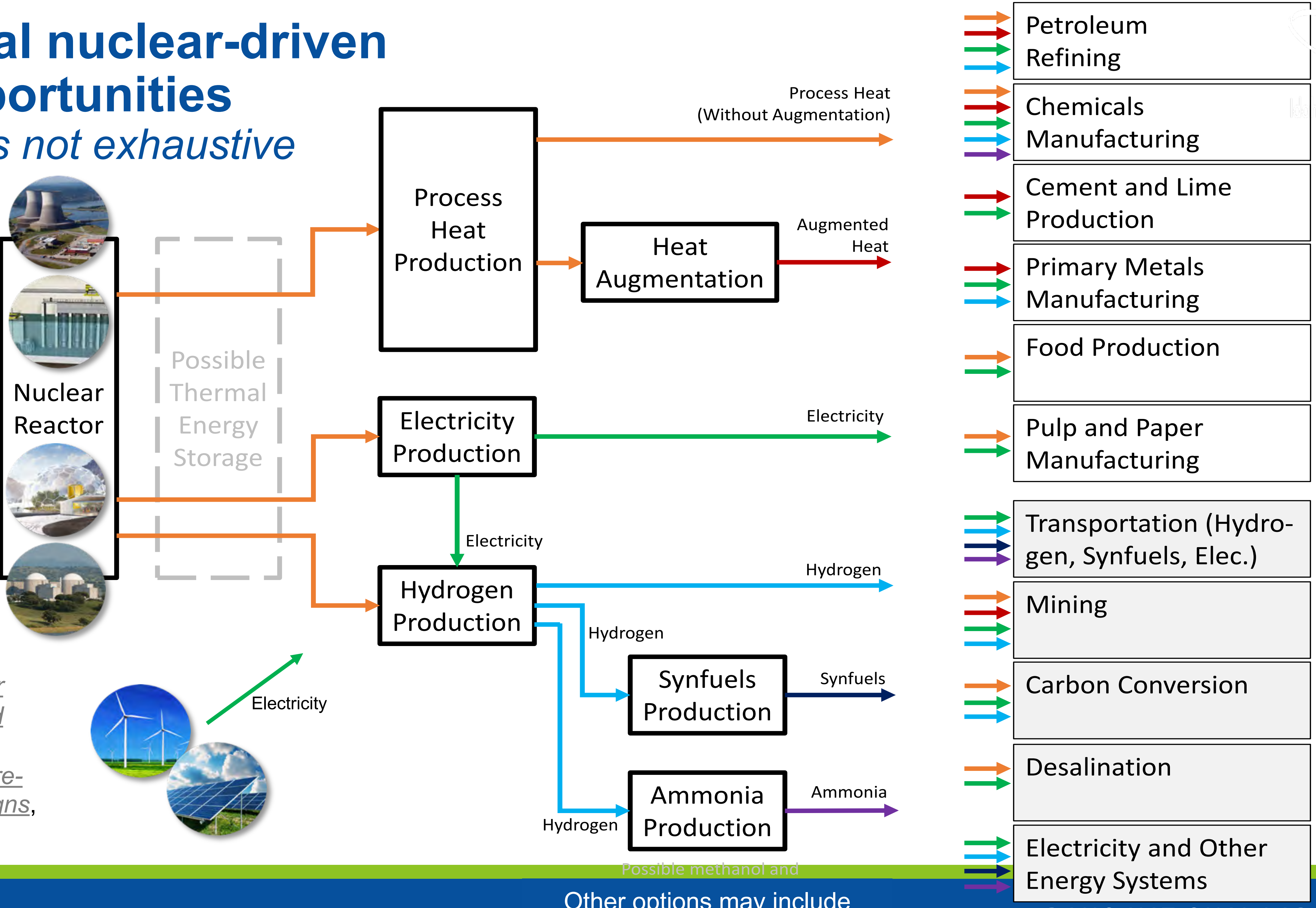
Variable renewables, municipal waste, fossil with carbon capture, etc.



Integrated energy systems (IES) leverage the contributions from nuclear fission beyond electricity

Potential nuclear-driven IES opportunities

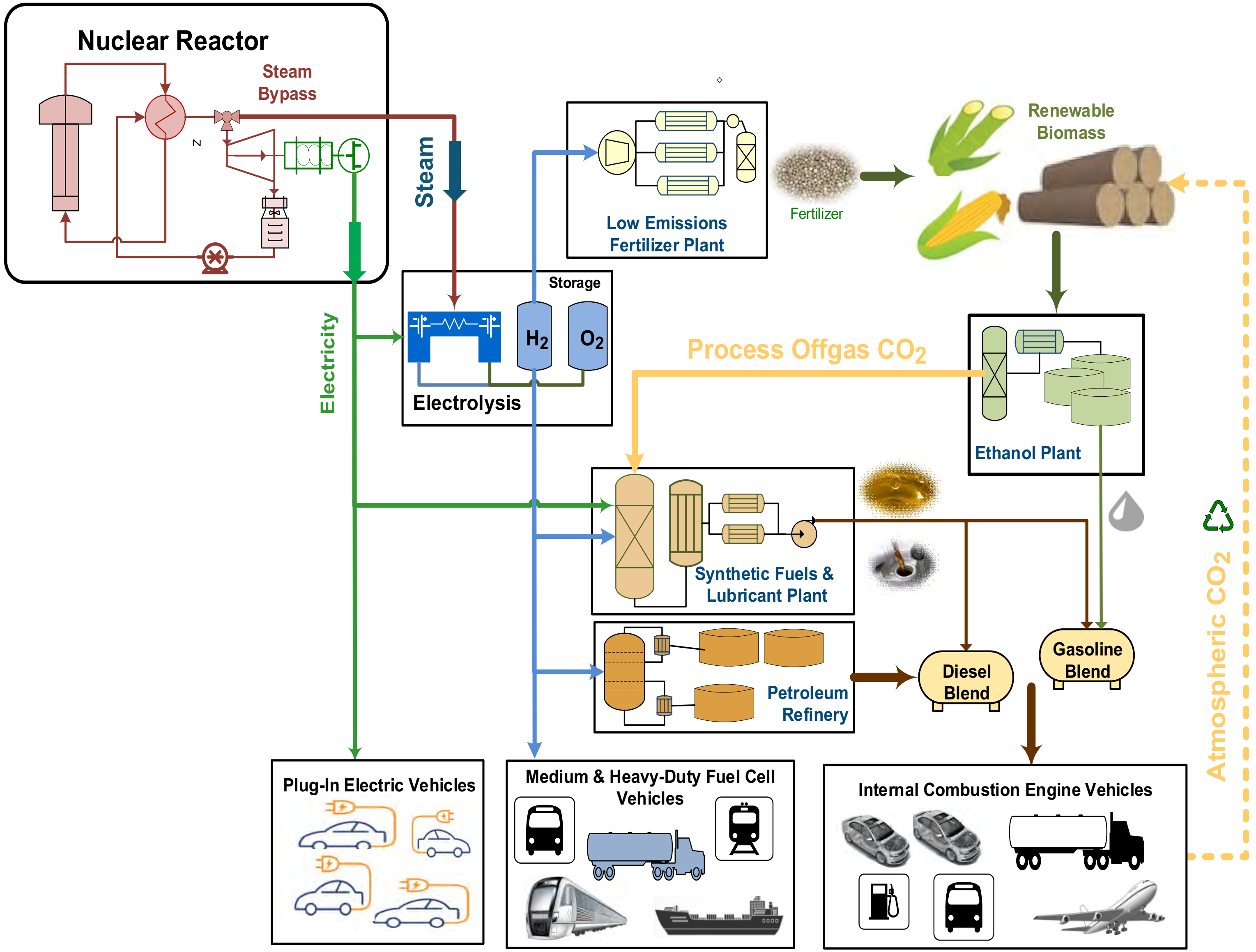
Examples not exhaustive



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

Other options may include methanol, synthetic methane

Nuclear-hydrogen production and utilization



Motivation for H_2 production to support multiple processes/ products beyond electricity

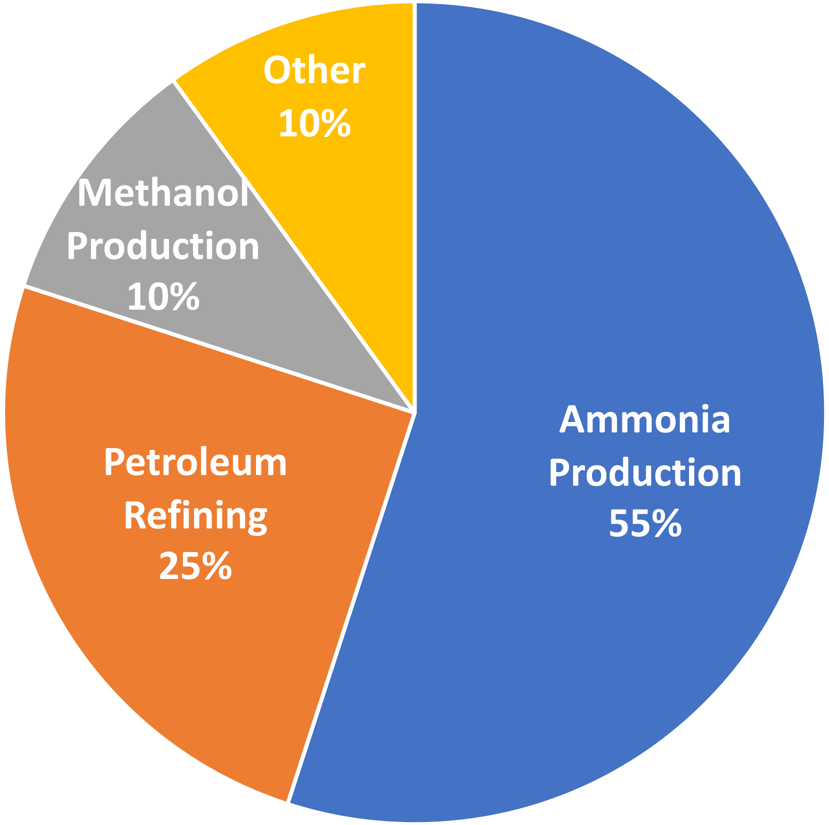
1) Provides energy storage, for electricity production or H_2 user (e.g., chemicals and fuels synthesis, steel manufacturing, ammonia-based fertilizers)
2) Provides second source of revenue to the generator; allows generator to operate at nominal power at all times
3) Provides opportunity for grid services, including reserves and grid regulation

Why hydrogen?

Hydrogen applications in industry

- Agriculture/chemical industry: ammonia, ammonia-based fertilizers
- Petroleum refining: hydrocracking to produce gasoline, diesel
- Methanol production
- Other:
  - Food (e.g., hydrogenated oils)
  - Metalworking
  - Welding
  - Flat glass production
  - Electronics manufacturing
  - Medical applications

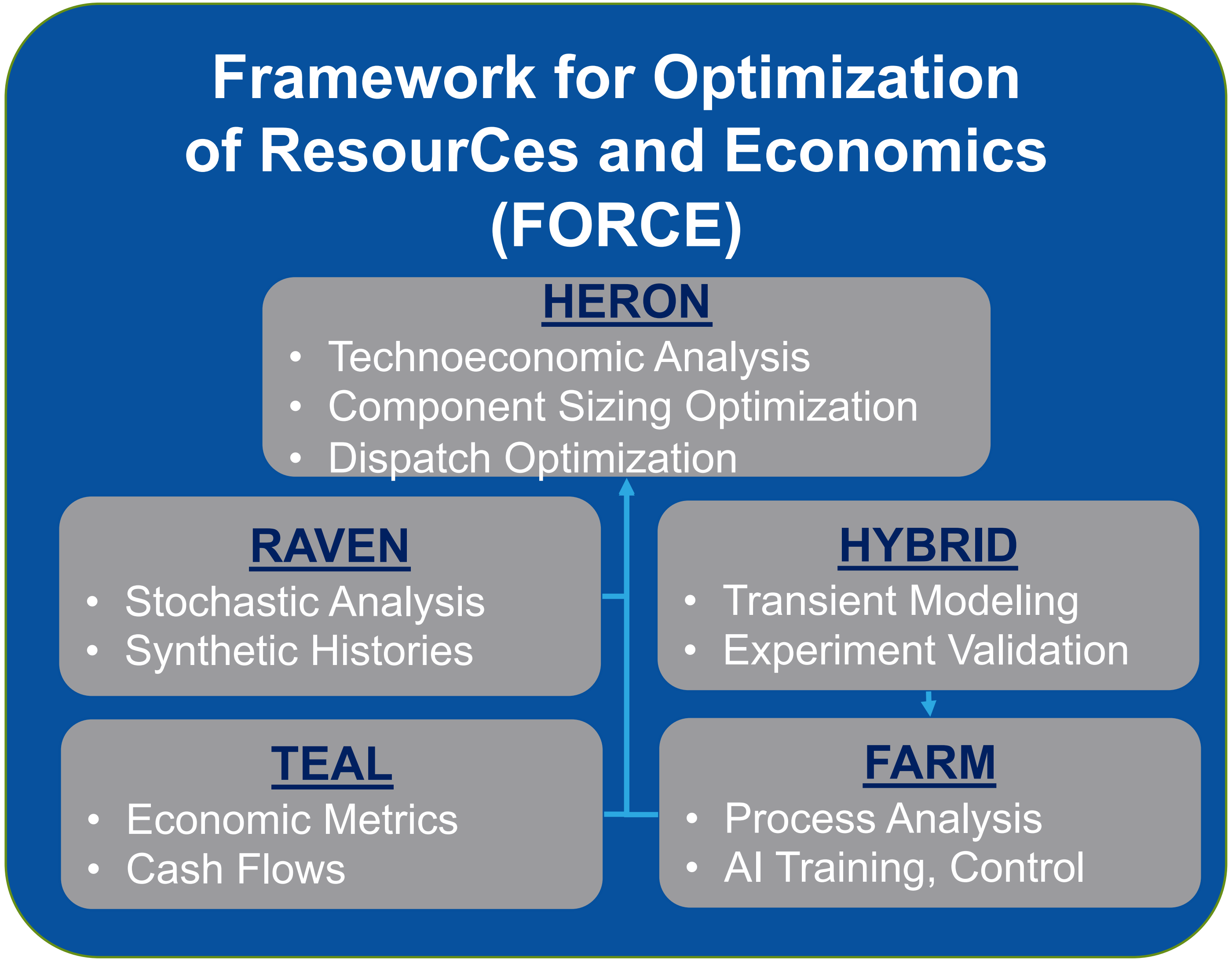
Fraction of Global Hydrogen Use by Industry



Data source: Hydrogen Europe
hydrogeneurope.eu/hydrogen-applications

Integrated energy systems analysis and optimization

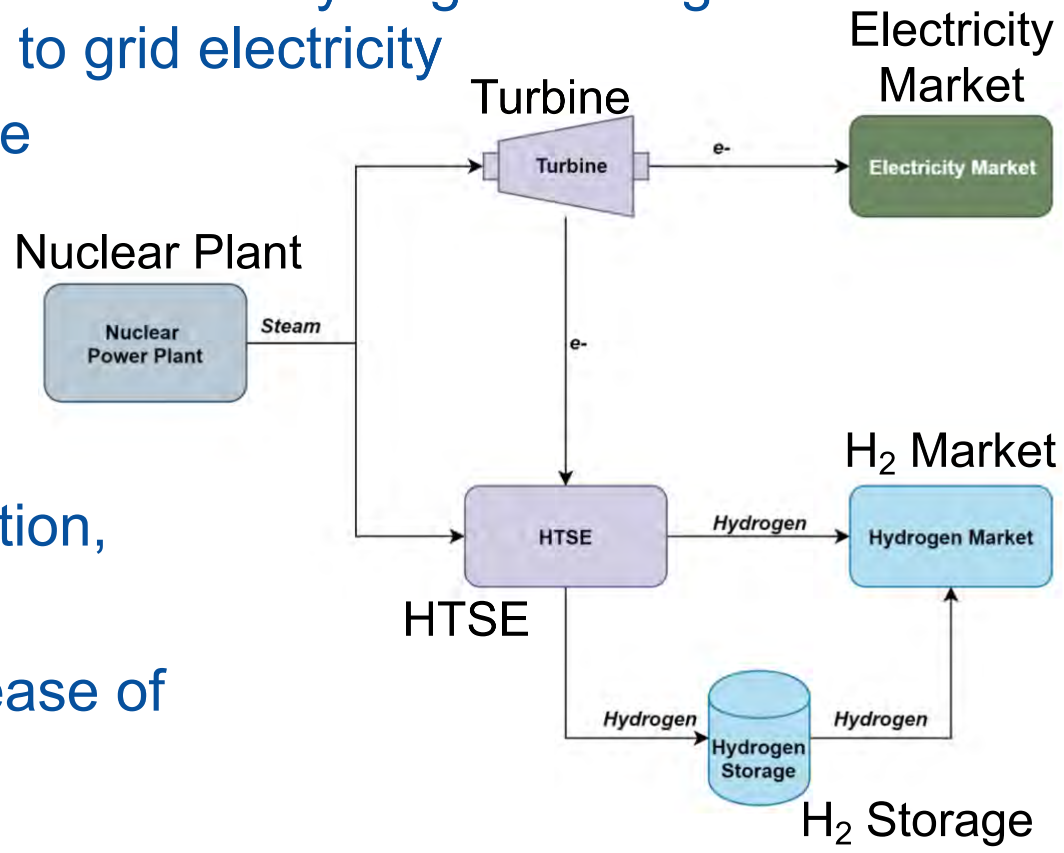
- **Technoeconomic assessment**
  - Portfolio Optimization
  - Dispatch Optimization
  - Process Model Simulation
  - Economic Analysis
  - Supervisory Control
  - Stochastic Analysis
  - Workflow Automation



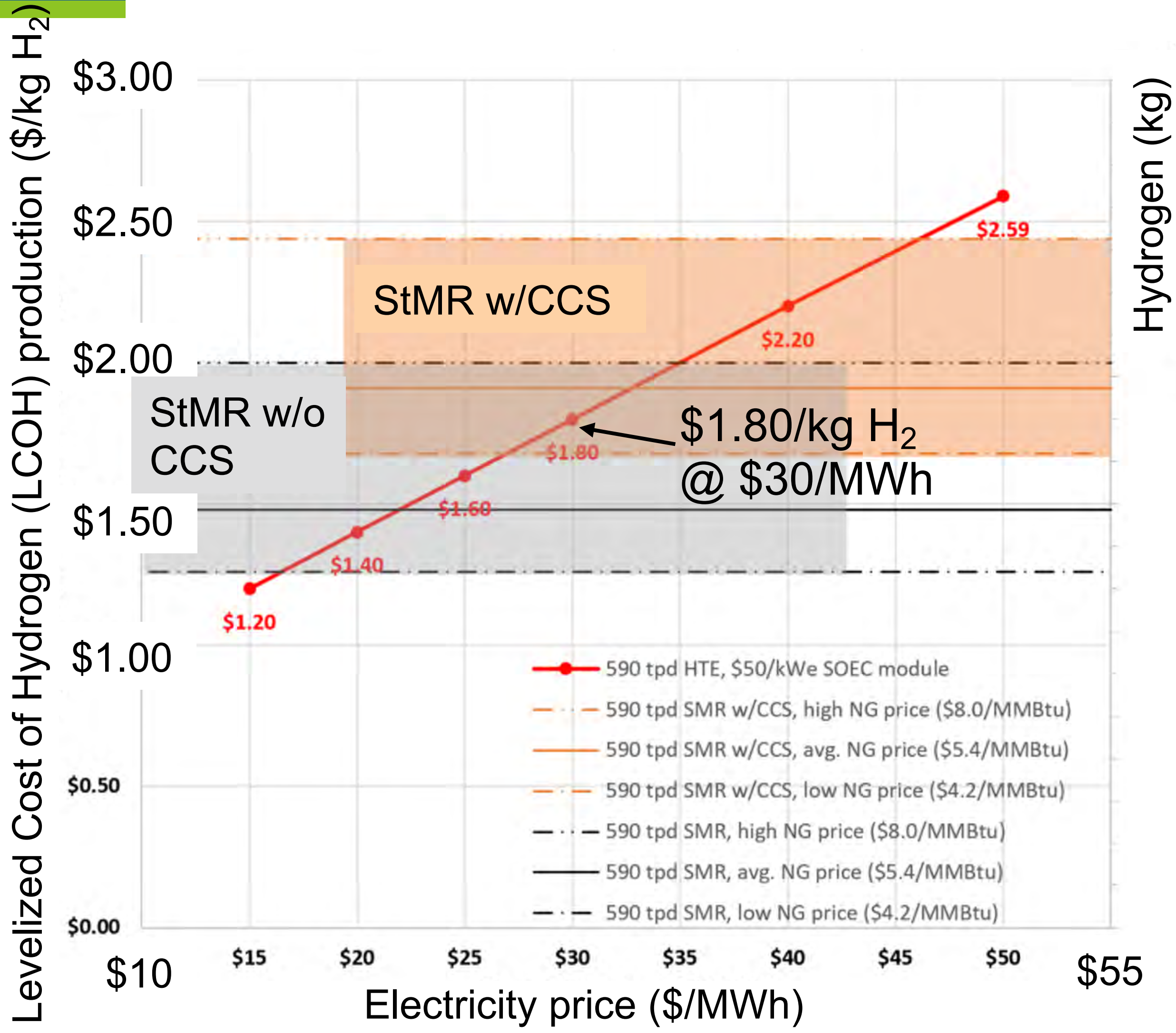
For more information and to access opensource tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.

Example: Disruptive potential of nuclear produced hydrogen

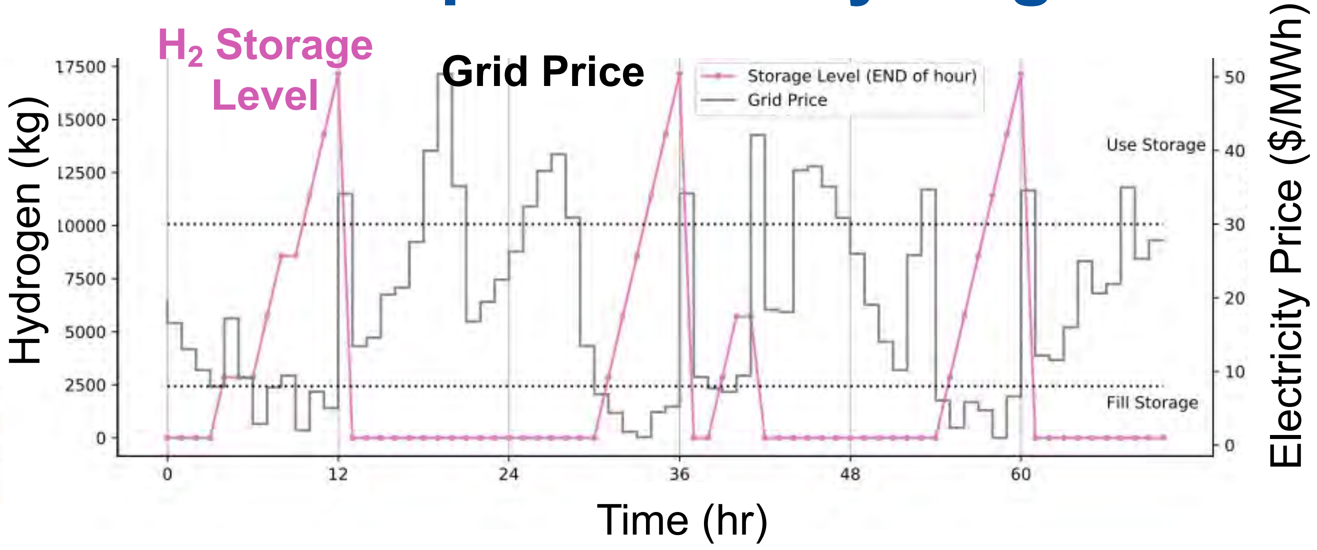
- Collaboration between INL, ANL, NREL, Constellation (Exelon), and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid 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



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 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-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

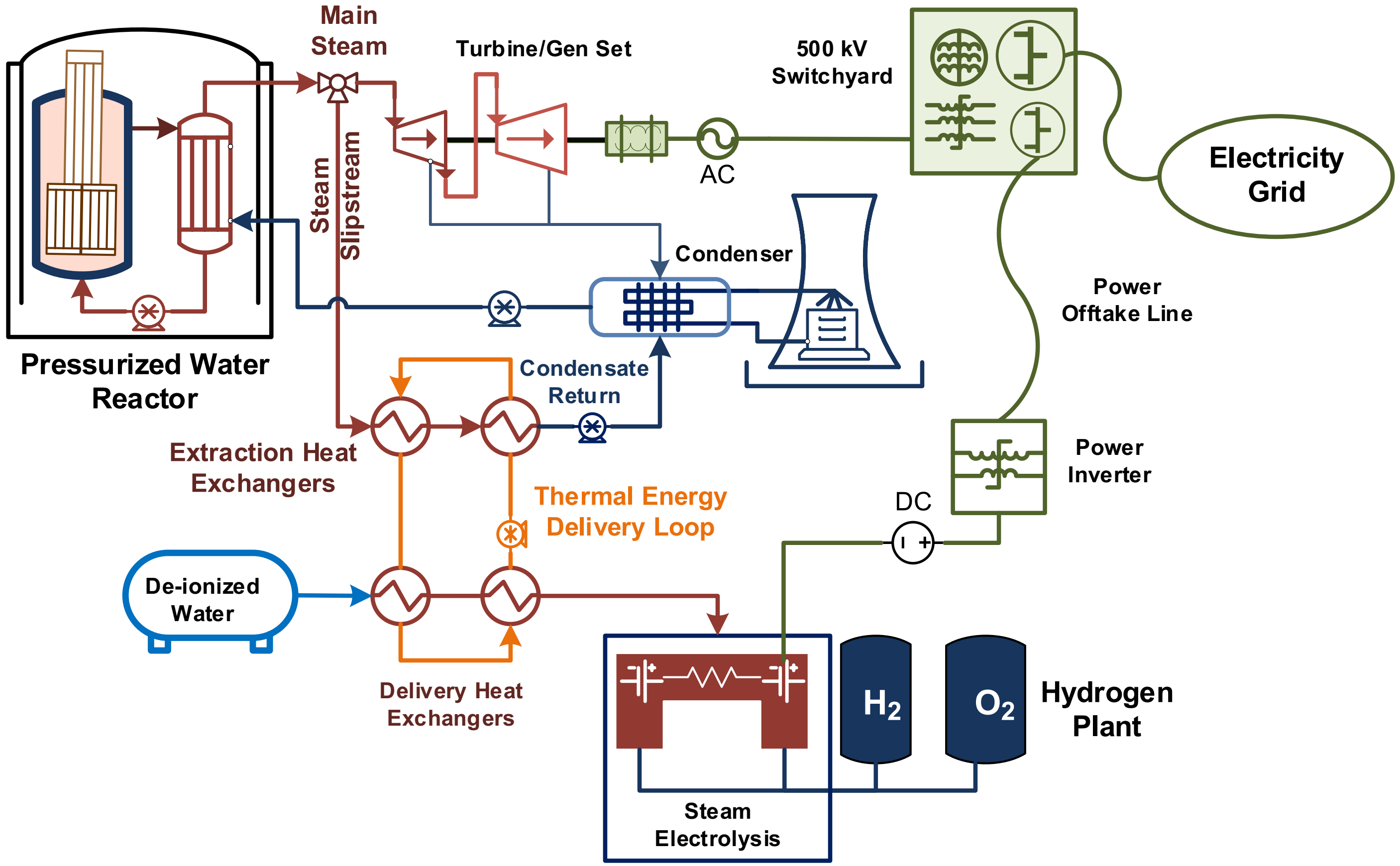
Palo Verde Generating Station, H_2 Production for Combustion and Synthetic Fuels

FuelCell Energy at INL, SOEC

Thermal integration of steam electrolysis

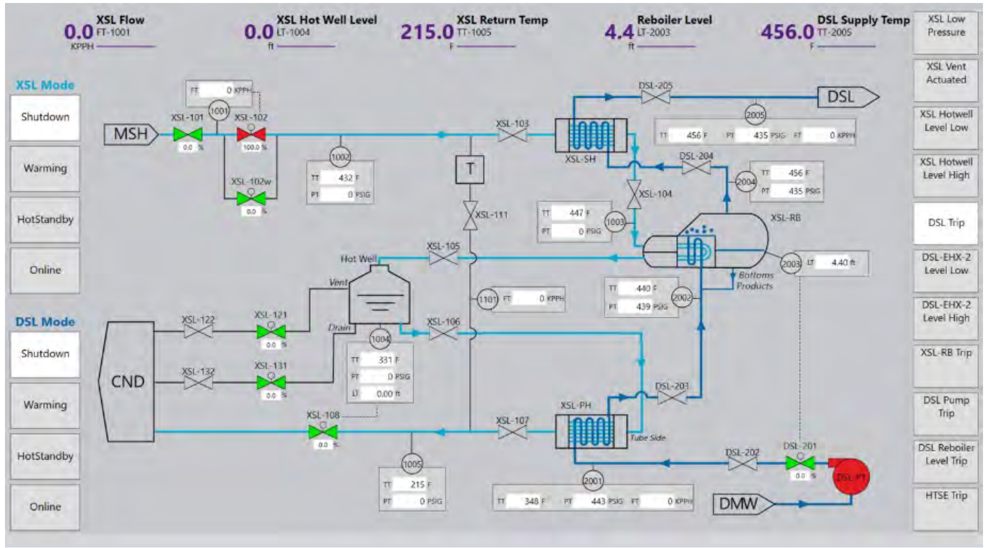
Safety analysis summary conclusions

- The LWRS generic probabilistic risk assessment (PRA) investigation into licensing considerations concluded that following the assumptions made:
  - The licensing criteria is met for a large-scale HTE facility sited 1 km from a generic PWR and BWR
  - The safety case for less than 1 km distance is achievable
- Report available: INL/EXT-20-60104, *Flexible Plant Operation and Generation Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant*, OSTI link: https://www.osti.gov/biblio/1691486

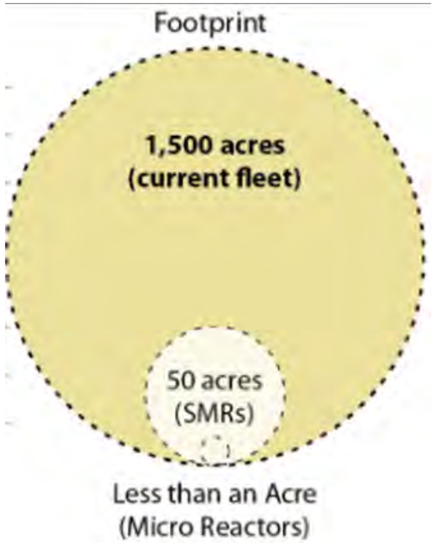


Operations with flexible thermal and electrical power dispatch

- The INL Human Systems Simulation Laboratory was used to test concepts for dispatching thermal and electrical power from nuclear reactors to a H_2 electrolysis plant
  - Two formerly licensed operators tested 15 scenarios
  - A modified full-scope generic Pressurized-Water Reactor 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 by
  - Leveraging automation to augment any additional operator tasking
  - Monitoring energy dispatch to a second user



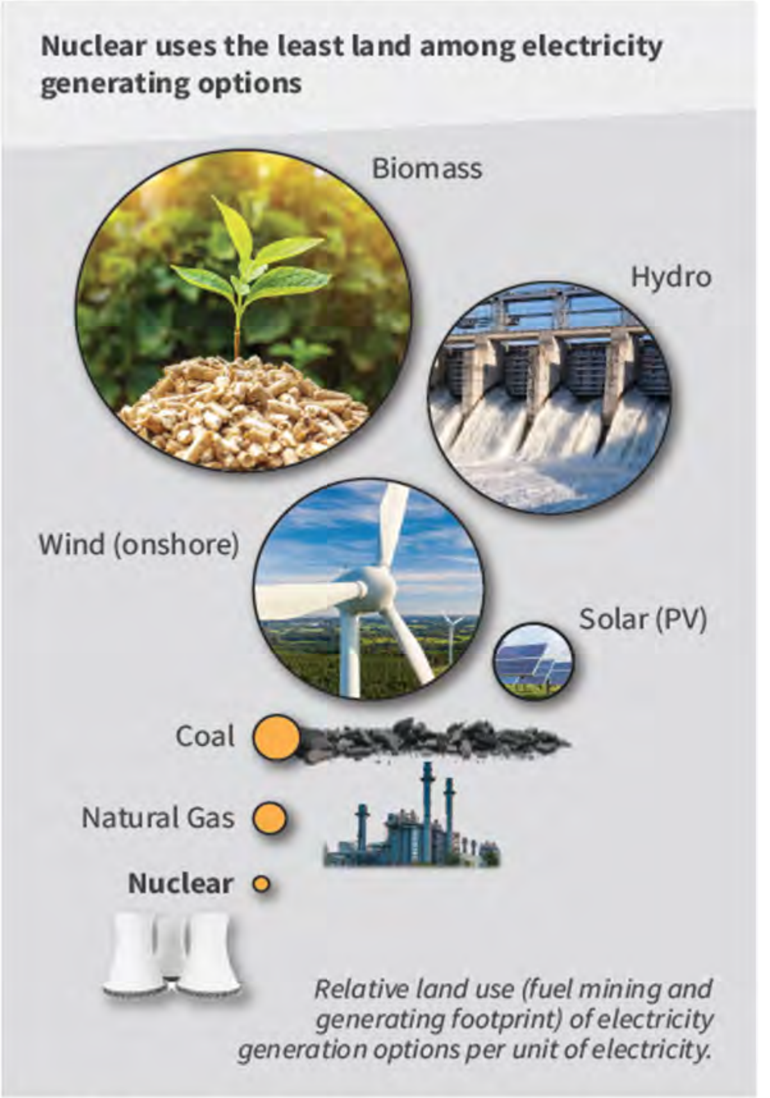
Nuclear energy and deployment flexibility



Artist renditions 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

Microreactors and small modular reactors can be deployed to provide reliable energy where it is needed with a small footprint that allows for siting very near to the intended use.

IES
Integrated Energy Systems



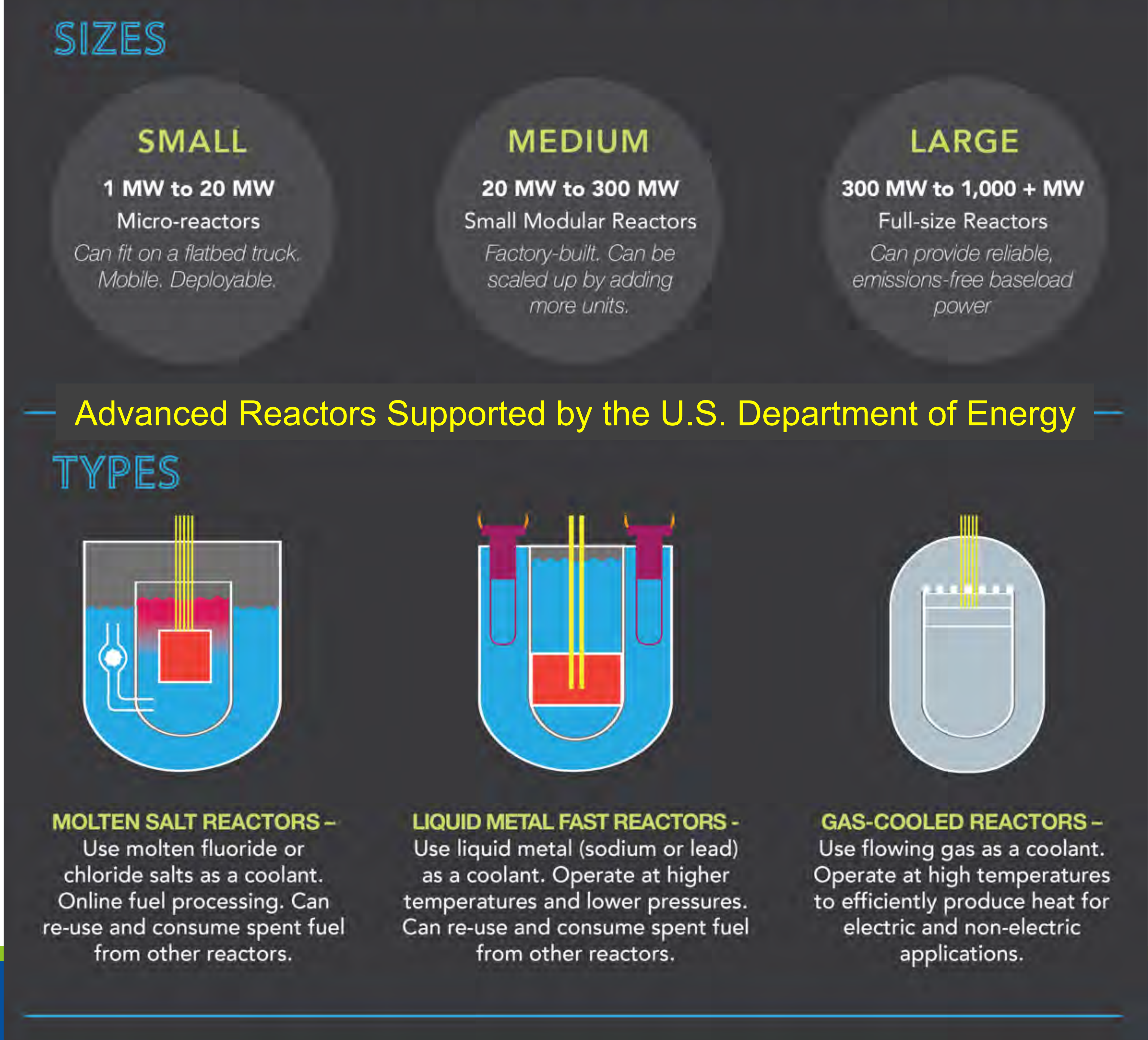
Source: https://world-nuclear.org/information-library/energy-and-the-environment/nuclear-energy-and-sustainable-development.aspx

Advanced Reactor Design Concepts

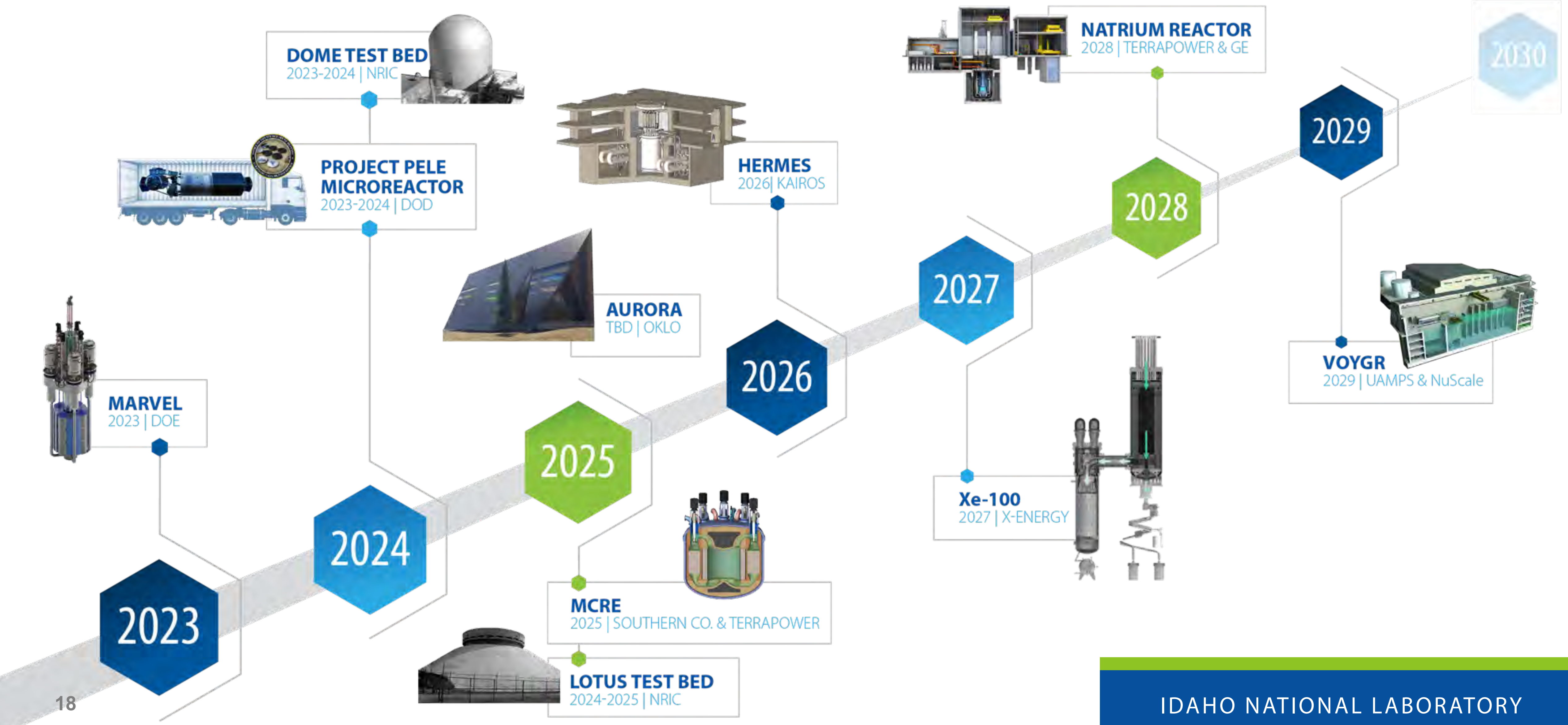
Key Benefits

- Inherent/passive safety
- Deployment flexibility
- Versatile applications
- Long fuel cycles
- Reduced waste
- Advanced manufacturing to reduce cost

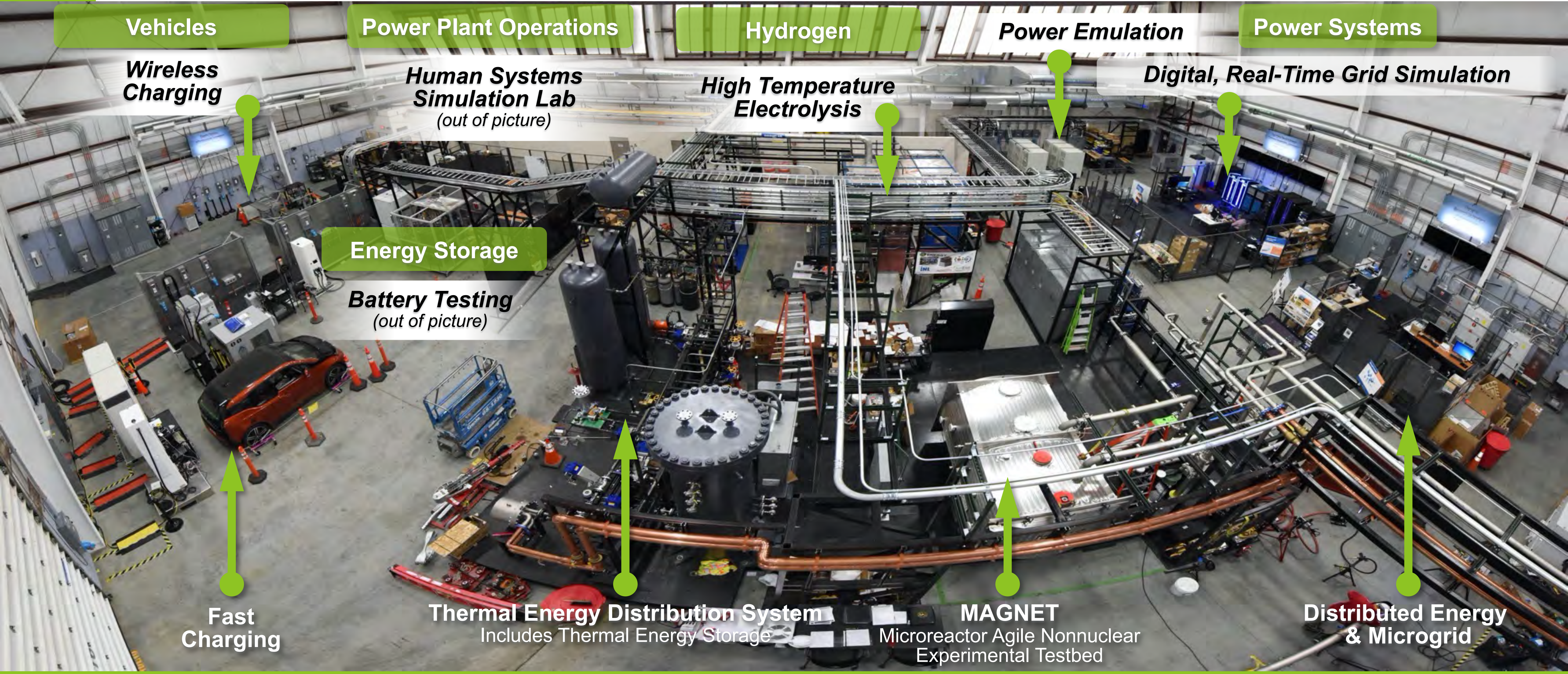
60+ private sector projects under development



Accelerating advanced reactor demonstration & deployment



Dynamic Energy Transport and Integration Laboratory (DETAIL)



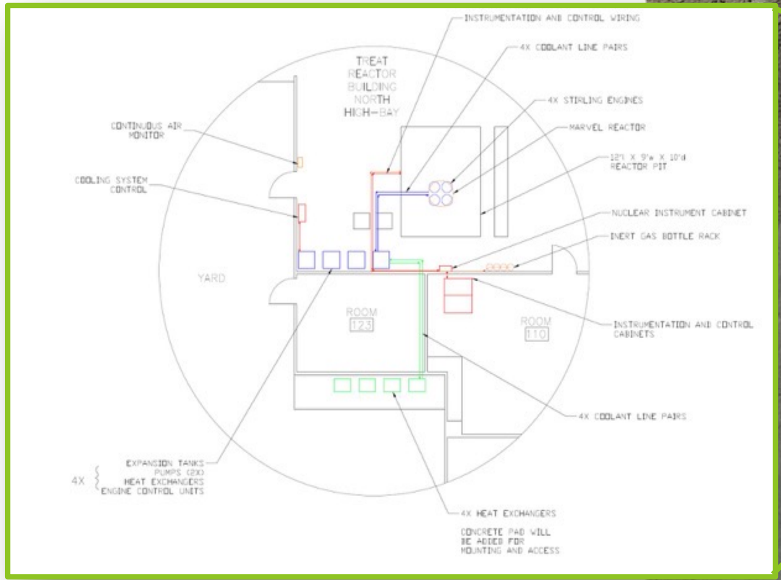
Microreactor integration with a microgrid

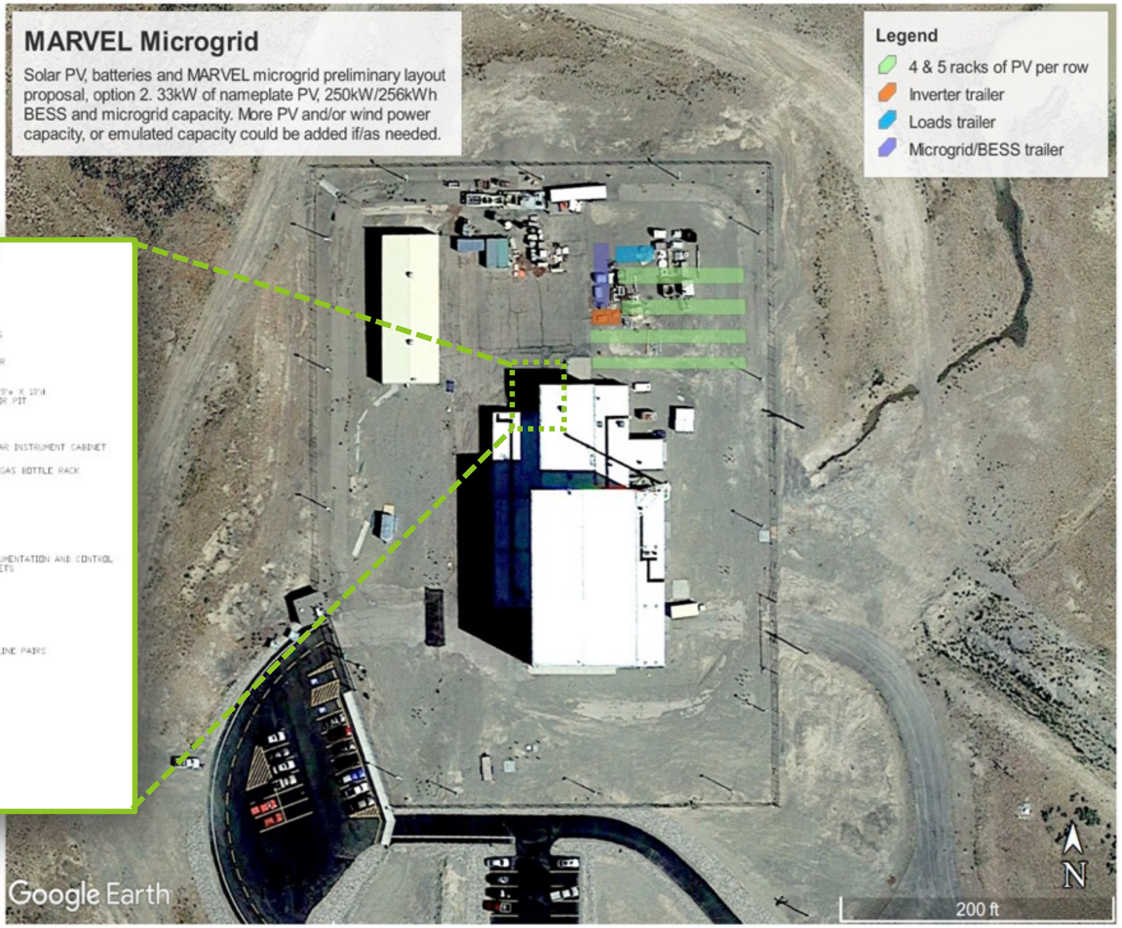
MARVEL

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

National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure

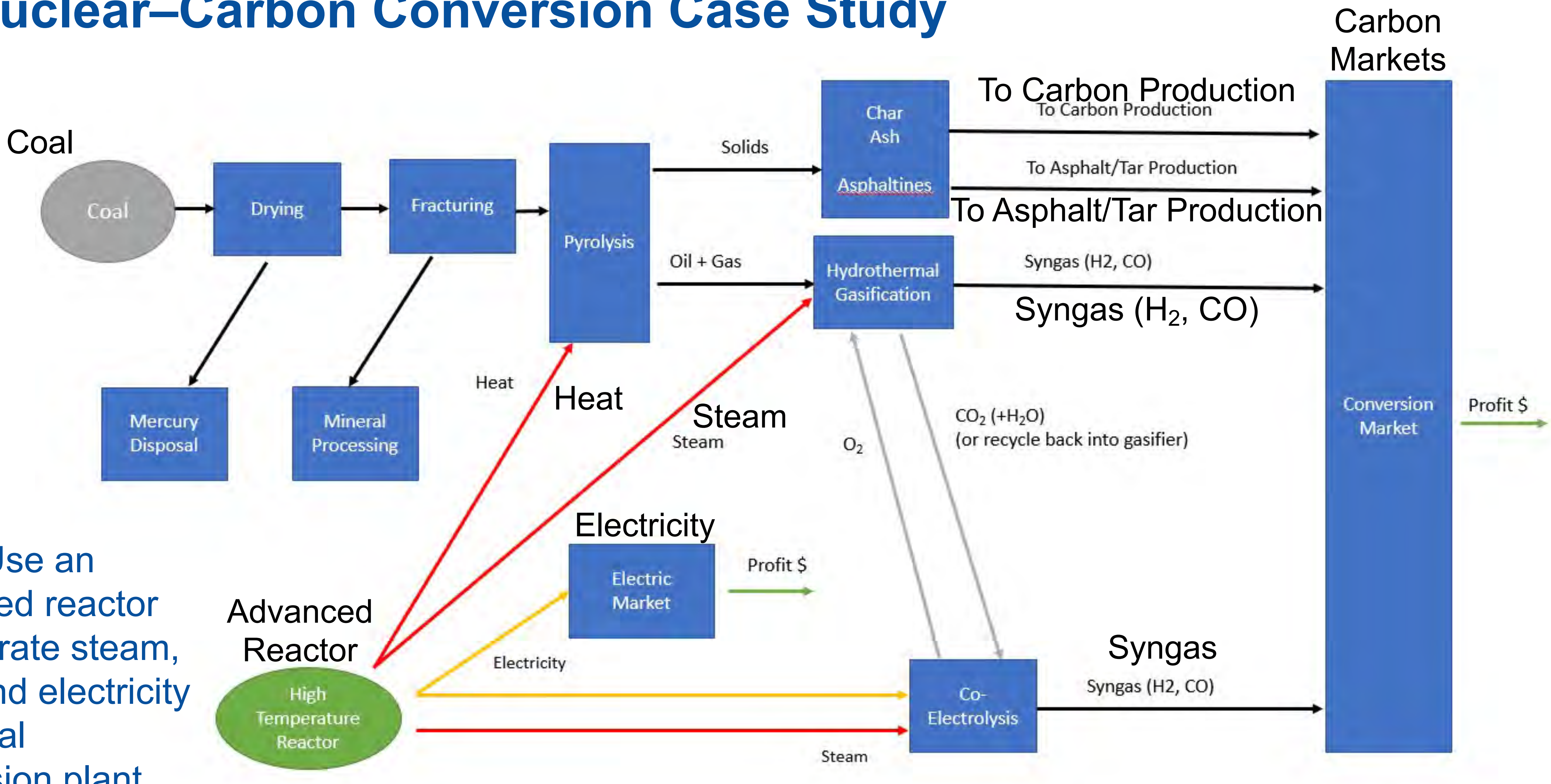
- Goal: Demonstrate two advanced reactors by 2025
- Strategy:
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components
- Capabilities:
  - NRIC DOME (Demonstration of Microreactor Experiments)
    - Advanced Microreactors up to 20 MWth
    - High-Assay Low-Enriched Uranium (HALEU) fuels < 20%
  - NRIC LOTUS (Laboratory for Operations and Testing in the US)
    - Up to 500 kWth experimental reactors
    - Safeguards category one fuels
  - Experimental Infrastructure
    - Molten Salt Thermophysical Examination Capability
    - Helium Component Test Facility

NRIC National Reactor Innovation Center

Anticipate initial reactor testing in ~2024. Flexible testbed to support testing of multiple reactor concepts using the same infrastructure ~annually.

 For more information on NRIC and to download resources, see https://nric.inl.gov/.

Nuclear–Carbon Conversion Case Study

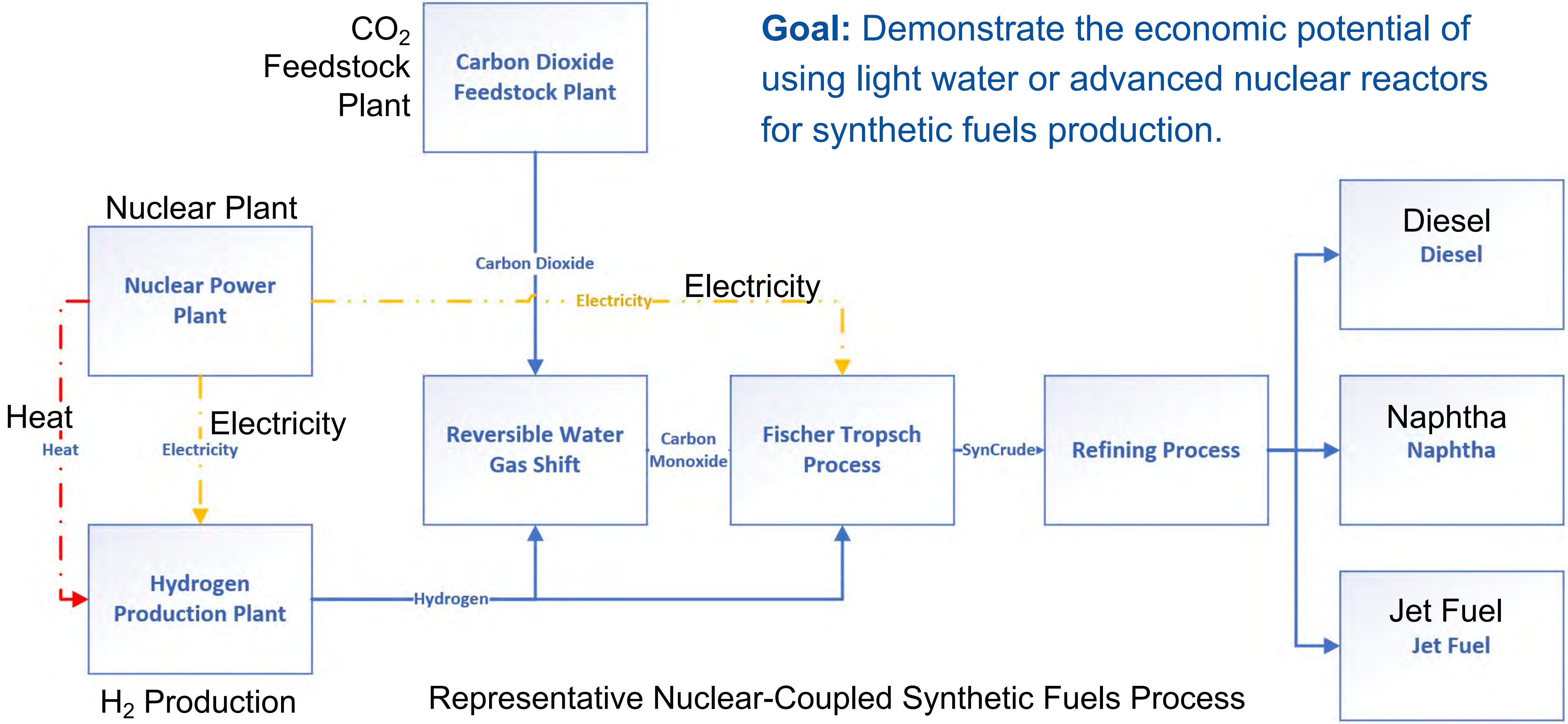


Goal: Use an advanced reactor to generate steam, heat, and electricity for a coal conversion plant.

Representative Coal Conversion Process

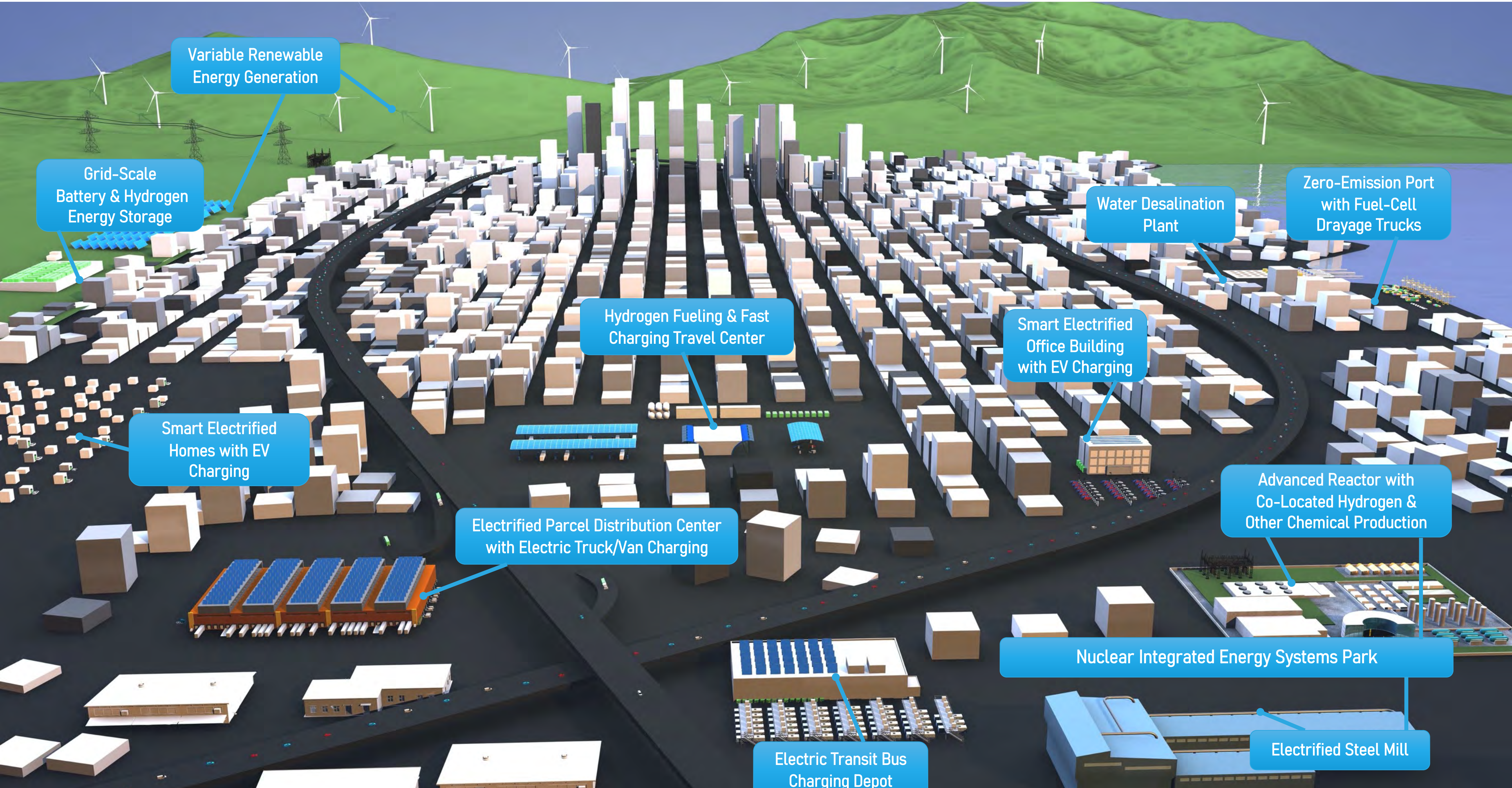
Nuclear Synthetic Fuels Production

Goal: Demonstrate the economic potential of using light water or advanced nuclear reactors for synthetic fuels production.



Representative Nuclear-Coupled Synthetic Fuels Process

A vision for a net-zero future



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Key References

- Integrated Energy Systems (IES): https://ies.inl.gov
- Gateway for Accelerated Innovation in Nuclear (GAIN): https://gain.inl.gov
- National Reactor Innovation Center (NRIC): https://nric.inl.gov
- Gen-IV International Forum: Education and Training webinars, https://www.gen-4.org/gif/jcms/c_82831/webinars, 2016-2021
- Light Water Reactor Sustainability Program (LWRS), Flexible Plant Operations and Generation, https://lwrs.inl.gov/SitePages/FlexiblePlantOperationGeneration.aspx
- LWR-H2 Reports
  - Exelon study: INL/EXT-19-55395, *Evaluation of Hydrogen Production for a Light Water Reactor in the Midwest, September 2019*
  - Midwest study: INL/EXT-19-55090, *Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest, August 2019*
- LWR Steam Markets
  - INL/EXT-20-58884, *Markets and Economics for Thermal Power Extraction from Nuclear Power Plants for Industrial Processes*, June 2020
- Additional reports available at https://ies.inl.gov/SitePages/Reports.aspx
- IES Simulation Toolset: https://ies.inl.gov/SitePages/System_Simulation.aspx
- Advanced Reactor Demonstration Program:
  - Program: https://www.energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-demonstration-program
  - 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