INL/CON-22-66397-Revision-0

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

March 2022

Changing the World's Energy Future

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Idaho National Laboratory

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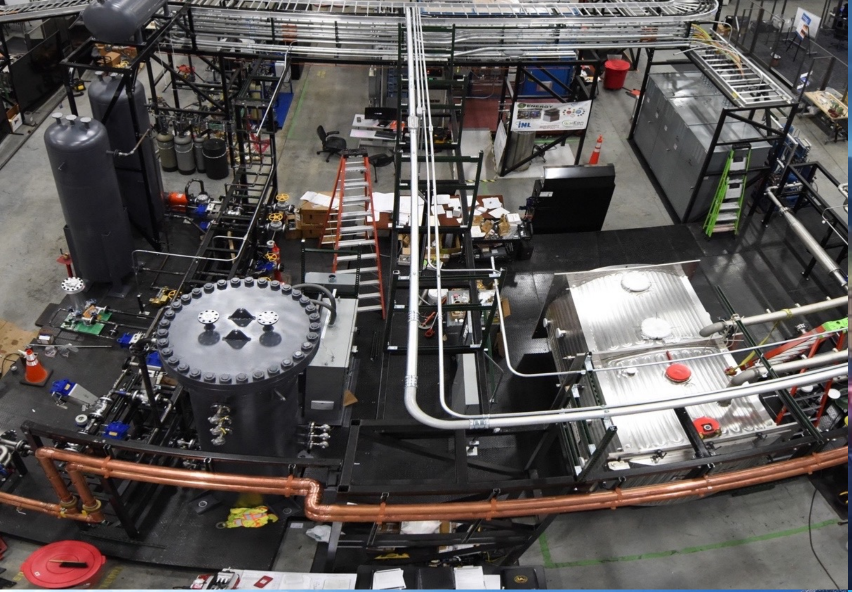
Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517



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The Essential Role of 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

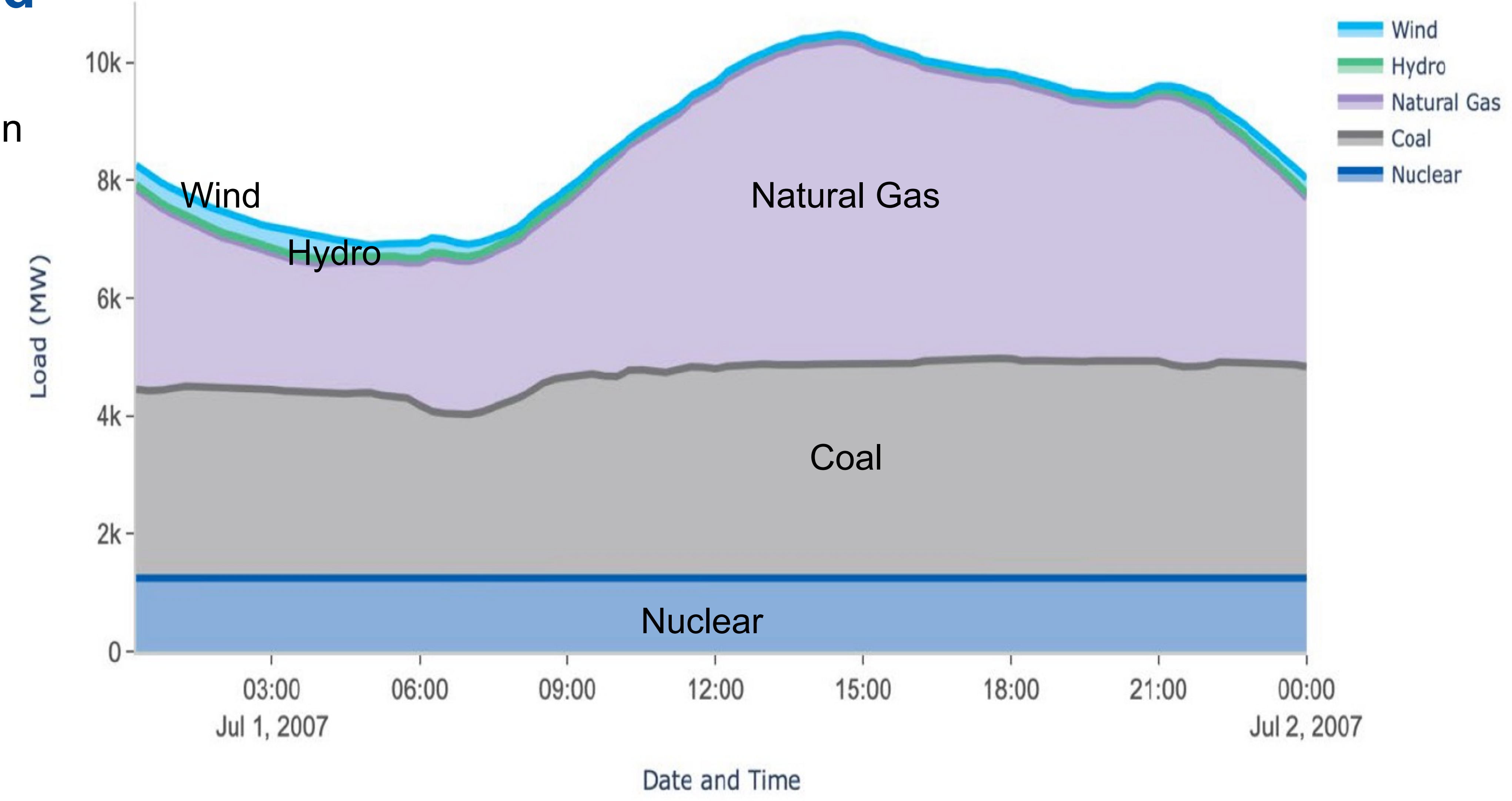
Today's electricity grid

- 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.

The electrical power sector is shifting away from traditional baseload

ERCOT generation by fuel source for July 1, 2007 (ERCOT 2020)

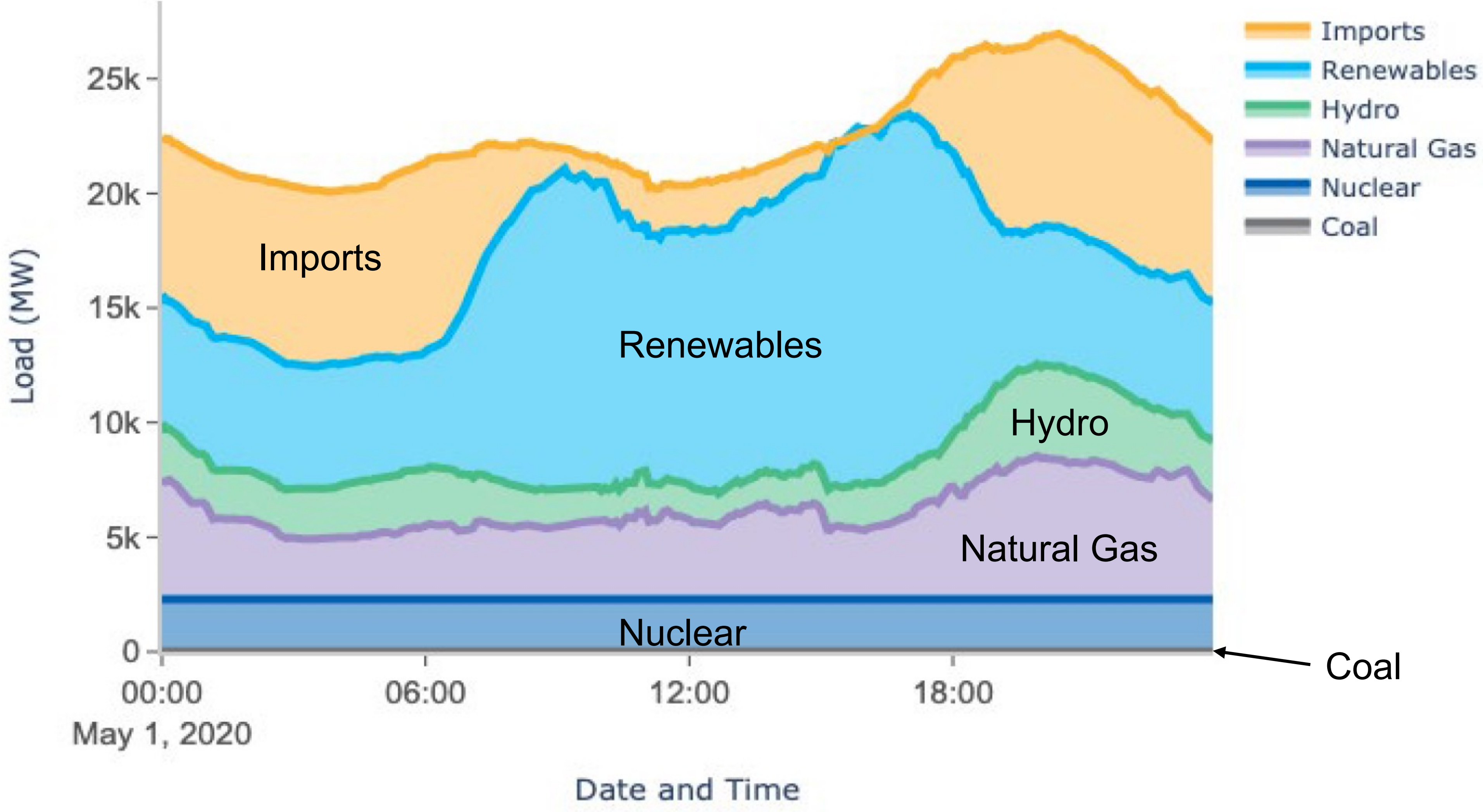


Flexible Nuclear Energy for Clean Energy Systems, September 2020, https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems.

The electrical power sector is shifting away from traditional baseload

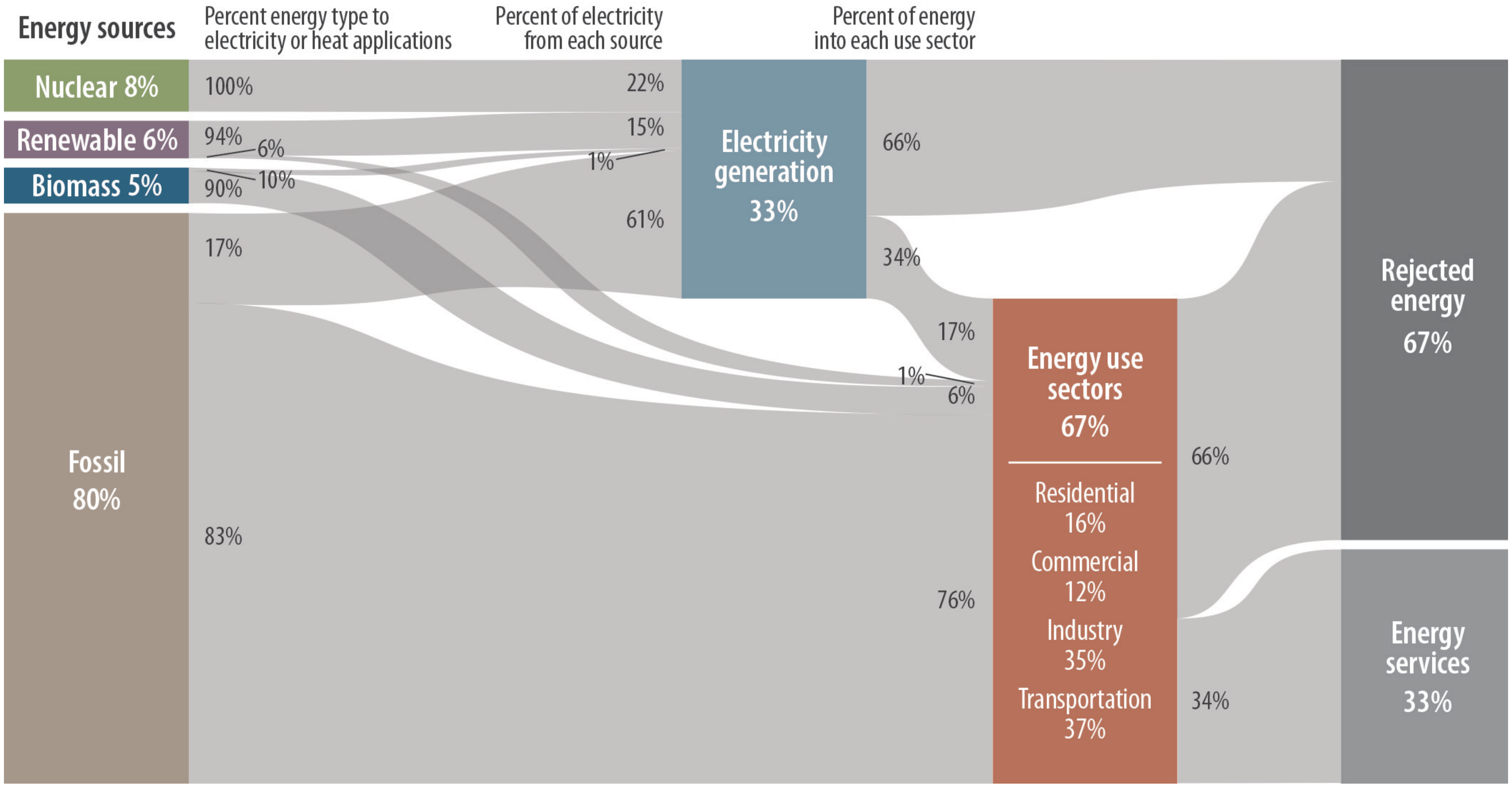
California Independent System Operator (CAISO) generation by fuel source for May 1, 2020

Source: "FERC: Documents & Filing – Forms – Form 714 – Annual Electric Balancing Authority Area and Planning Area Report – Data Downloads", n.d.



Flexible Nuclear Energy for Clean Energy Systems, September 2020, https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems.

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

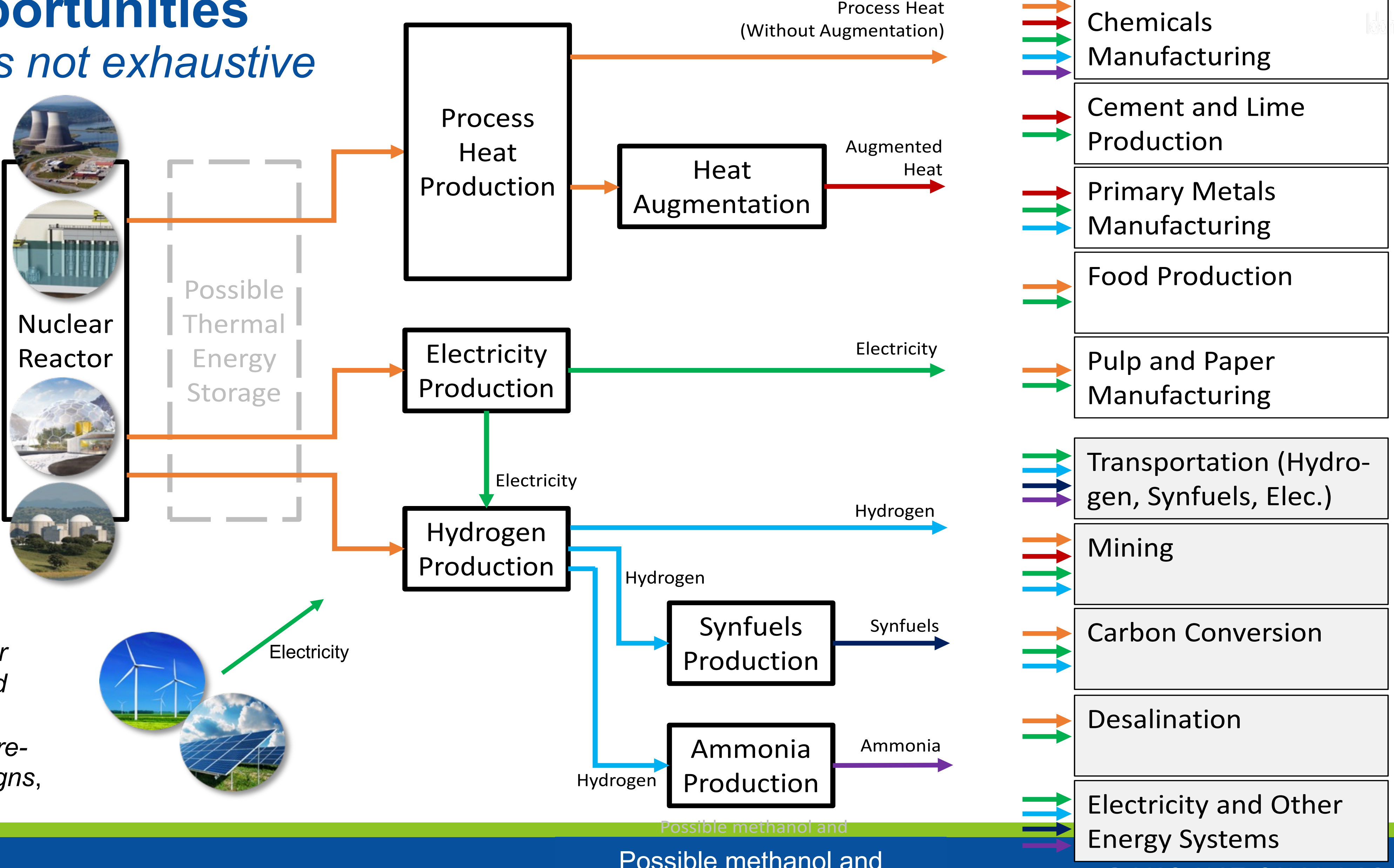
Nuclear Energy Generation

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

Integrated energy systems leverage the contributions from nuclear fission beyond electricity

Potential nuclear-driven IES opportunities

Examples not exhaustive



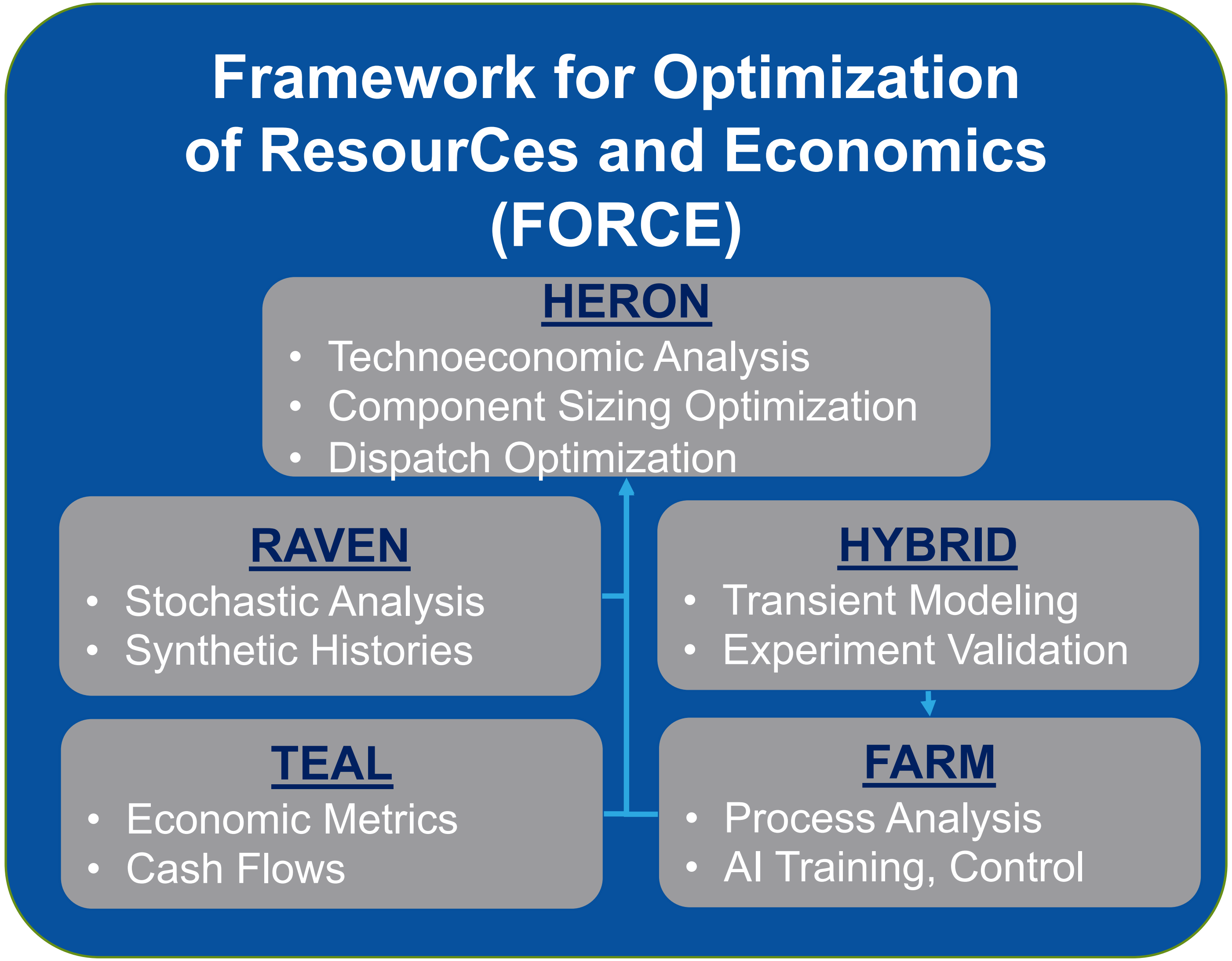
Source: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, April 2021

Possible methanol and

Possible methanol and synthetic methane as well

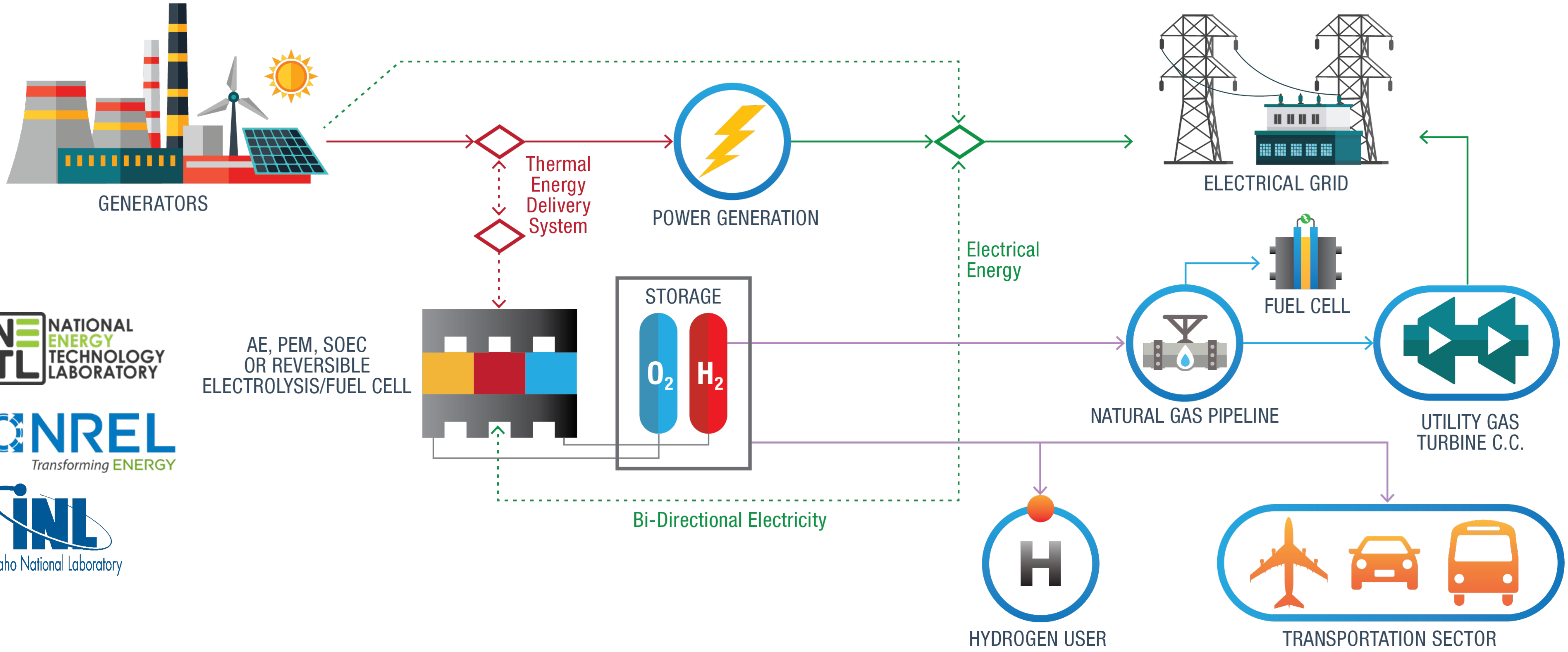
Integrated energy systems analysis and optimization

- **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: Multiple generators for hydrogen production



NATIONAL ENERGY TECHNOLOGY LABORATORY

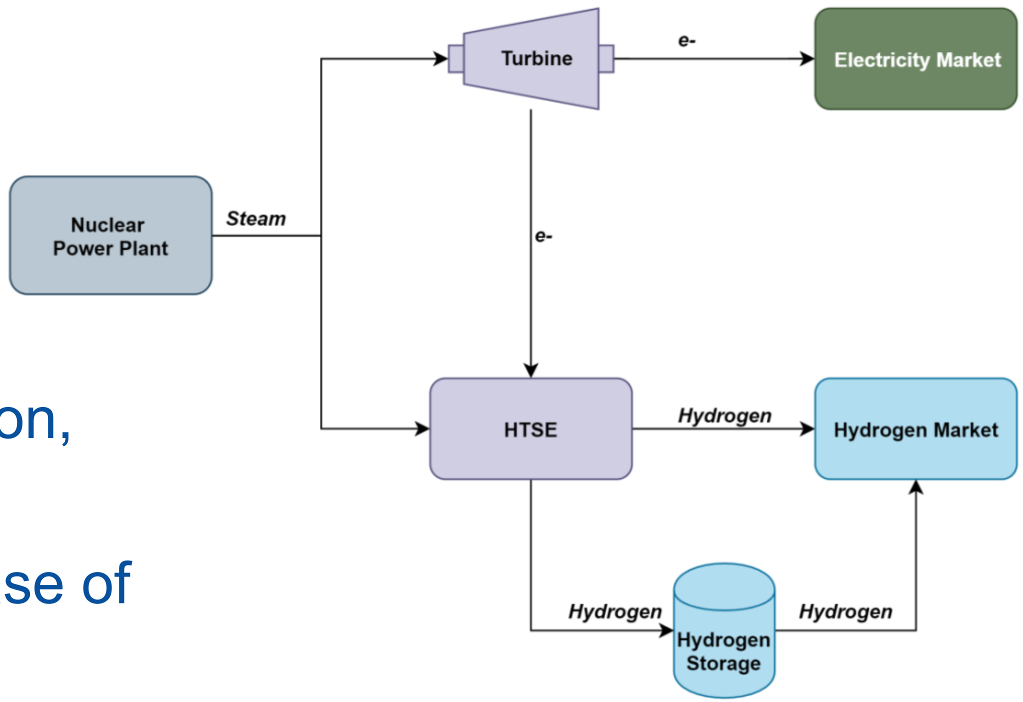
NREL Transforming ENERGY

INL Idaho National Laboratory

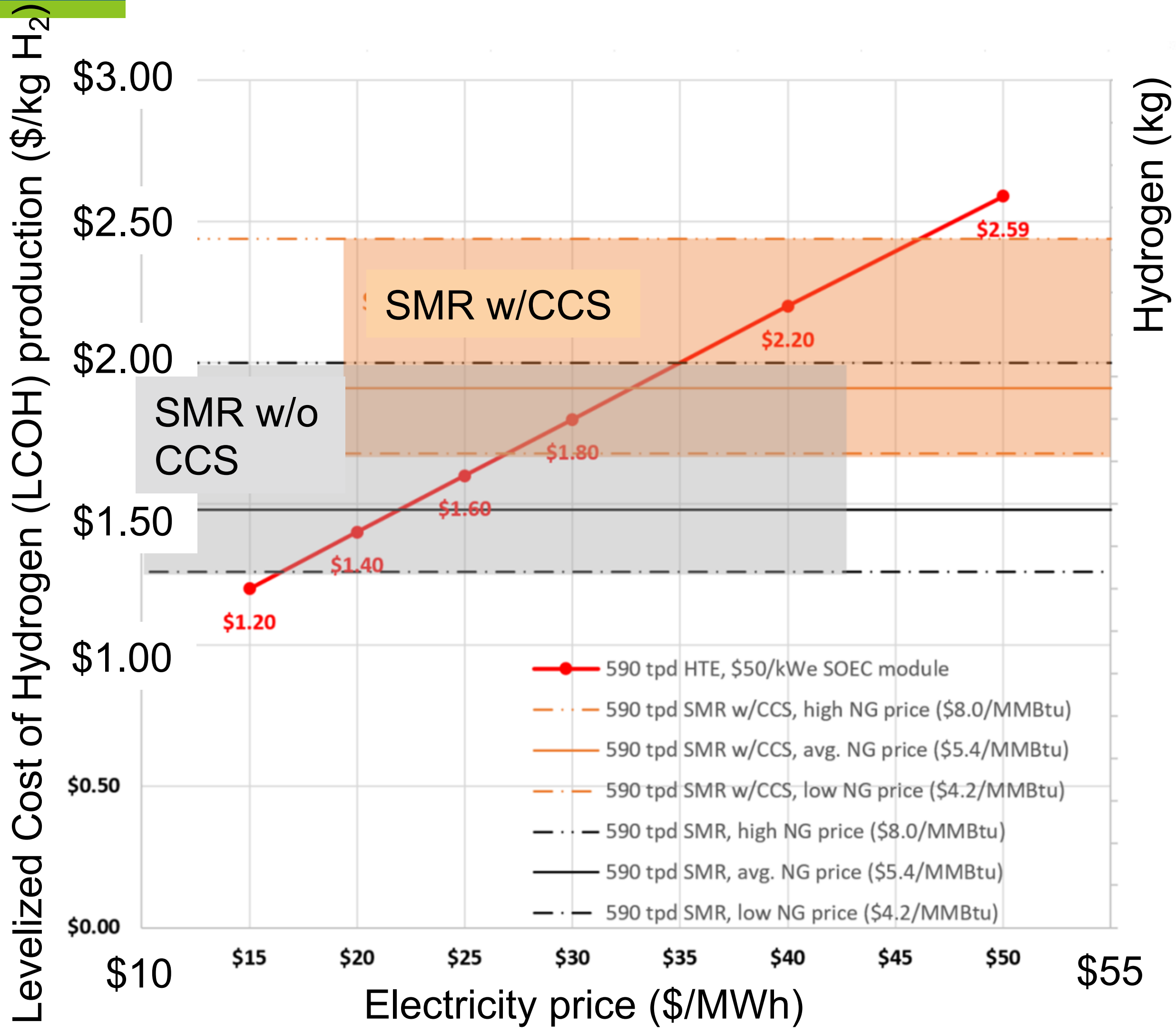
IES Integrated Energy Systems

Example: Disruptive potential of nuclear produced H2

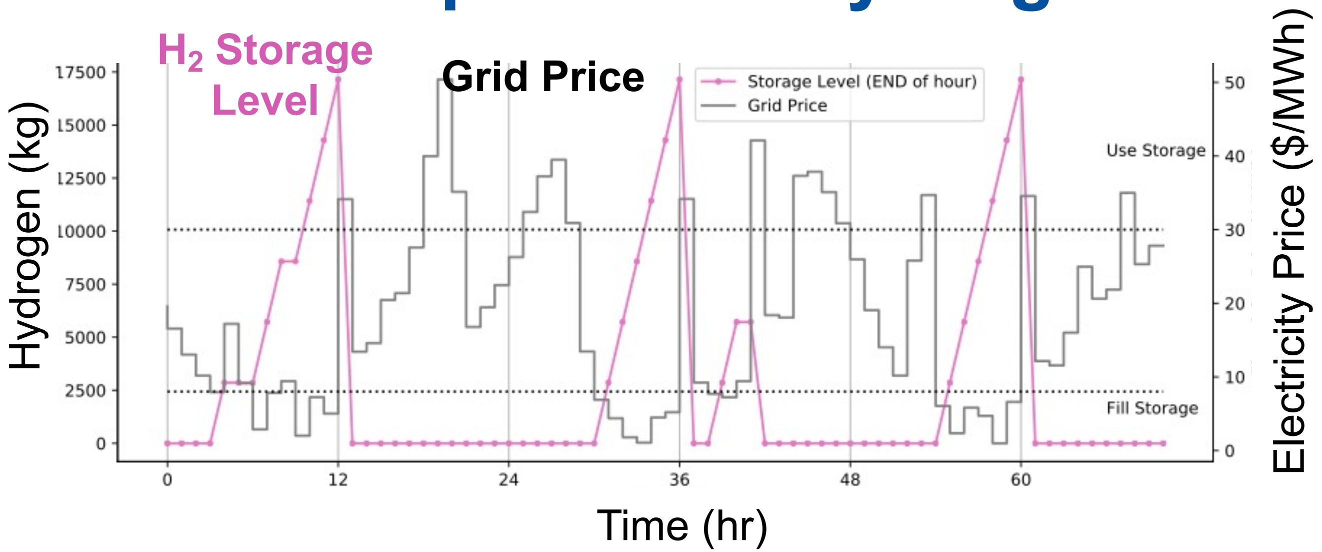
- Collaboration between INL, ANL, NREL, Exelon, and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid pricing → grid is 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 (SMR) 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 or Monticello NPP (~150 kWe HTSE)
- APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~15-20 MWe LTE/PEM)

Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

Thermal & Electrical Integration at an Xcel Energy NPP HTSE/SOEC

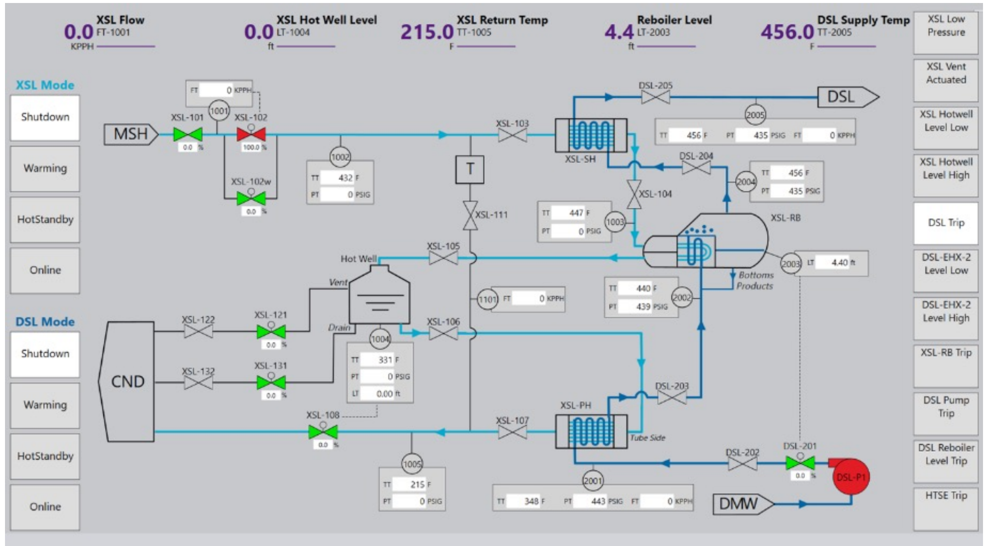
Prairie Island

Monticello

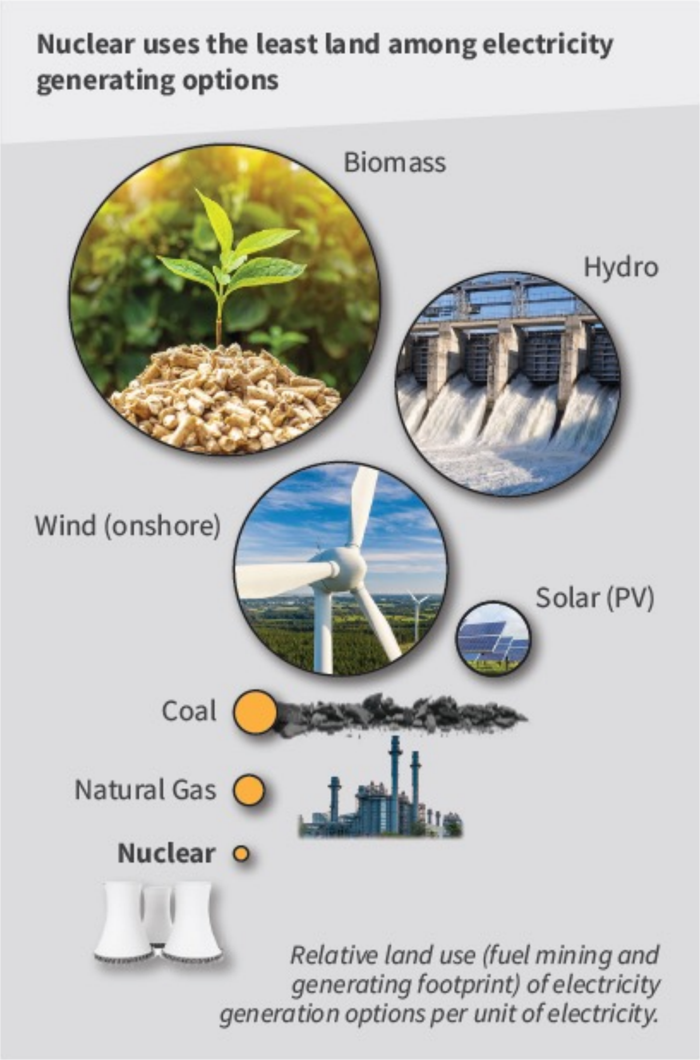
Palo Verde Generating Station, H_2 Production for Combustion and Synthetic Fuels

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



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 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

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

SIZES

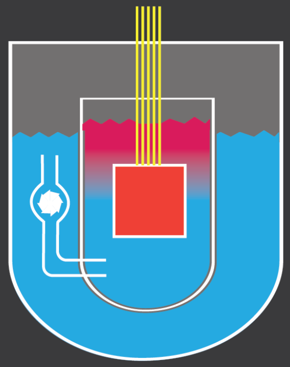
SMALL
1 MW to 20 MW
Micro-reactors
Can fit on a flatbed truck. Mobile. Deployable.

MEDIUM
20 MW to 300 MW
Small Modular Reactors
Factory-built. Can be scaled up by adding more units.

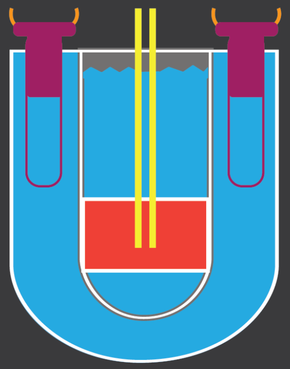
LARGE
300 MW to 1,000 + MW
Full-size Reactors
Can provide reliable, emissions-free baseload power

Advanced Reactors Supported by the U.S. Department of Energy

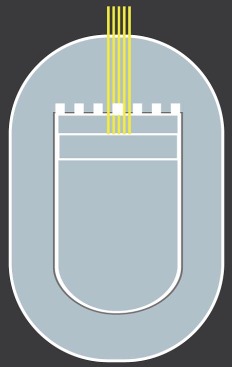
TYPES



MOLTEN SALT REACTORS – Use molten fluoride or chloride salts as a coolant. Online fuel processing. Can re-use and consume spent fuel from other reactors.

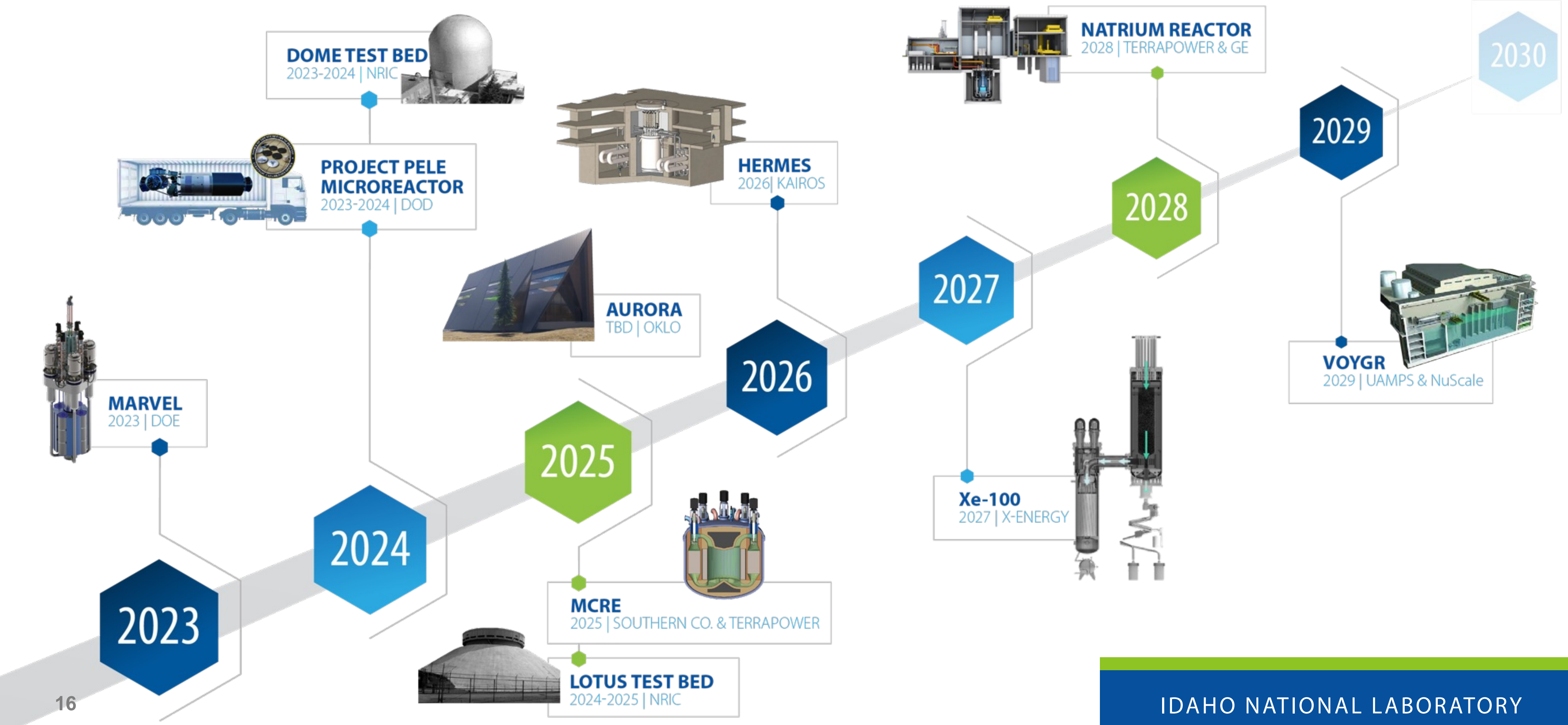


LIQUID METAL FAST REACTORS - Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.



GAS-COOLED REACTORS – Use flowing gas as a coolant. Operate at high temperatures to efficiently produce heat for electric and non-electric applications.

Accelerating advanced reactor demonstration & deployment



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/.

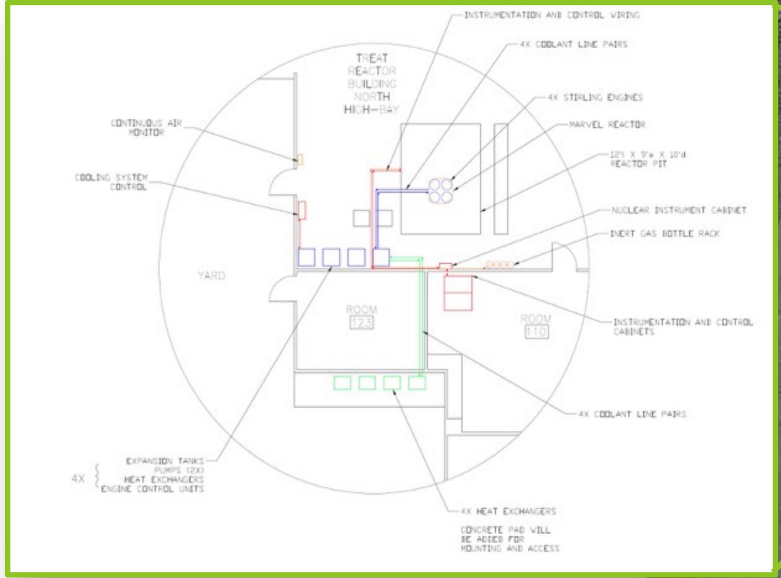
Microreactor integration with a microgrid

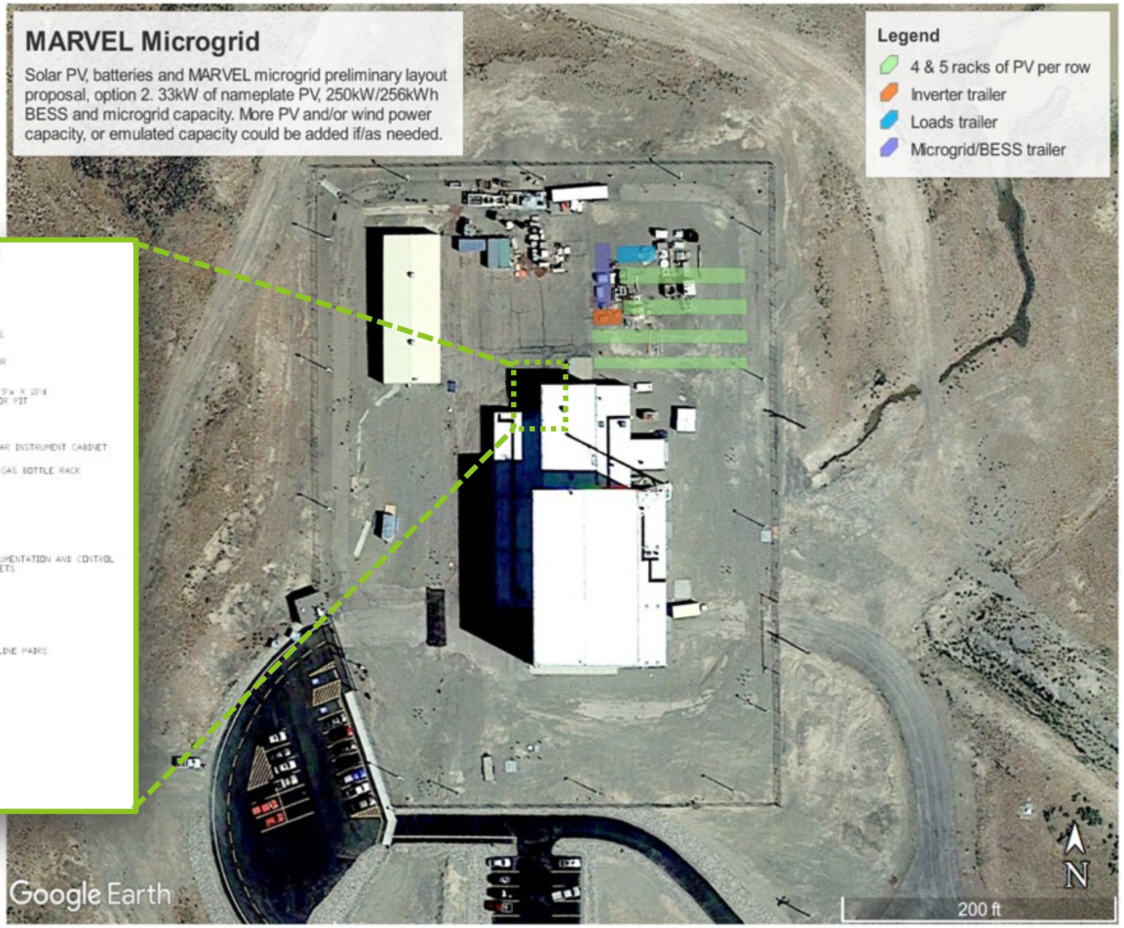
MARVEL

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.



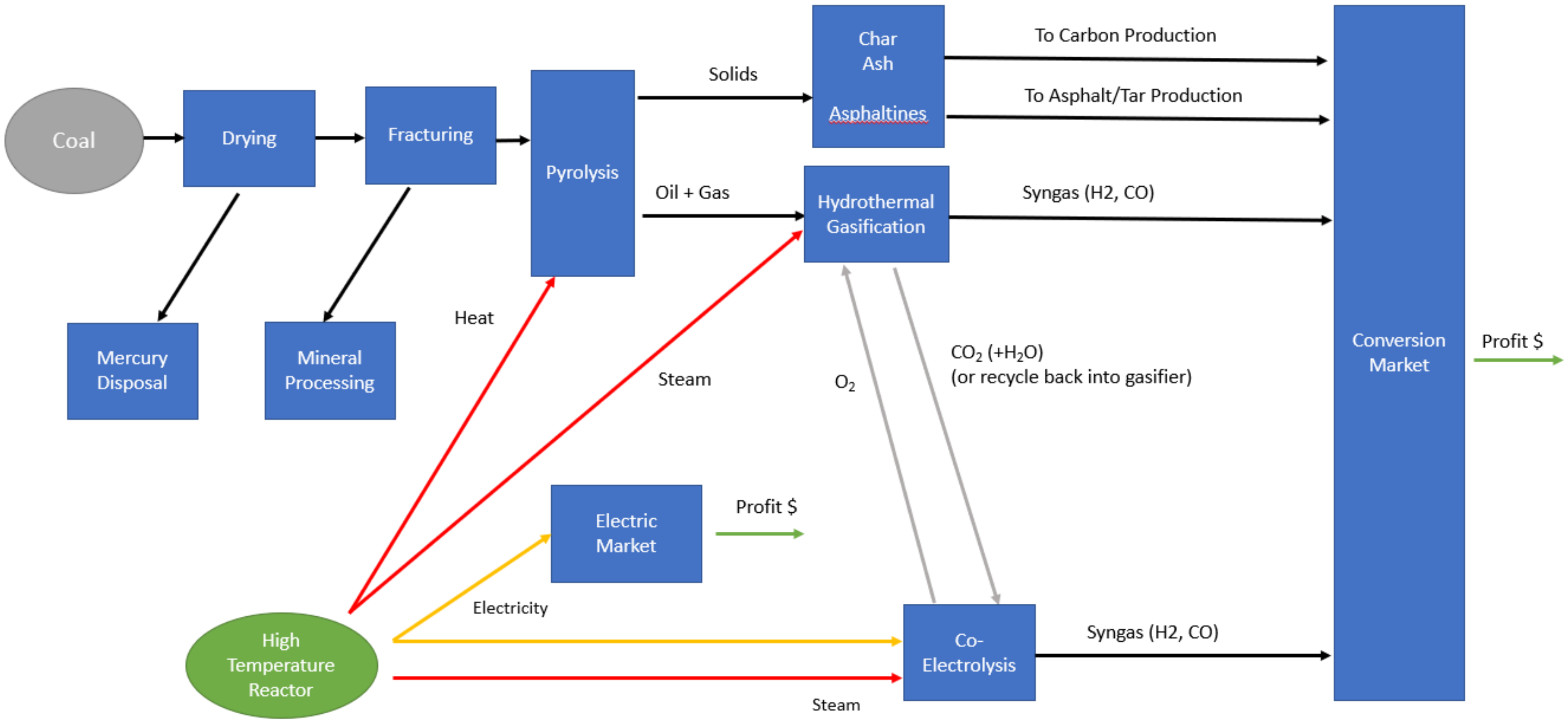


MARVEL Construction: Dec 2022
MARVEL Criticality: Dec 2023

Nuclear–Carbon Conversion Case Study

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

1) Dry coal and drive off as much mercury as possible
2) Mechanical process to fracture the coal and separate mineral matter
3) Pyrolysis
4) Oil/Gas Processing
   - Hydrothermal Gasification
   - Supercritical water oxidation
   - Plasma Gasification
5) Syngas Refining
   - Methanol
   - Alcohols
   - Polymers



Representative Coal Conversion Process

Nuclear Synthetic Fuels Production

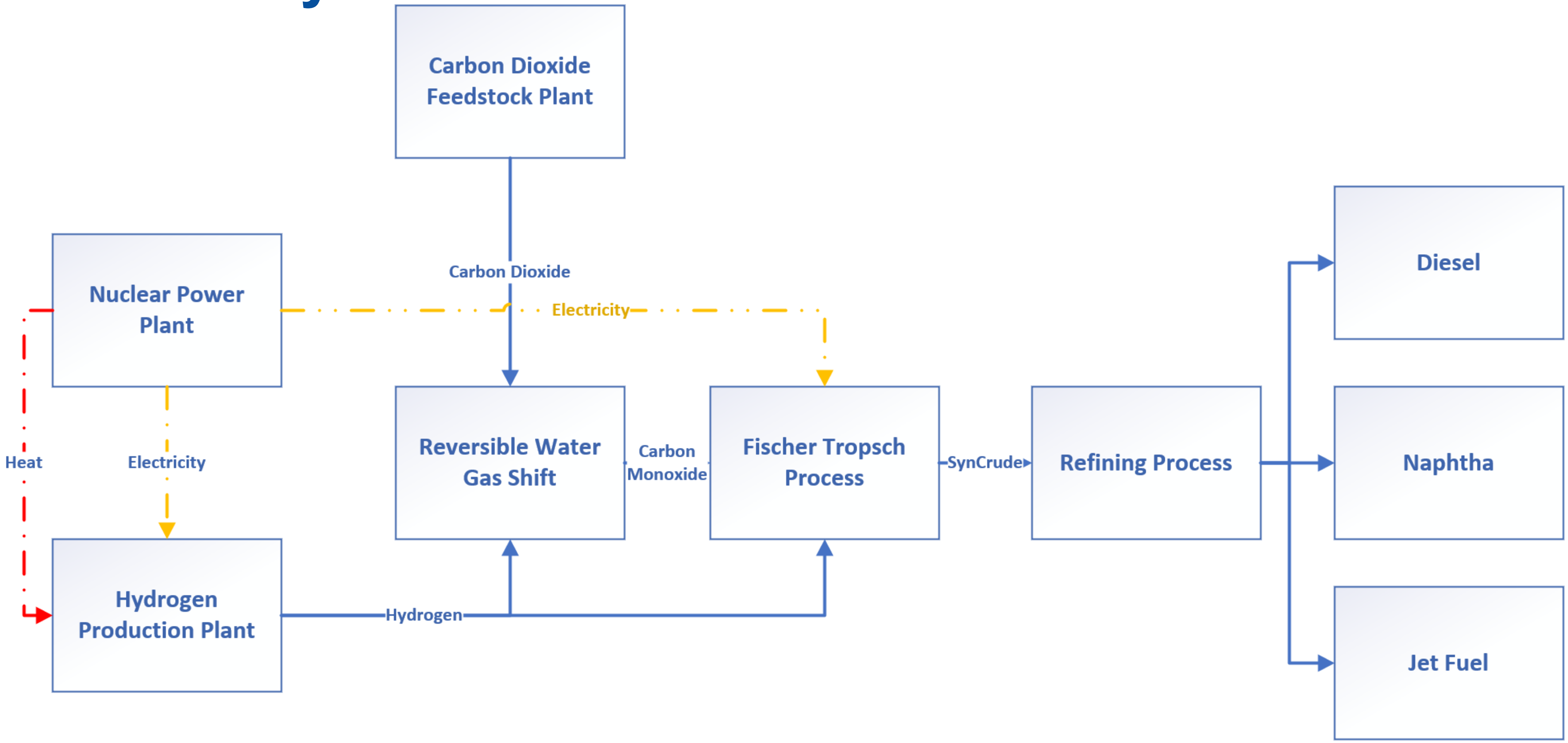
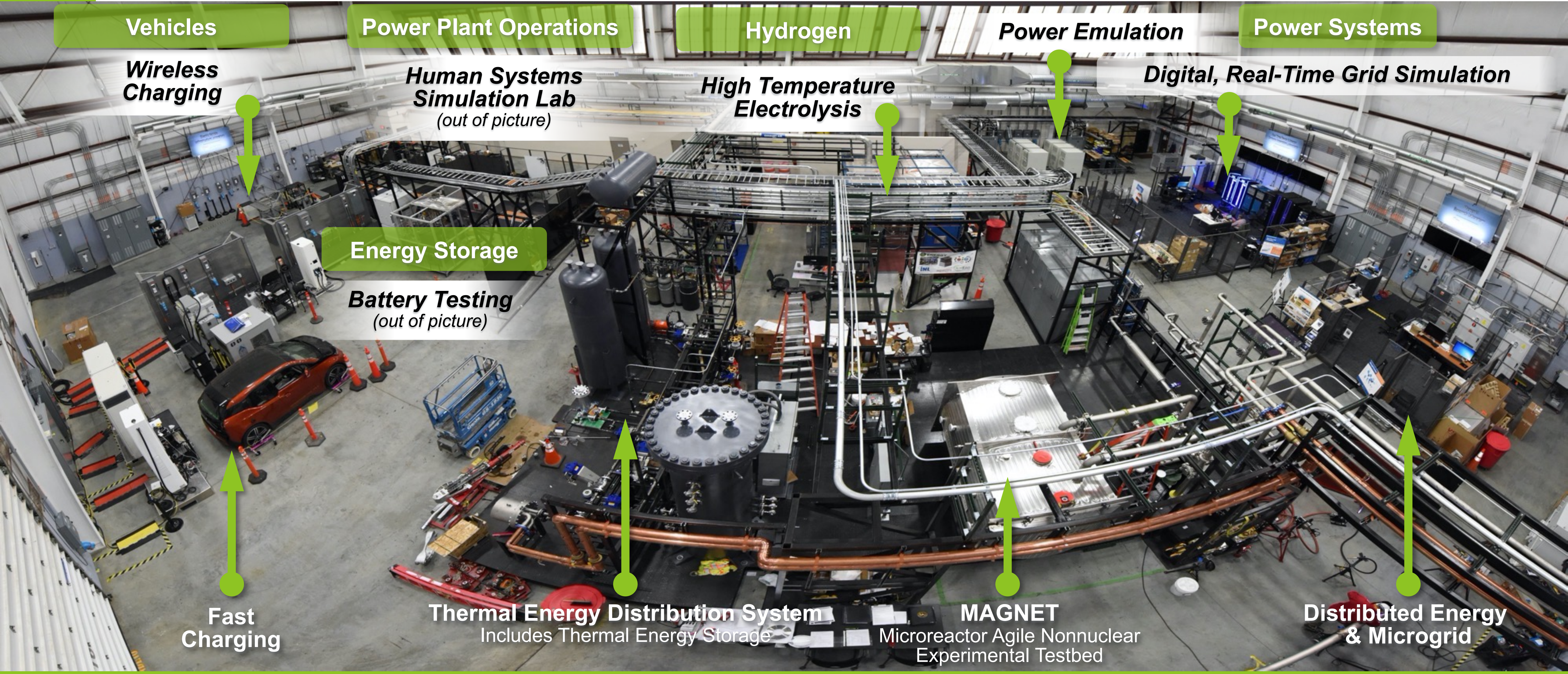
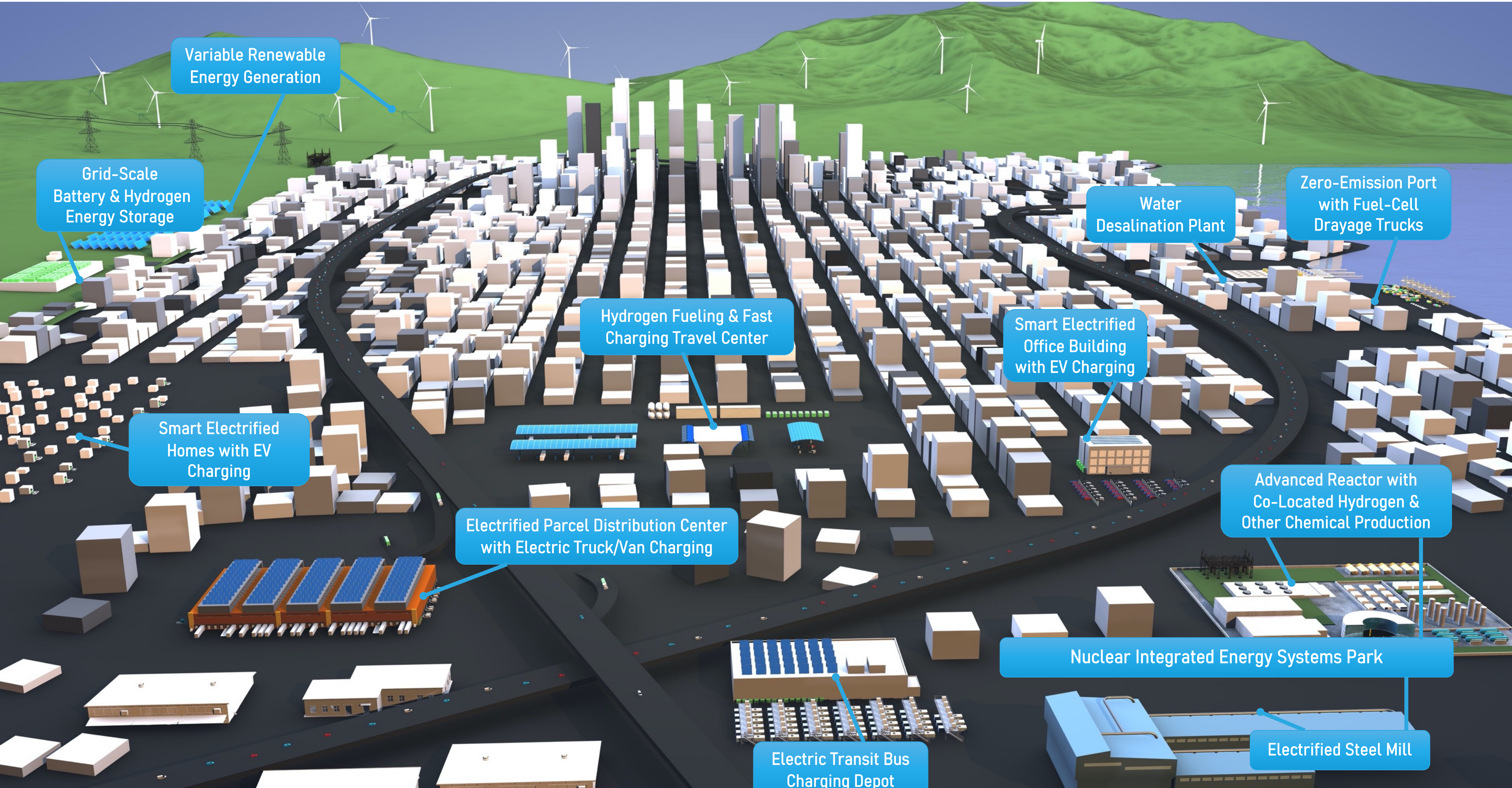


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

Dynamic Energy Transport and Integration Laboratory (DETAIL)



Distributed energy systems for a net-zero future



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  - News release: https://www.powermag.com/final-doe-advanced-reactor-demonstration-awards-announced/
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