INL/MIS-22-66725-Revision-0

Advancing Nuclear Energy to Support a Net-Zero Future

April 2022

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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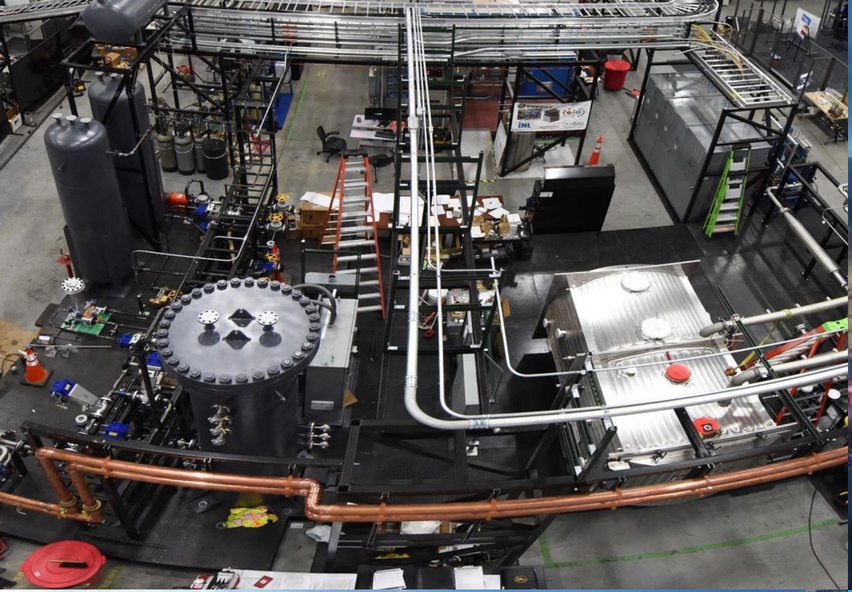

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Advancing Nuclear Energy to Support a Net-Zero Future

KEPCO International Nuclear Graduate School (KINGS)

Seminar

April 28, 2022

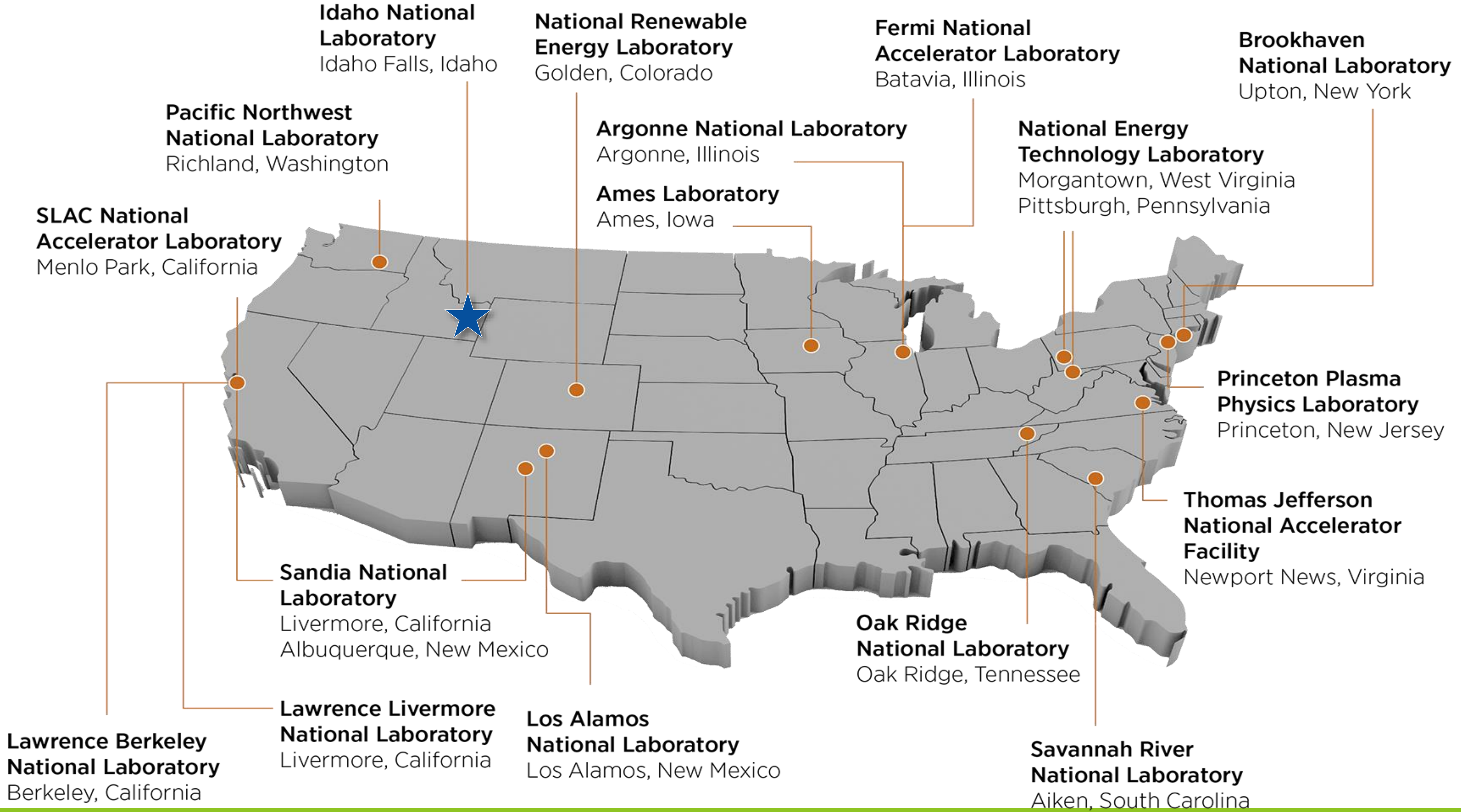
Idaho National Laboratory

Expanded from INL/CON-22-66717

Presentation overview

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

U.S. Department of Energy National Laboratories



Addressing the world’s most challenging problems

VISION
INL will change the world’s energy future and secure our critical infrastructure.

MISSION
Discover, demonstrate, and secure innovative nuclear energy solutions, clean energy options and critical infrastructure.

Leveraging INL site, infrastructure, and facilities to enable energy and security R&D at scale

$1,572 M	FY21 Total Operating Cost
5,300+	Employees
569,178	Acres
890	Square Miles

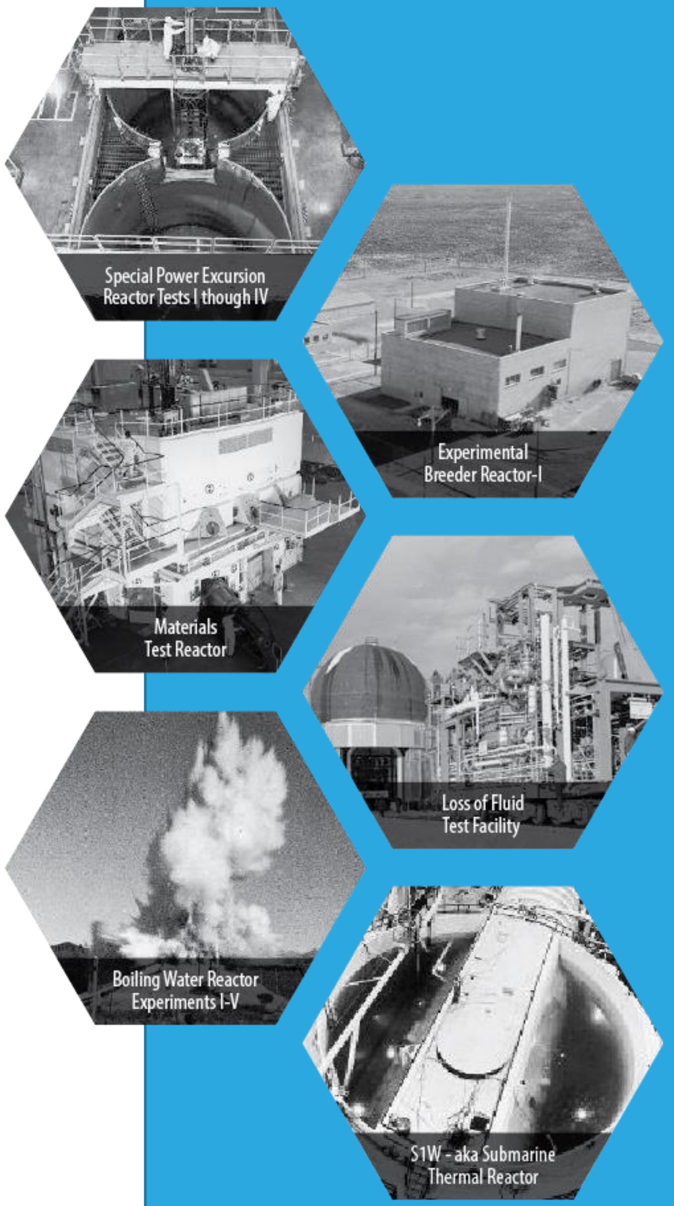
112	Miles high-voltage transmission lines
17.5	Miles railroad for shipping nuclear fuel
4	Operating reactors
12	Hazard Category II & III non-reactor facilities/activities
50	Radiological facilities/activities
3	Fire Stations

Our Heritage: *The National Reactor Testing Station drove nuclear innovation in the U.S. and around the world*

1st

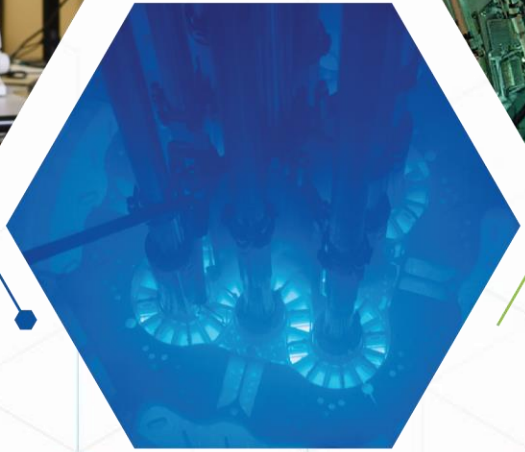
- Nuclear power plant
- U.S. city to be powered by nuclear energy
- Submarine reactor tested; training of nearly 40,000 reactor operators until mid-1990s
- Mobile nuclear power plant for the army

Demonstration of self-sustaining fuel cycle	Basis for LWR reactor safety	Aircraft and aerospace reactor testing	Materials testing reactors



Creating a secure, resilient, clean energy future

Nuclear Science & Technology



Advanced Test Reactor Complex

Materials and Fuels Complex

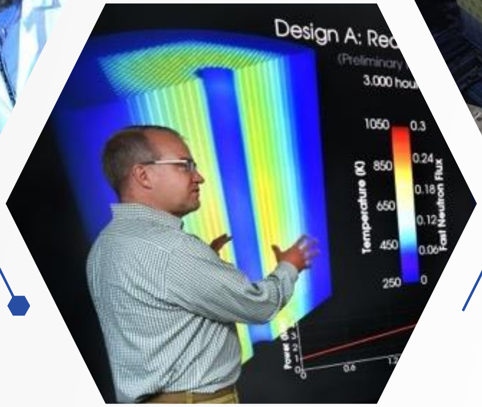
Energy & Environment Science & Technology

National & Homeland Security Science & Technology

Sustaining the existing commercial reactor fleet and expanding deployment of future reactors

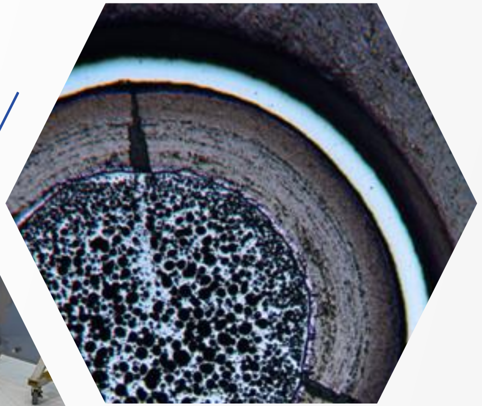
New nuclear materials and fuels

HPC for advance modeling and simulation



National nuclear energy strategic infrastructure

Powering space exploration



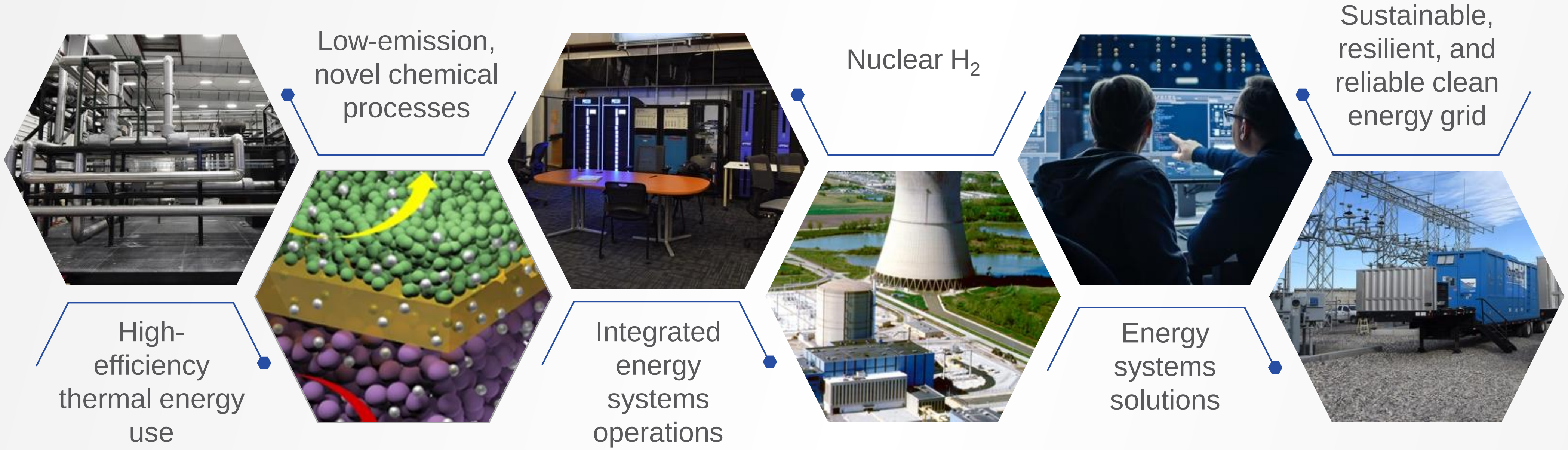
Next-generation fuels

NRIC National Reactor Innovation Center

GAIN Gateway for Accelerated Innovation in Nuclear

IDAHO NATIONAL LABORATORY

Transforming the energy paradigm through innovation and demonstration



Solving urgent national security challenges

Secure and Resilient Grid

Industrial Control Systems Security

Wireless Security

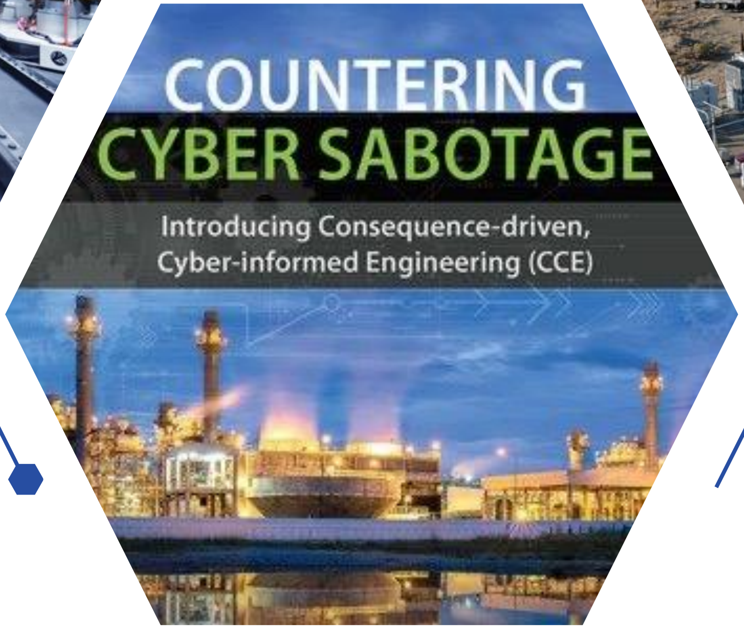
First Responder Training

Nuclear Safety and Security

National Defense Support

Ensuring the security and resiliency of critical infrastructure

Cyber-informed science and engineering to protect infrastructure



Leading industrial control systems security R&D for the digital supply chain and manufacturing automation

Enhanced electric power grid test bed

UTSA
The University of Texas at San Antonio™

CYMANII
cybersecurity manufacturing innovation institute

A quick look at today's energy systems…

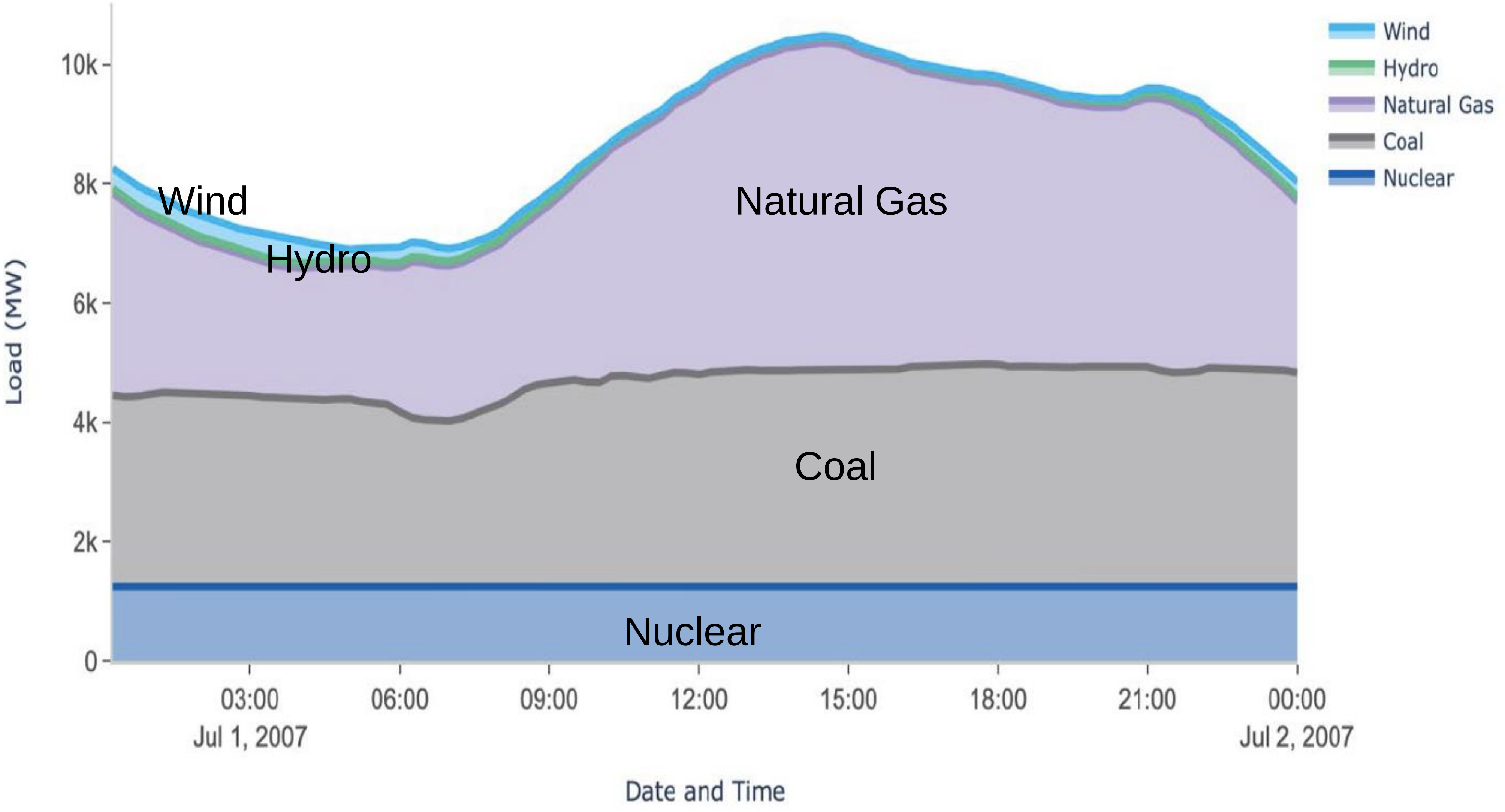
Energy systems today

- Individual generators contribute to meeting electric 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.

A snapshot of the "traditional" electrical power sector

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

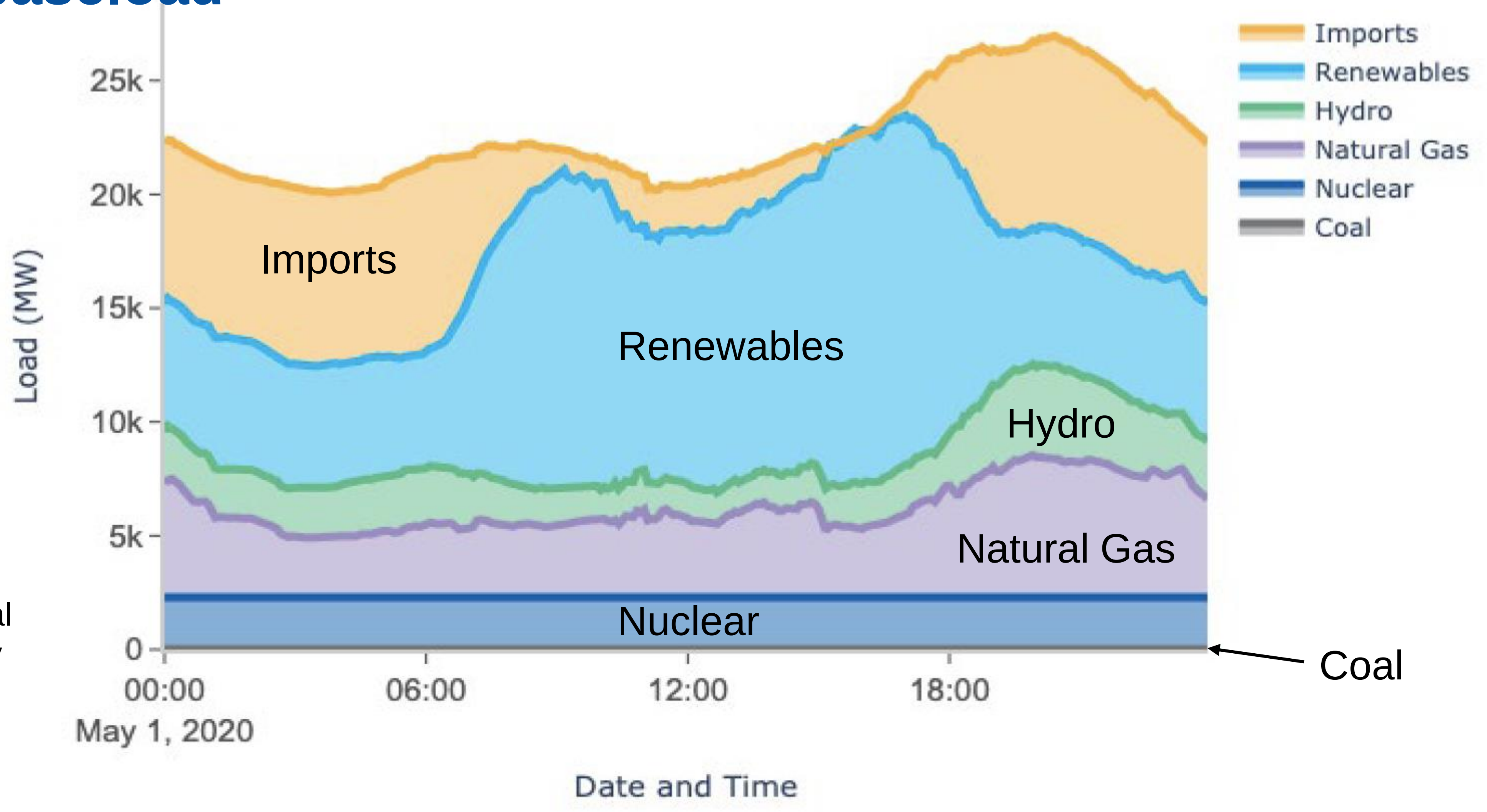


Flexible Nuclear Energy for Clean Energy Systems, September 2020, https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems.

But… the electrical power sector is shifting away from traditional baseload

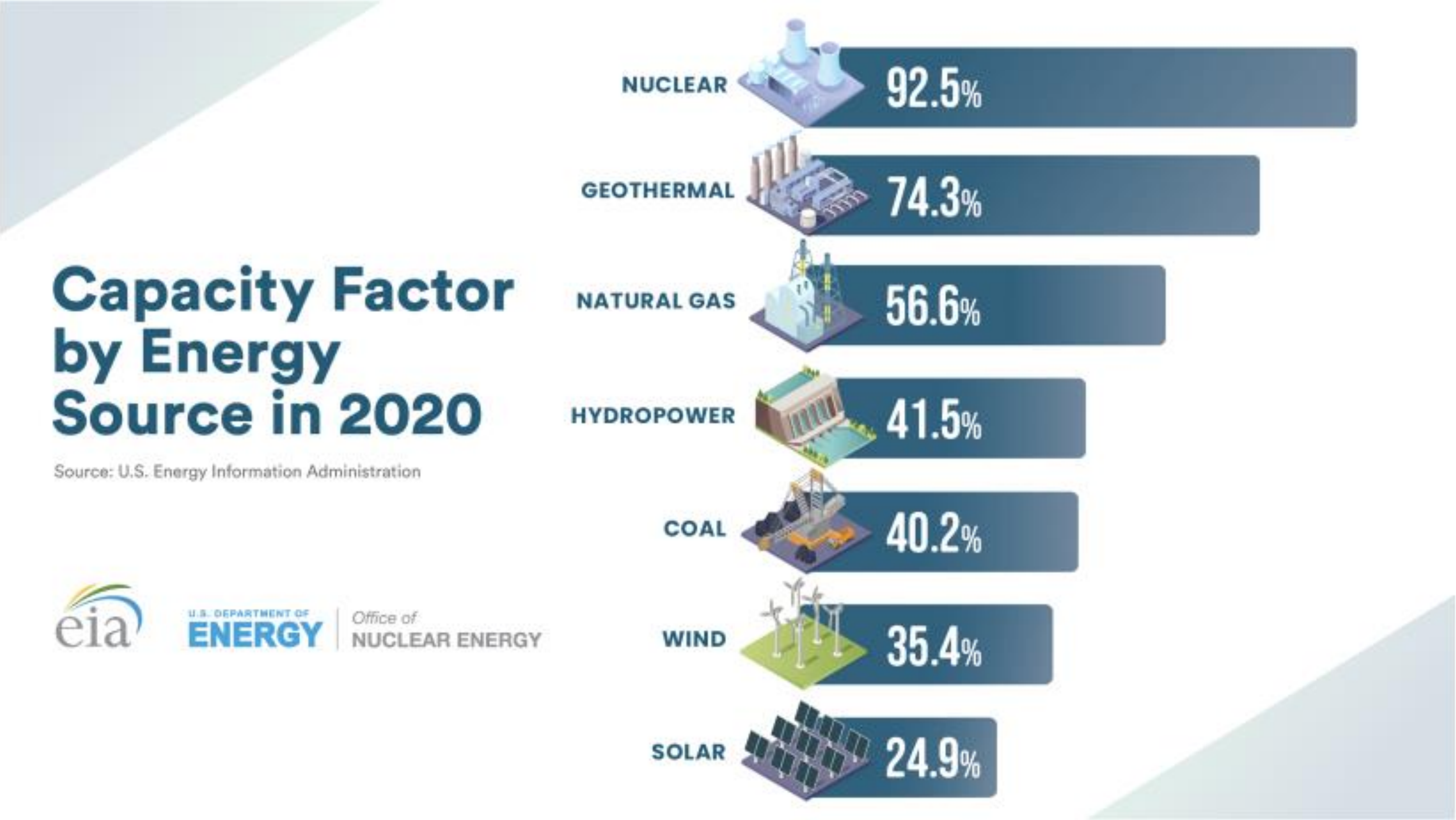
California Independent System Operator (CAISO) generation by fuel source for May 1, 2020

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.

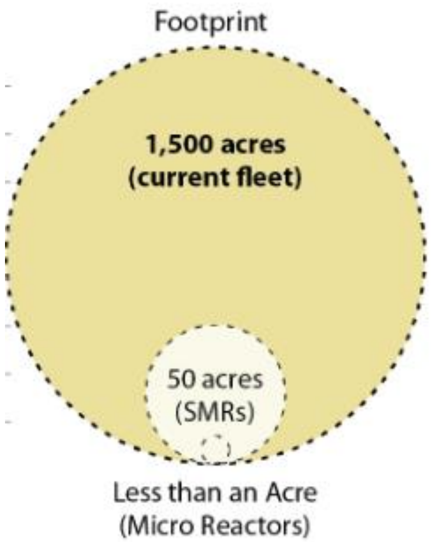
The current role of nuclear energy in the U.S.



energy.gov/nuclear

So, what’s new in nuclear technology, and when will it be ready for deployment?

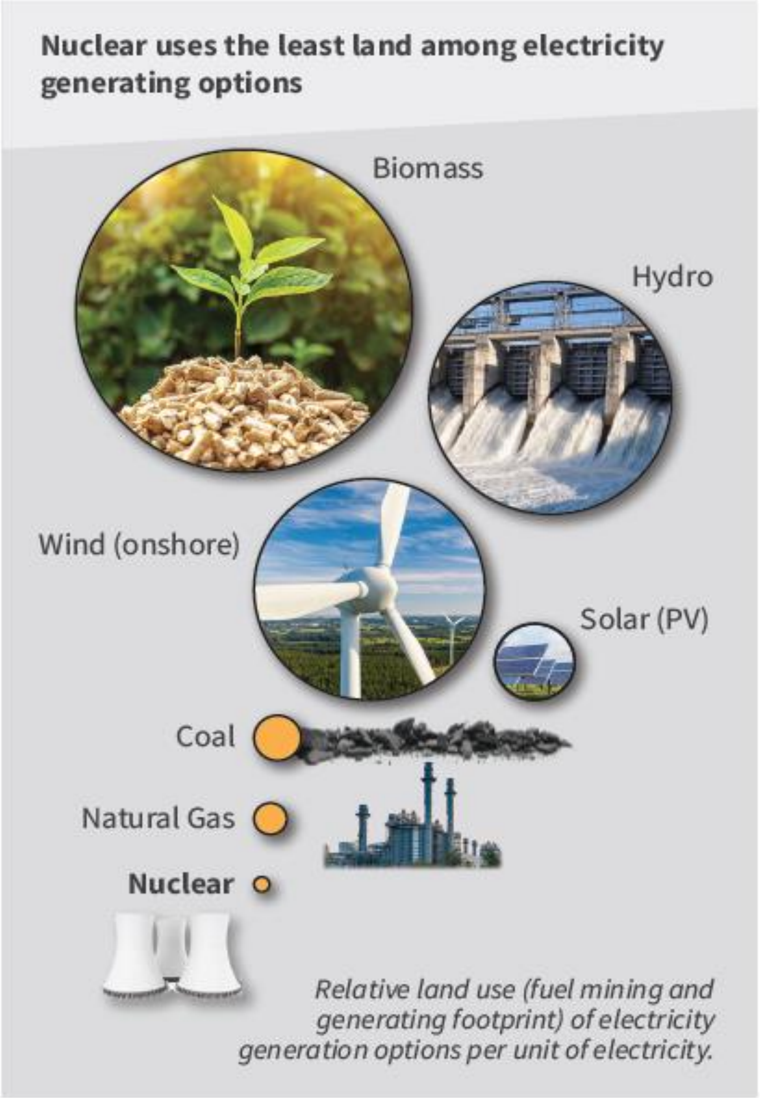
Nuclear energy and deployment flexibility



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

- Enhanced inherent/passive safety
- Deployment flexibility
- Versatile applications
- Long fuel cycles
- Reduced waste
- Advanced manufacturing and factory manufacturing to reduce costs

60+ private sector projects under development

SIZES

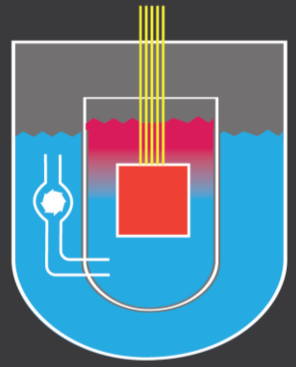
SMALL
1 MW to 20 MW
Micro-reactors
Can fit on a flatbed truck. Mobile. Deployable.

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

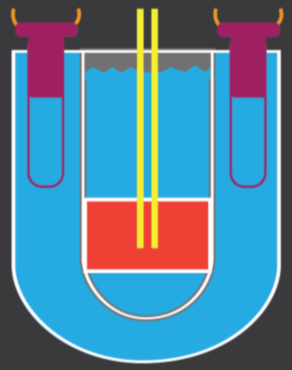
LARGE
300 MW to 1,000 + MW
Full-size Reactors
Can provide reliable, emissions-free baseload power

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

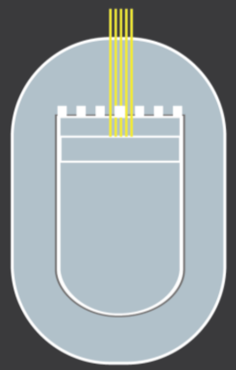
TYPES



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.



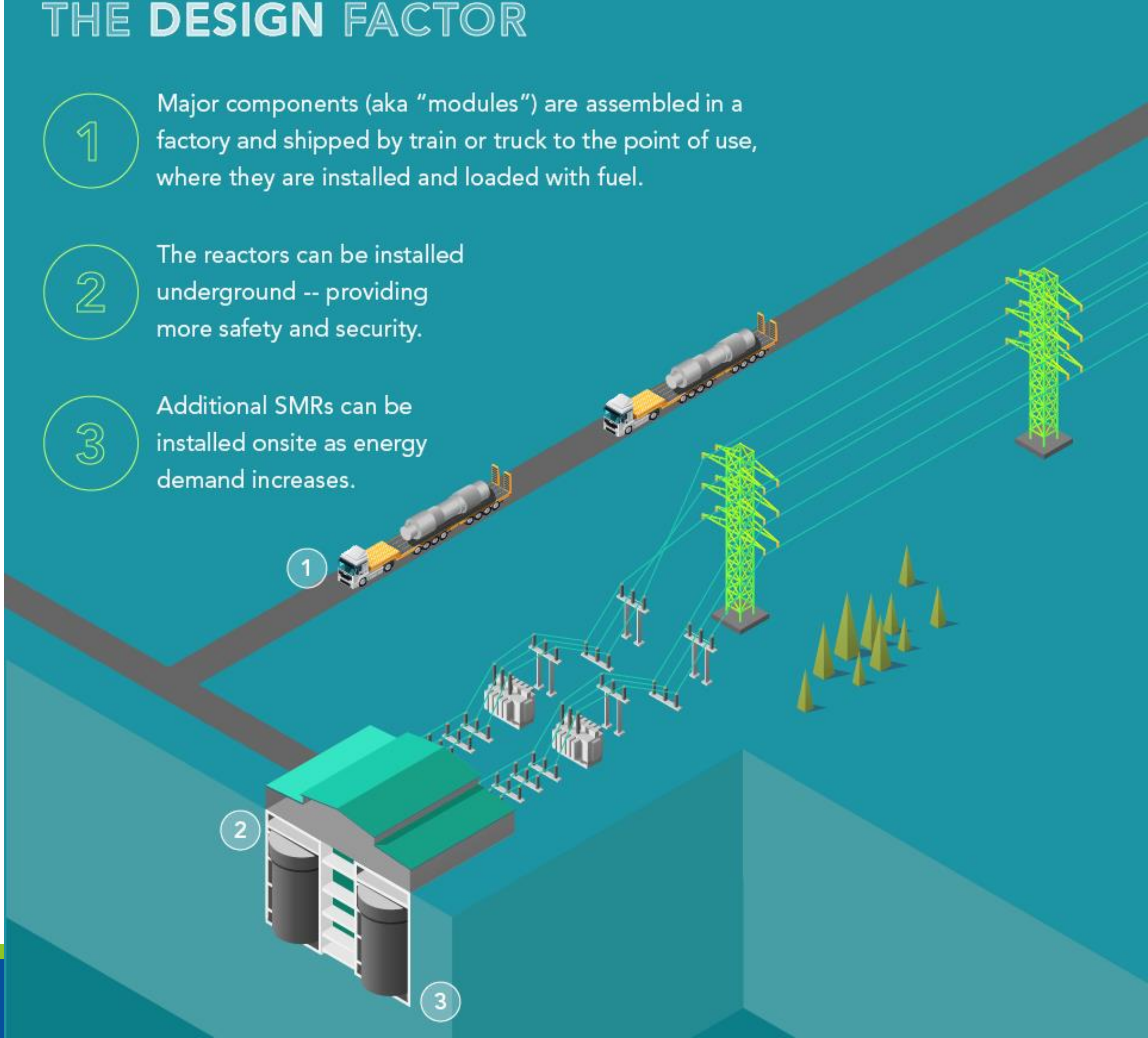
LIQUID METAL FAST REACTORS - Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.



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

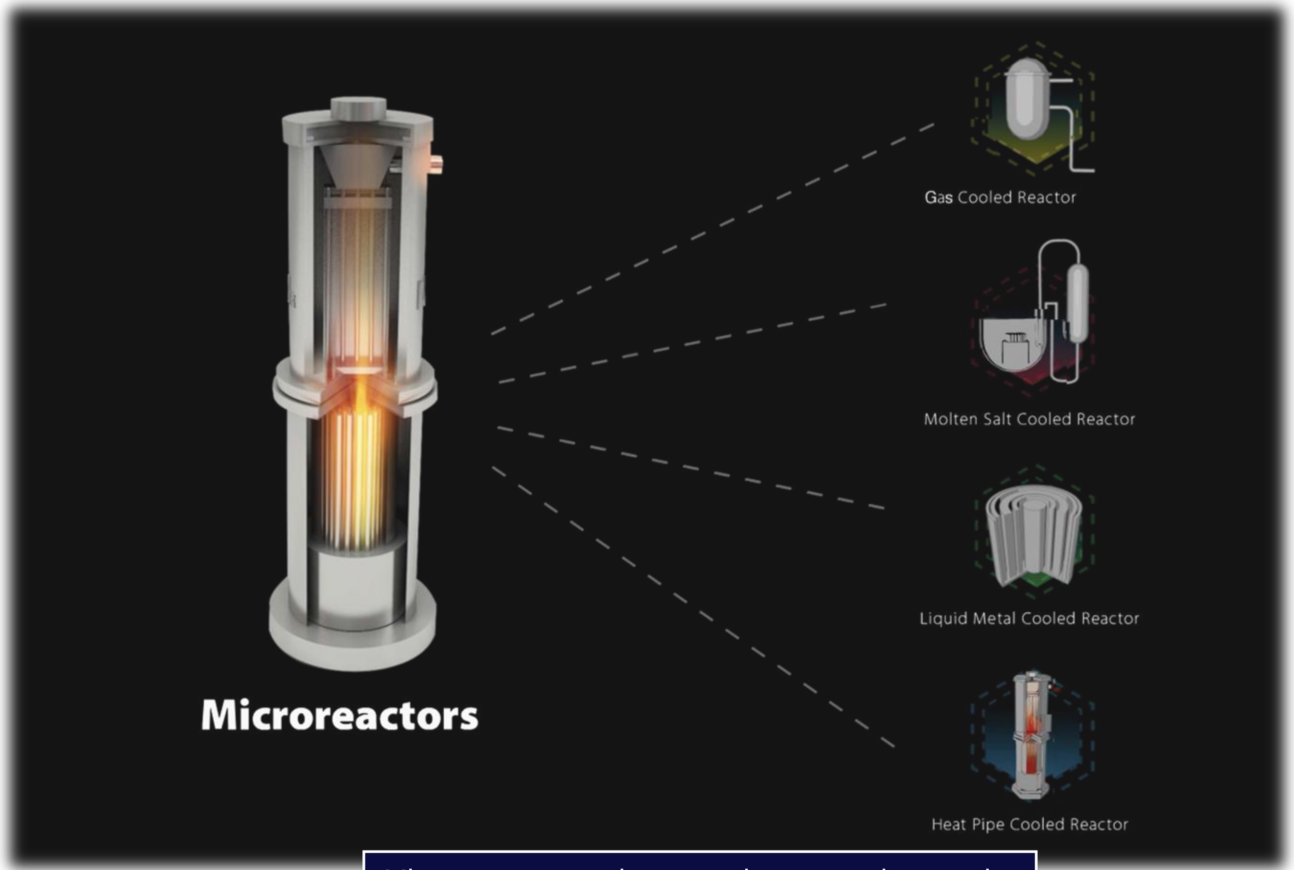
Small modular reactors

- Less site preparation
- More deployment options
- Flexible operation
- New business opportunities



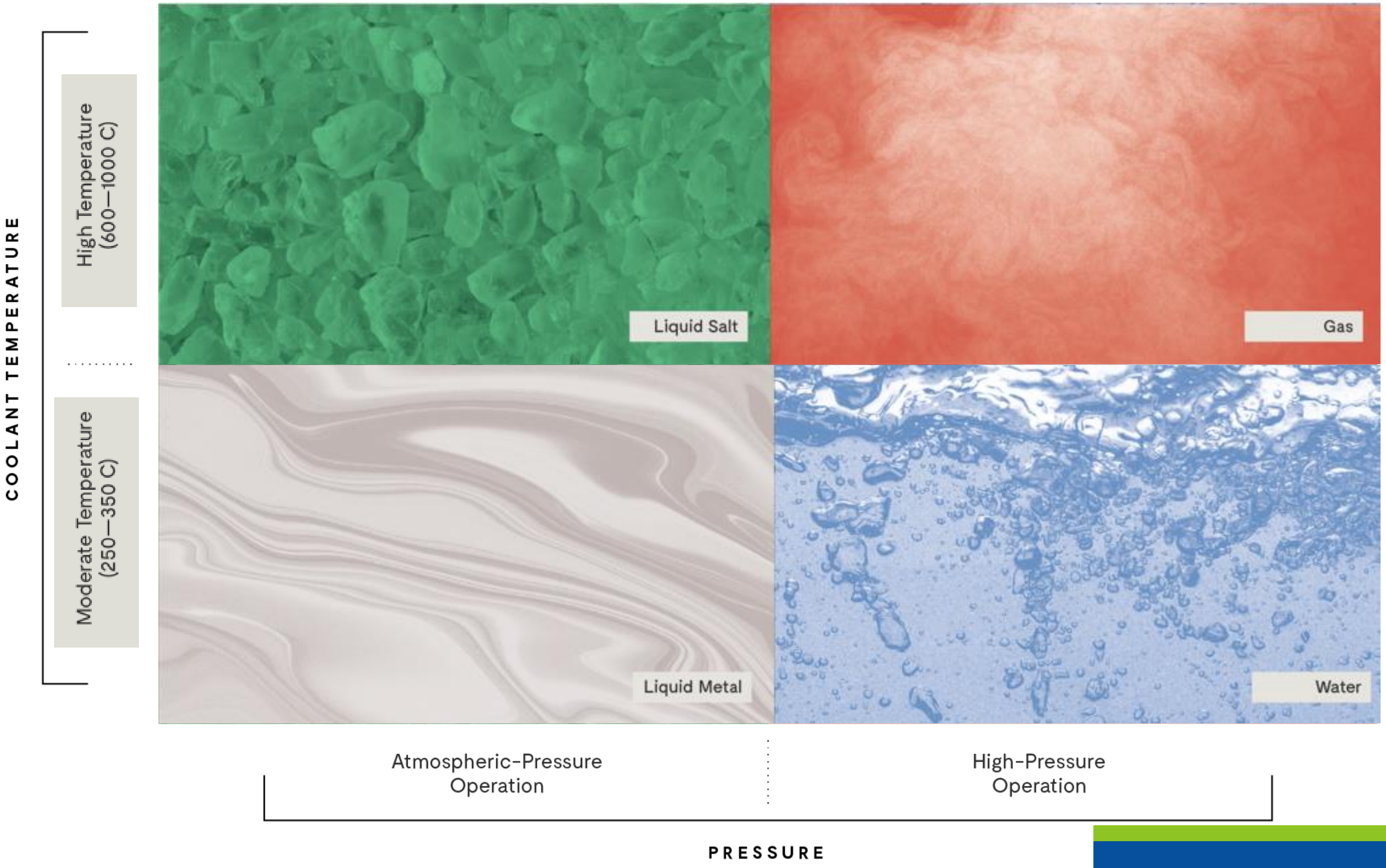
What are Microreactors?

- Small size and power level: <1 MW – 20 MW
- Factory build, easily transportable to and from site
- Minimum site preparation
- Flexible operation; self-regulating
- Designs enable remote and/or semi-autonomous operation
- High-degree of passive safety
- Operational lifetime: 5 – 20 yrs
- Technologies evolving from advances in materials, space reactor technologies, advanced nuclear fuels, and modeling & simulation
- Well suited for remote areas and applications:
  - Remote communities
  - Isolated microgrids
  - Mining sites
  - DOD applications
- Broadly distributed, reliable, energy sources



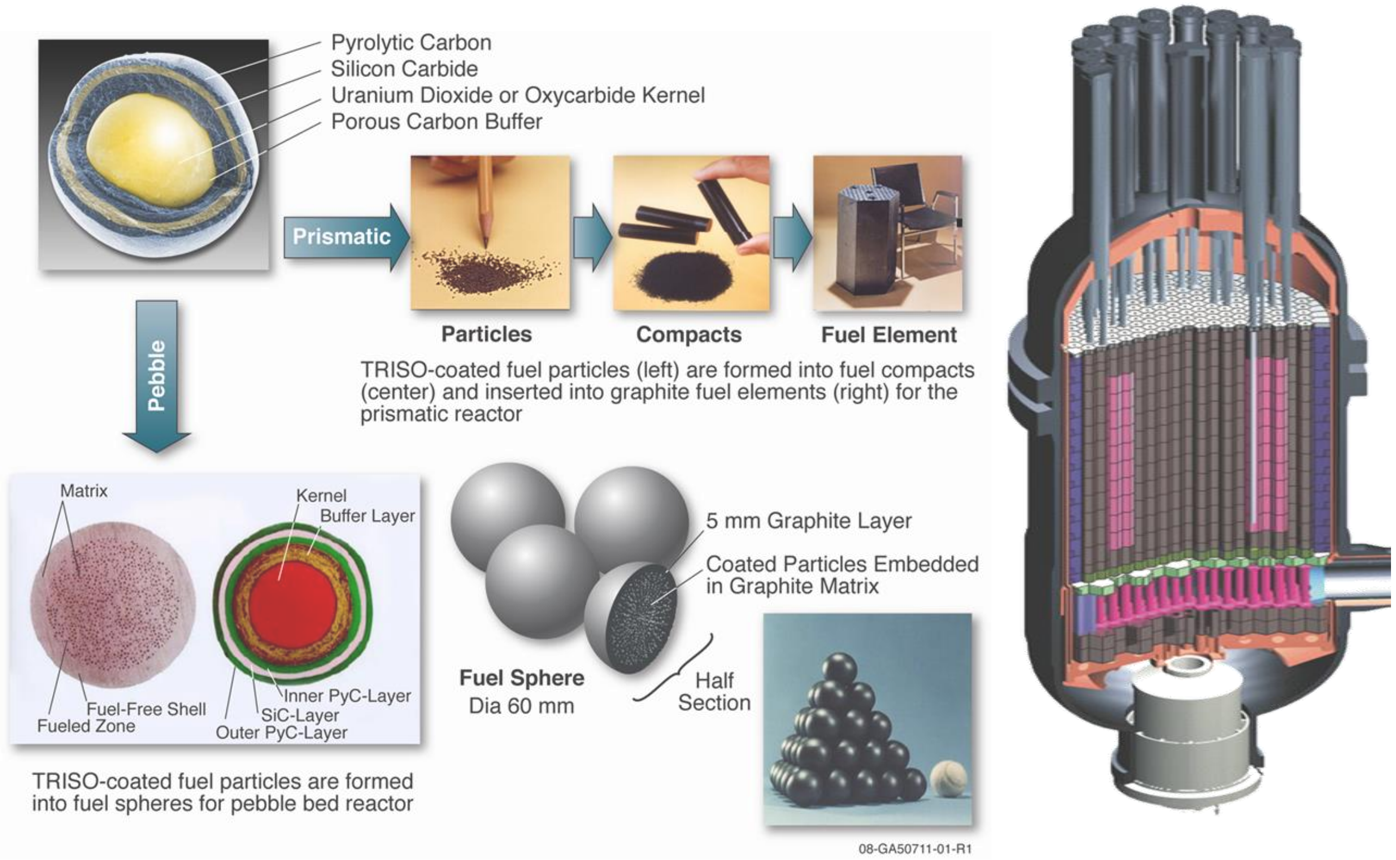
Microreactors are integrated systems that can be based on a range of reactor technologies

Reactor coolant choices



High temperature gas reactor: General characteristics

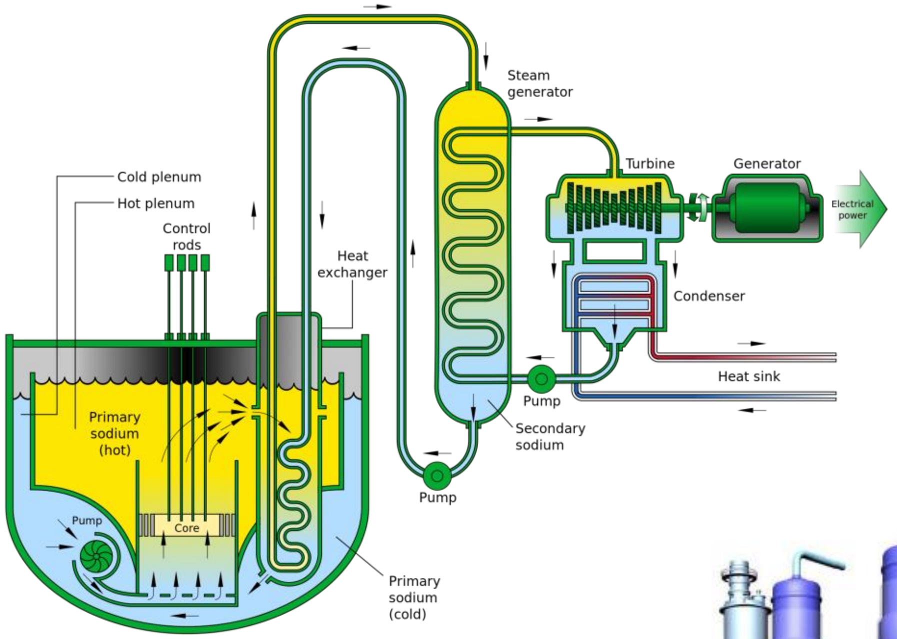
- Moderator: Graphite
  - Solid at high temperatures
  - High moderating ratio, heat capacity, thermal inertia
- Coolant: Helium
  - Inert (chemical & neutron) and single phase
- Fuel: Tri-structural Isotropic (TRISO)
  - Structural coatings act as safety layers
  - Transport of fission products out of fuel very limited up to 1,800^{o}C during loss of cooling transient

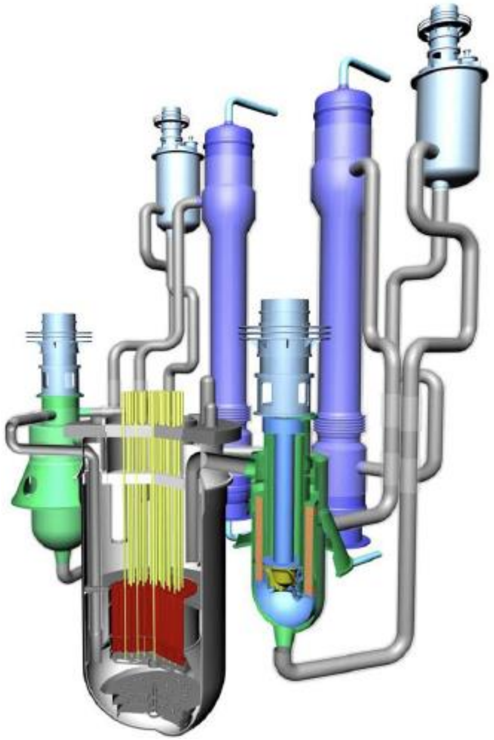


Example: X-energy Xe-100

Information courtesy G. Strydom, HTGR National Technical Director

Liquid Metal Fast Reactor





Gen-IV International Forum, Sodium Fast Reactor concept
Top: Pool-type
Right: Loop-type

- Liquid metals as a primary coolant, allow higher power density
- Leading coolants considered in the U.S. include sodium, lead
  - Sodium: Chemically reactive w/water, air; SS compatible
  - Lead: Non-reactive w/water, air; corrosive
  - Coolant temperature ~550ºC
  - Operate near atmospheric pressure
- Typically intended for a closed fuel cycle
  - Metal fuel, although oxides also possible
- Fast neutron spectrum (no moderator)
- Power conversion: Rankine/steam cycle or sCO_2 Brayton
- Allows for natural circulation and passive safety
- Many designs use electromagnetic or mechanical pumps
- Significant global experience; U.S. experience includes EBR-II (pool-type), Fermi-I (loop), and FFTF (loop)

Example: TerraPower/GE Natrium, Westinghouse LFR

Molten Salt Reactors

General characteristics

- Molten salts have high heat capacity
- Allow for low pressure operation
- Large margin to boiling
- High operating temperature: ~700ºC

Molten salt *cooled*

- Fluoride or chloride salt coolant
- Solid fuel, typically TRISO
- Low-pressure
- Steam cycle

Molten salt *fueled*

- Nuclear fuel dissolved in a liquid salt, circulated through system
  - U or Th fuel cycle
  - Fluoride or chloride salt
- Heat produced directly in the heat transfer fluid
- Chemical separation of fission products on-line
- Possibility for on-line reprocessing

Example: TerraPower MCFR (liquid fuel), Kairos Hermes (solid fuel)

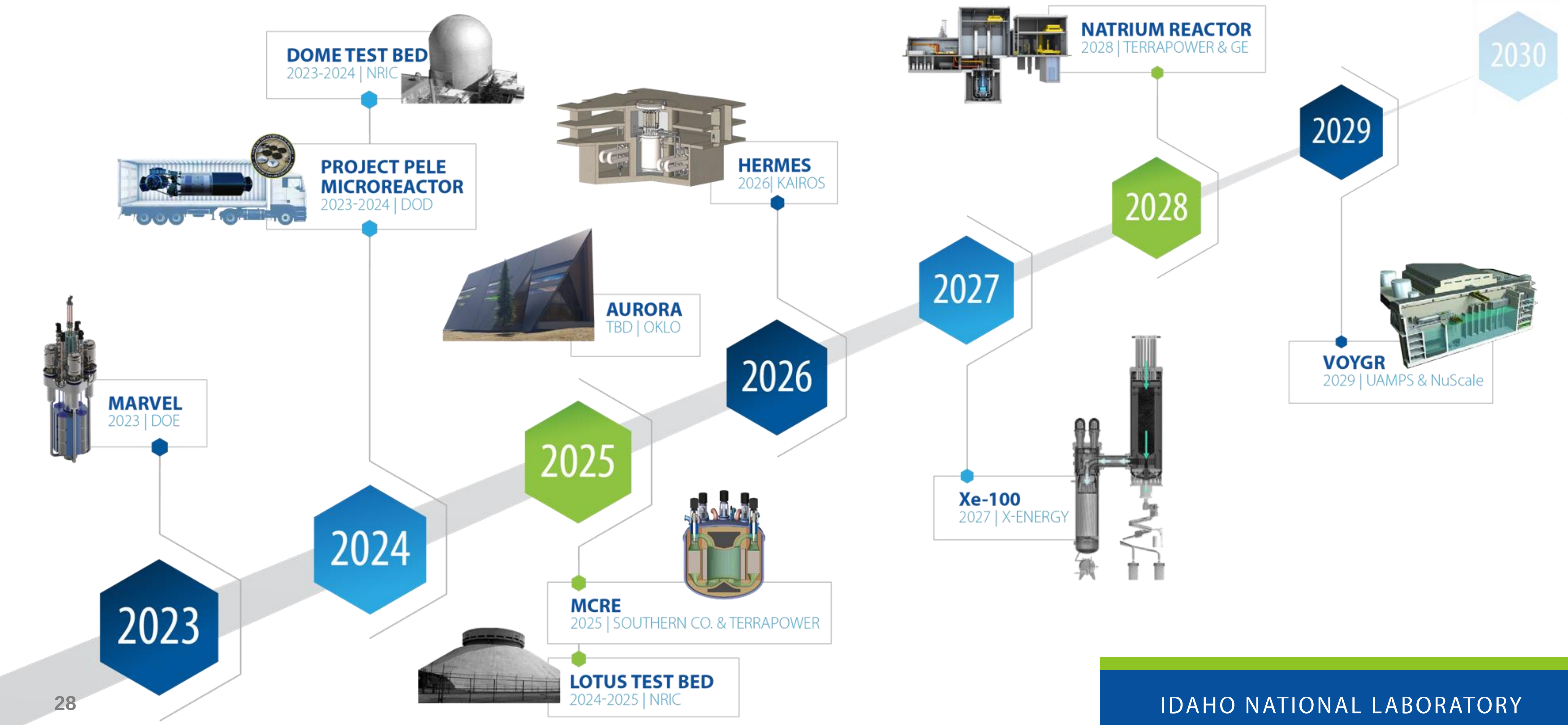
US DOE Advanced Reactor Demonstration Program (ARDP)

- Established in fiscal year (FY) 2020 budget language ($230 million (M)); overall FY21 budget for ARDP activities $250 M
- Focuses DOE and non-federal resources on **actual construction** of demonstration reactors
- Establishes ambitious timeframe for demonstration reactors – five to seven years from award, including design, licensing, construction and start of operations
- Program also addresses technical risks for less mature designs
- Desired outcomes:
  - Support diversity of advanced designs that offer significant improvements to current generation of operational reactors
  - Enable a market environment for commercial products that are safe and affordable to both construct and operate in the near-and mid-term
  - Stimulate commercial enterprises, including supply chains

ARDP demonstrations

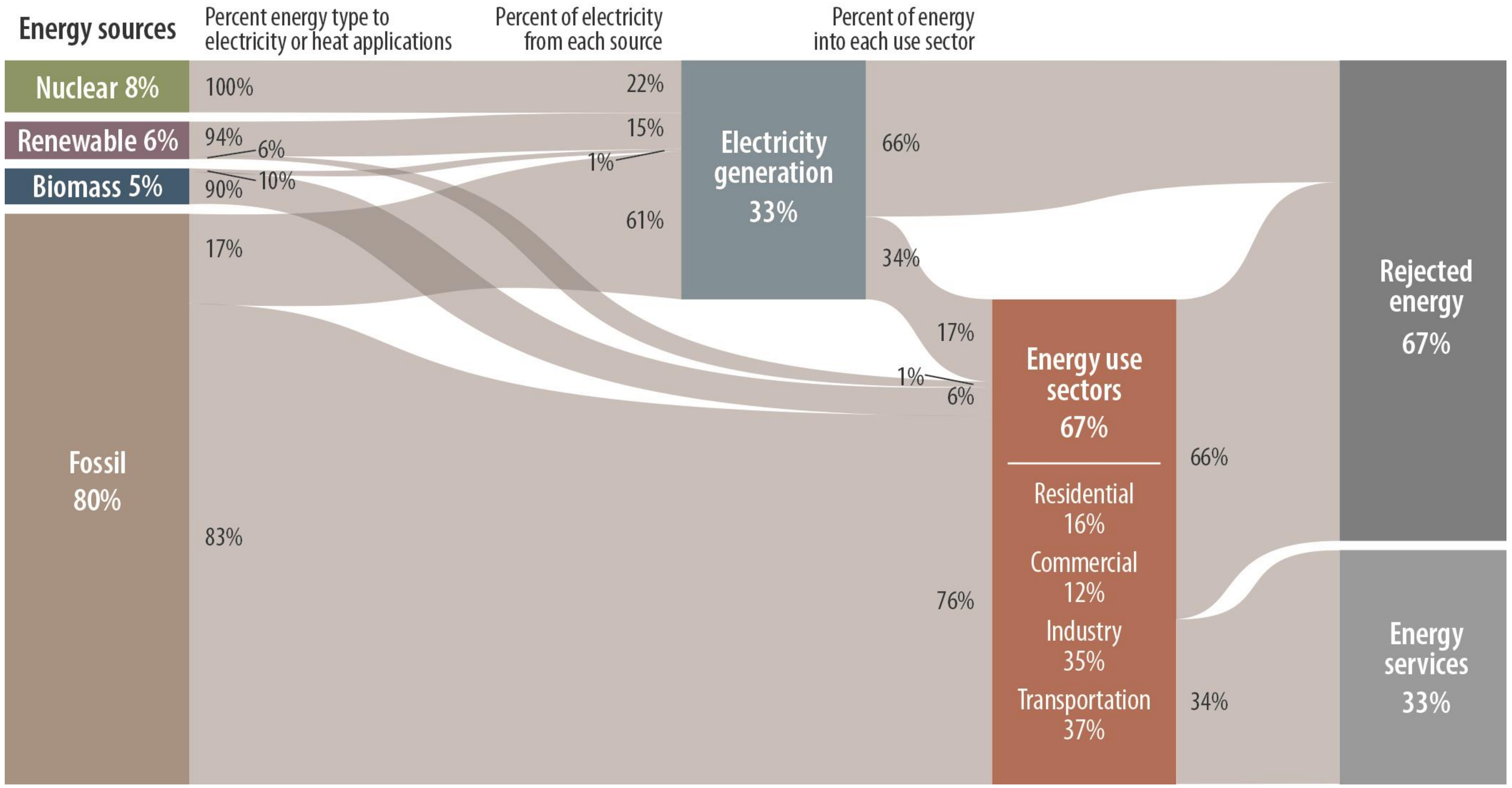
- **TerraPowerLLC – Natrium Reactor**
  - Sodium-cooled fast reactor that leverages of decades of development, including fuel
  - High temperature reactor coupled with thermal energy storage for flexible electricity output
  - New metal fuel fabrication facility
  - Site: Kemmerer, Wyoming (retiring coal plant site)
  - https://natriumpower.com/
- **X-energy – Xe-100 reactor**
  - High temperature gas-cooled reactor that leverages decades of development and robust fuel form
  - Provides flexible electricity output and process heat for a wide range of industrial heat applications
  - Commercial scale TRISO fuel fabrication facility
  - Site: Washington state, near Hanford
  - https://x-energy.com/

Accelerating advanced reactor demonstration & deployment



Thinking outside the box: Clean nuclear energy for non-grid applications

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

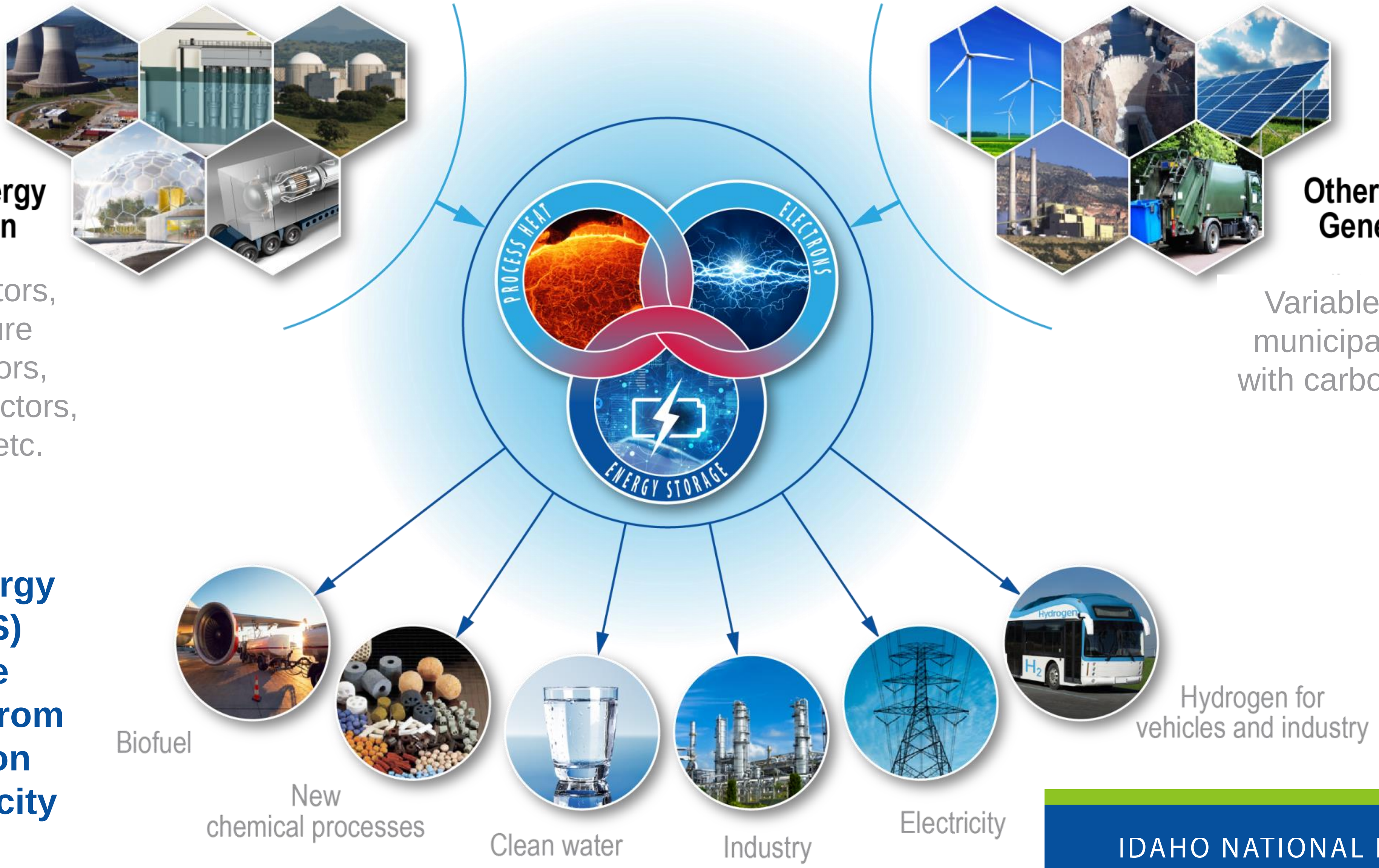
Electricity accounts for only 17% of total energy use in the U.S. across all “Energy use sectors,” with the remaining 83% used in the form of heat.

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.



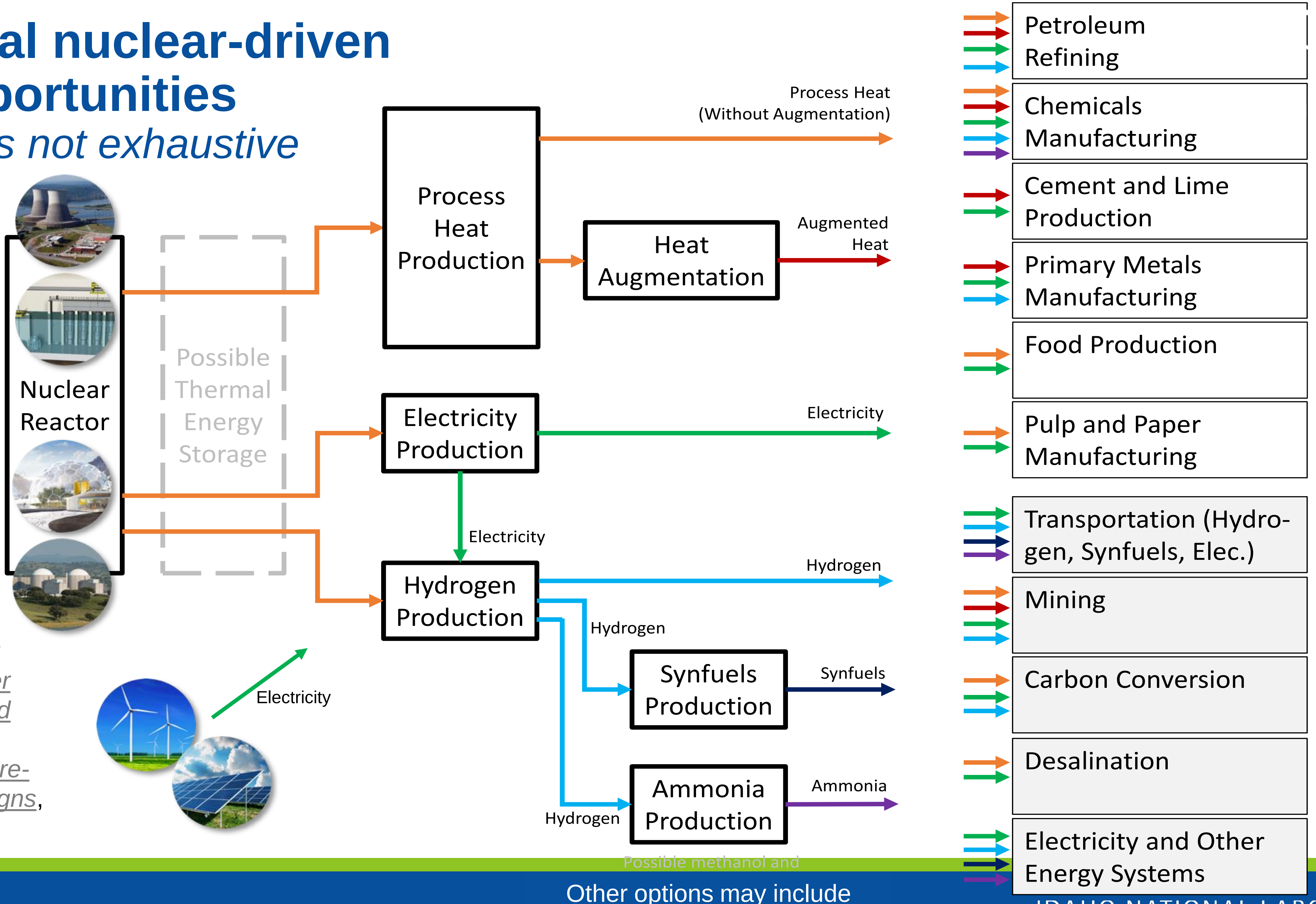
Other Energy Generation

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

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]

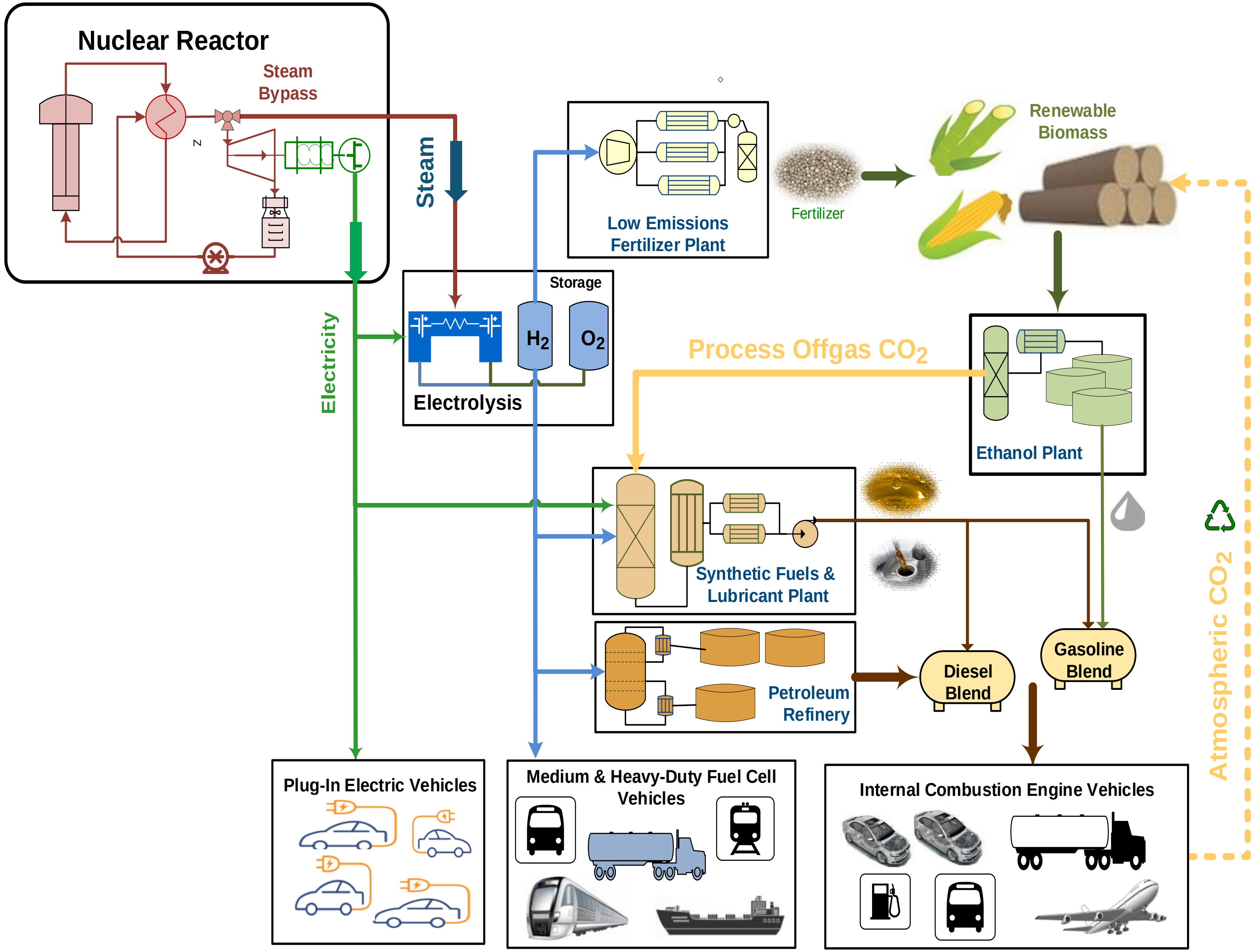
[1] *National Renewable Energy Laboratory*
[2] *Idaho National Laboratory*

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

Nuclear-hydrogen production and utilization



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

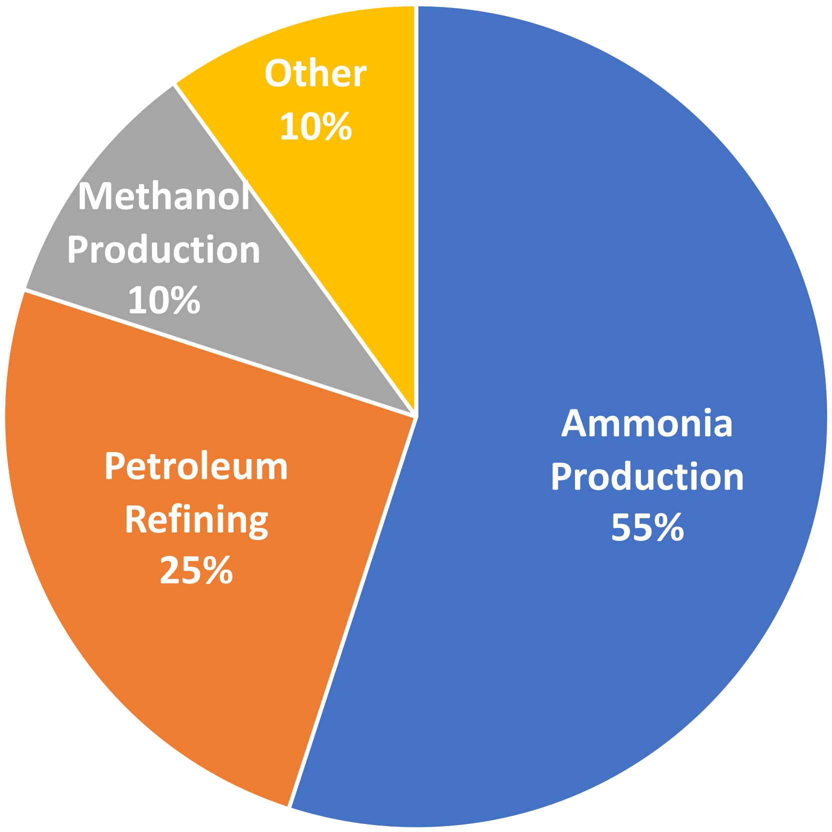
1) Provides energy storage, for electricity production or H_2 user (e.g., chemicals and fuels synthesis, steel manufacturing, ammonia-based fertilizers)
2) Provides second source of revenue to the generator; allows generator to operate at nominal power at all times
3) Provides opportunity for grid services,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

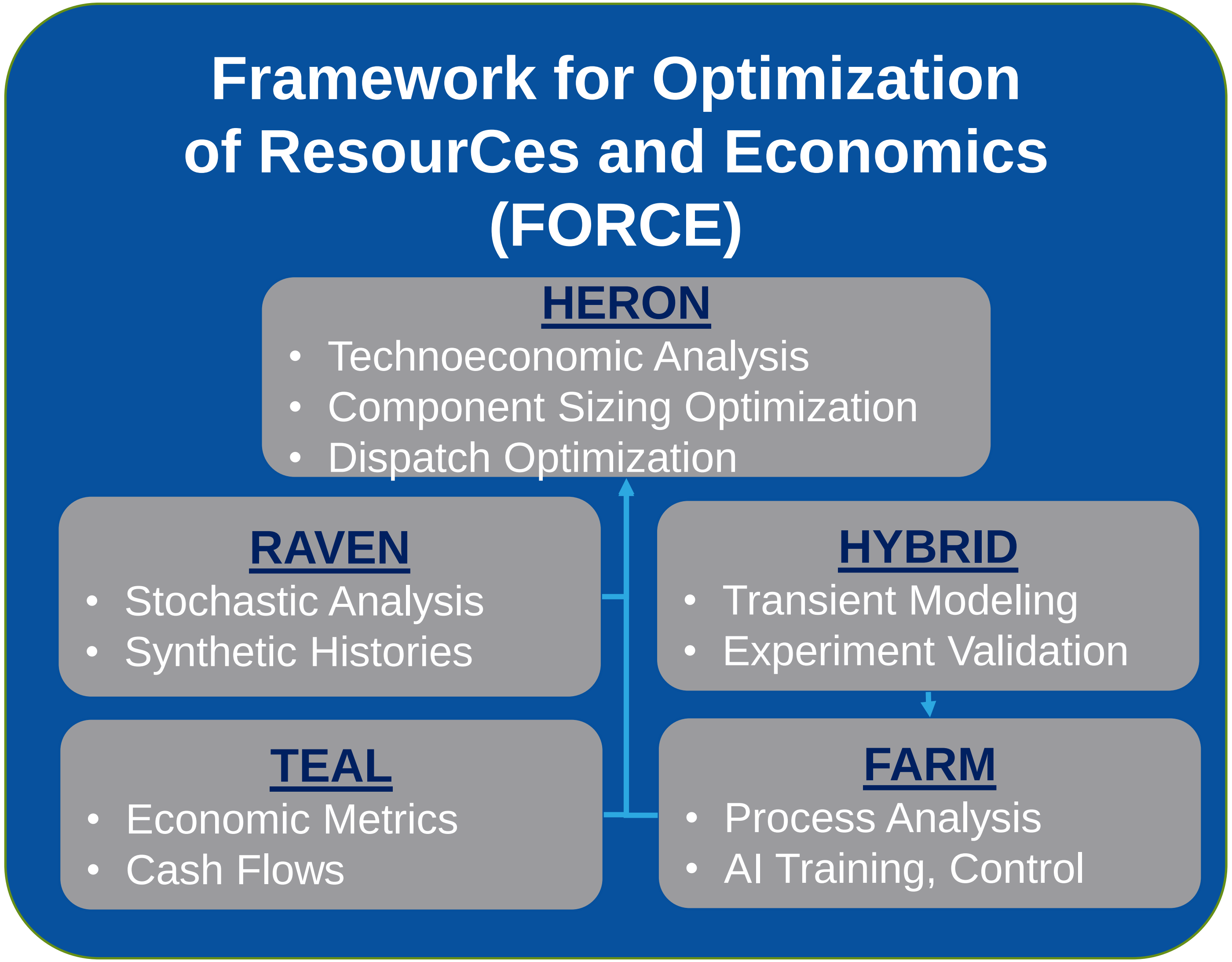
Fraction of Global Hydrogen Use by Industry



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

Integrated energy systems analysis and optimization

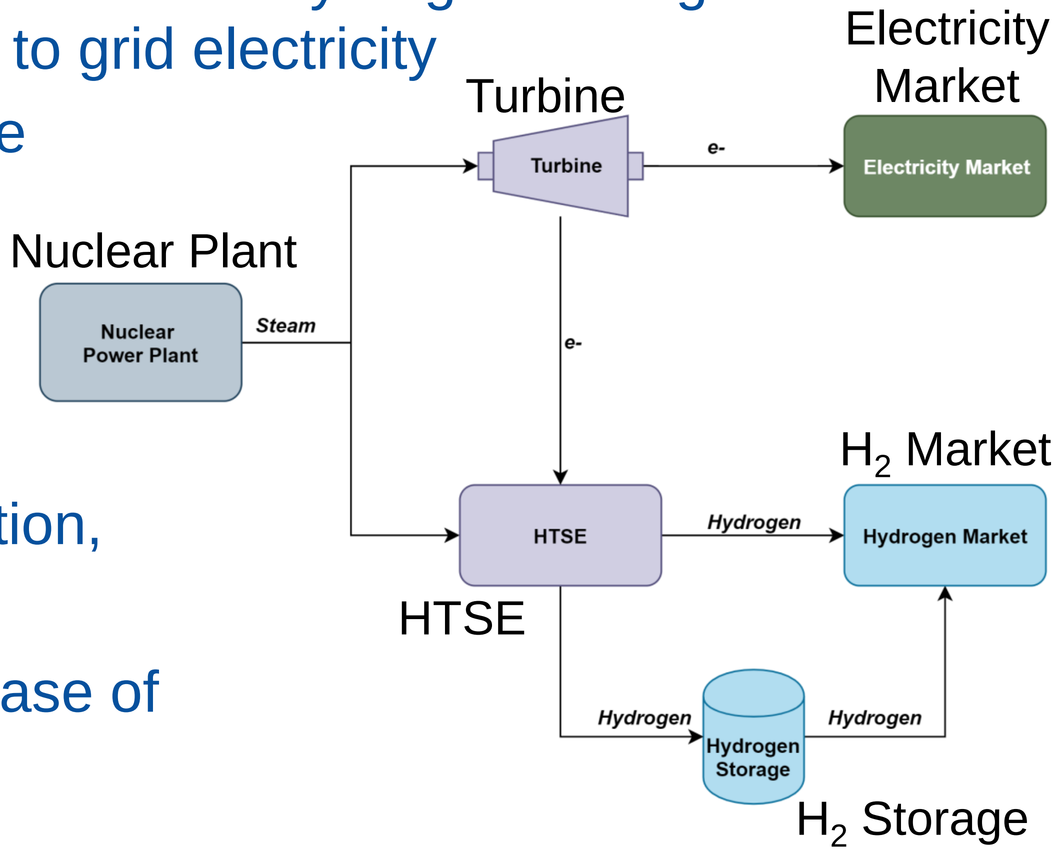
- **Technoeconomic assessment**
  - Portfolio Optimization
  - Dispatch Optimization
  - Process Model Simulation
  - Economic Analysis
  - Supervisory Control
  - Stochastic Analysis
  - Workflow Automation



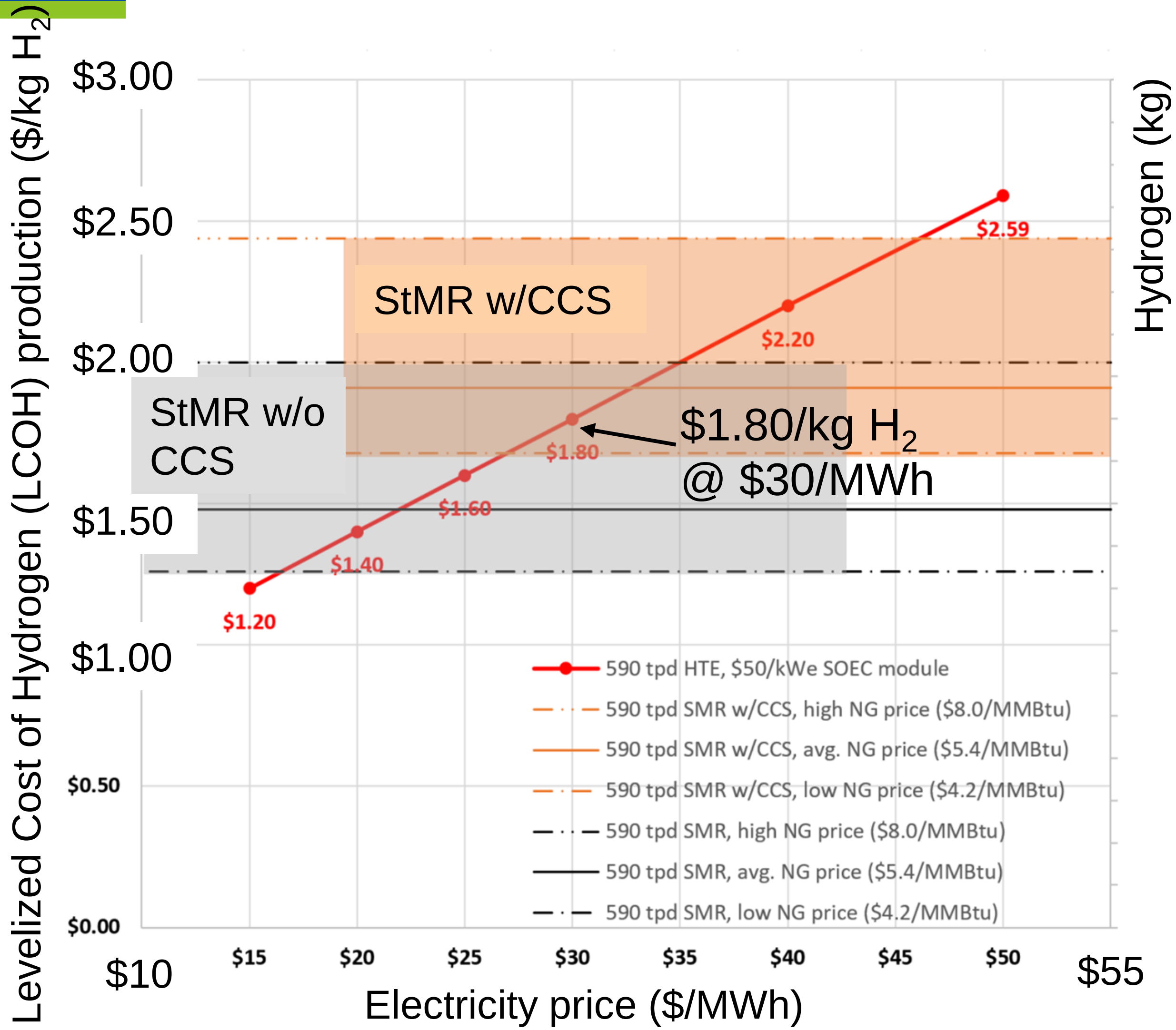
For more information and to access opensource tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.

Example: Disruptive potential of nuclear produced hydrogen

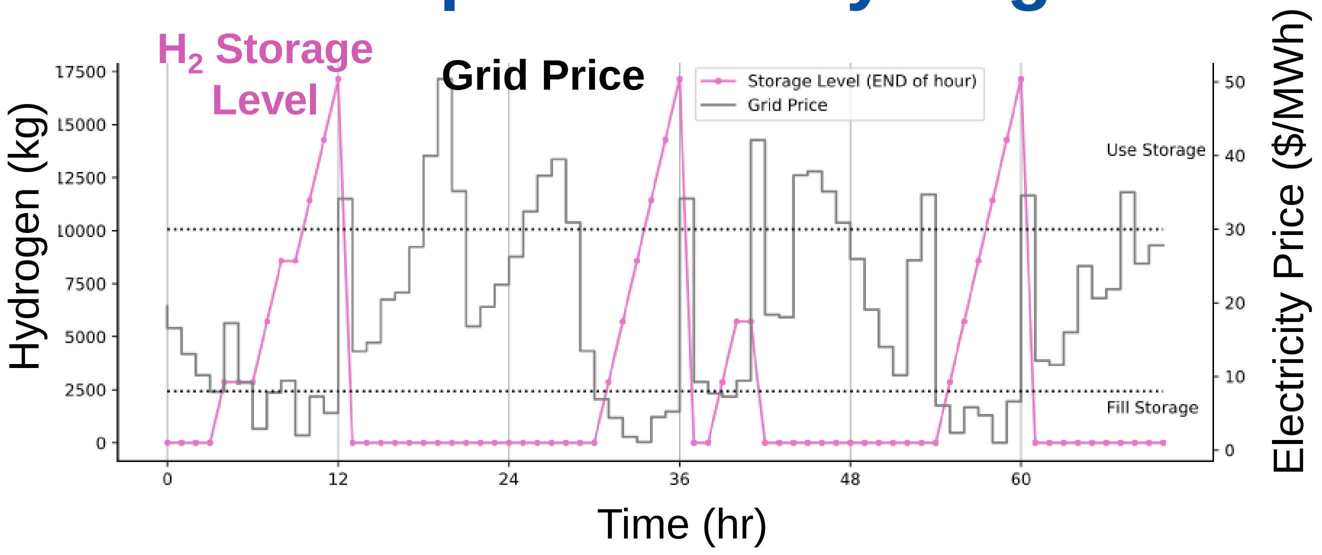
- Collaboration between INL, ANL, NREL, Constellation (Exelon), and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid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

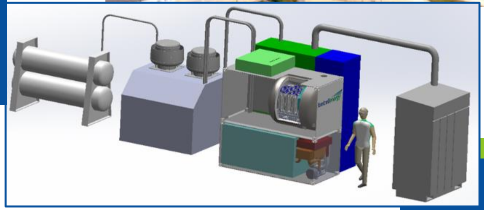
Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

Thermal & Electrical Integration at Prairie Island NPP HTSE/SOEC

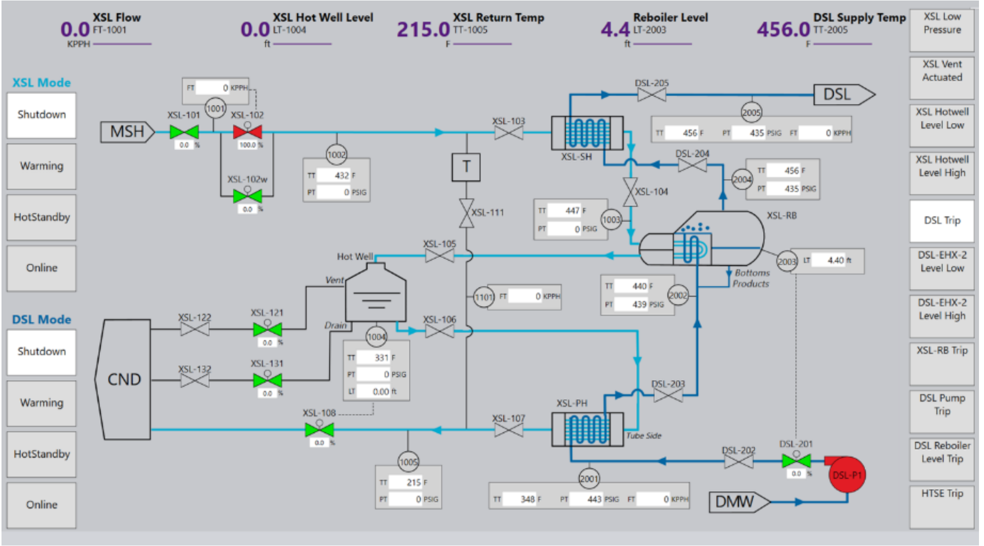
Palo Verde Generating Station, H_2 Production for Combustion and Synthetic Fuels

FuelCell Energy at INL, SOEC



Operations with flexible thermal and electrical power dispatch

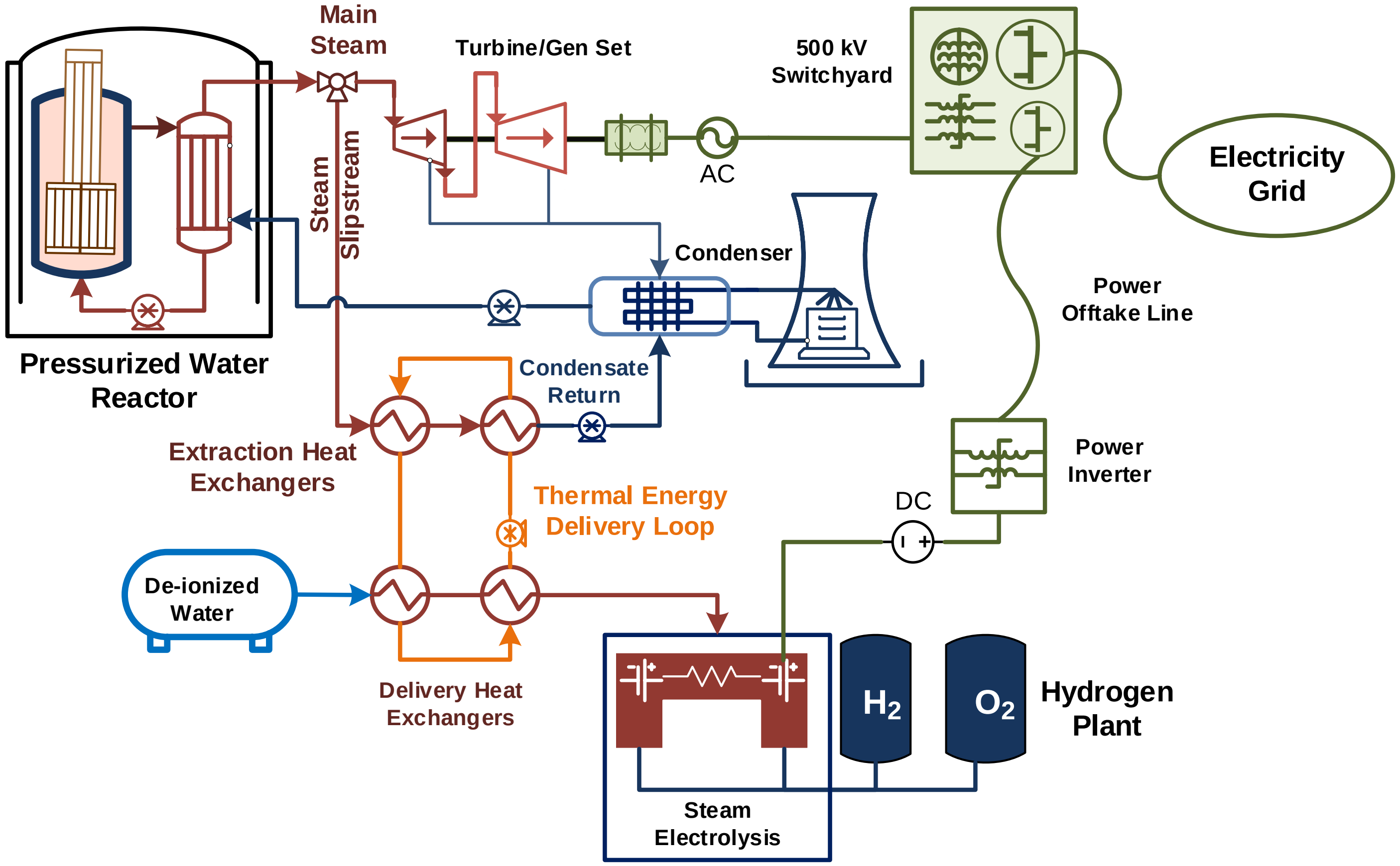
- The INL Human Systems Simulation Laboratory was used to test concepts for dispatching thermal and electrical power from nuclear reactors to a H_2 electrolysis plant
  - Two formerly licensed operators tested 15 scenarios
  - A modified full-scope generic Pressurized-Water Reactor was used to emulate 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



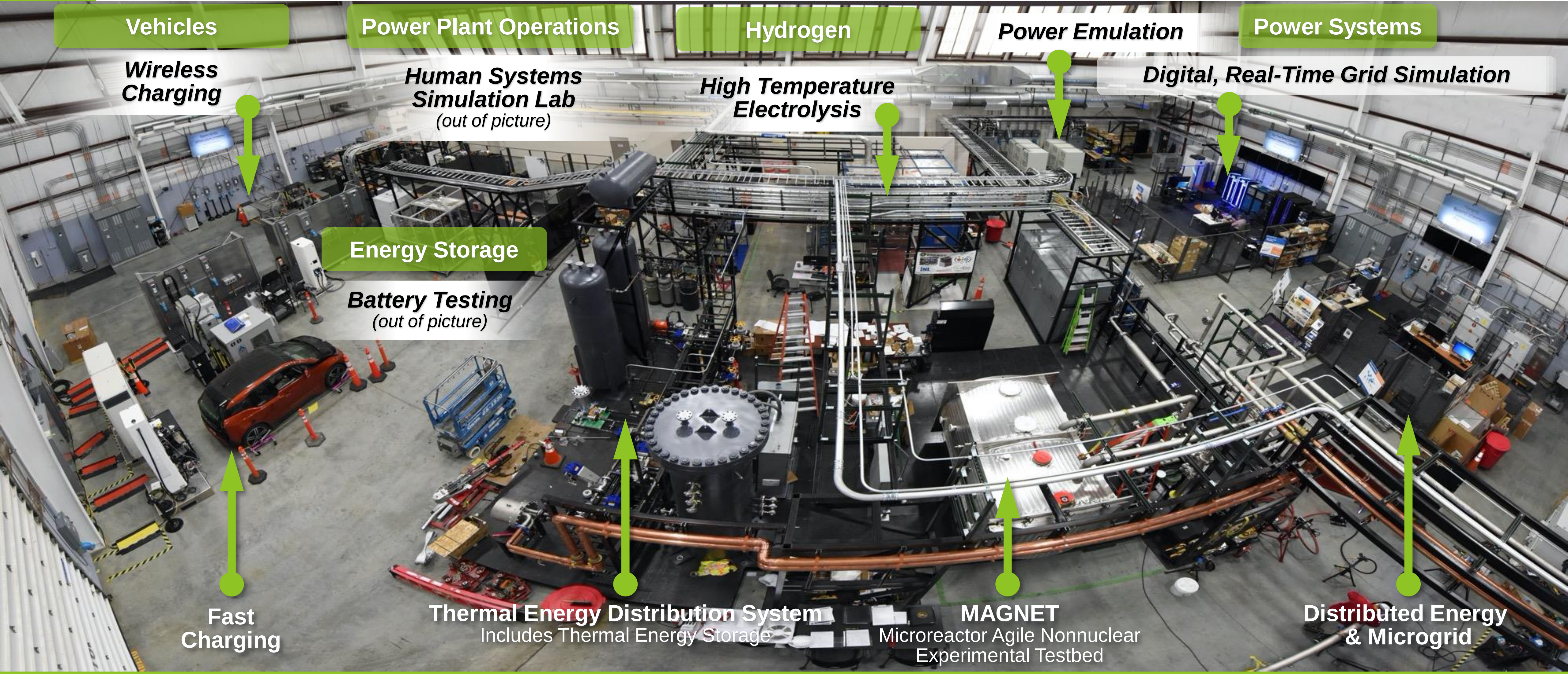
Thermal integration of steam electrolysis

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



Dynamic Energy Transport and Integration Laboratory (DETAIL)



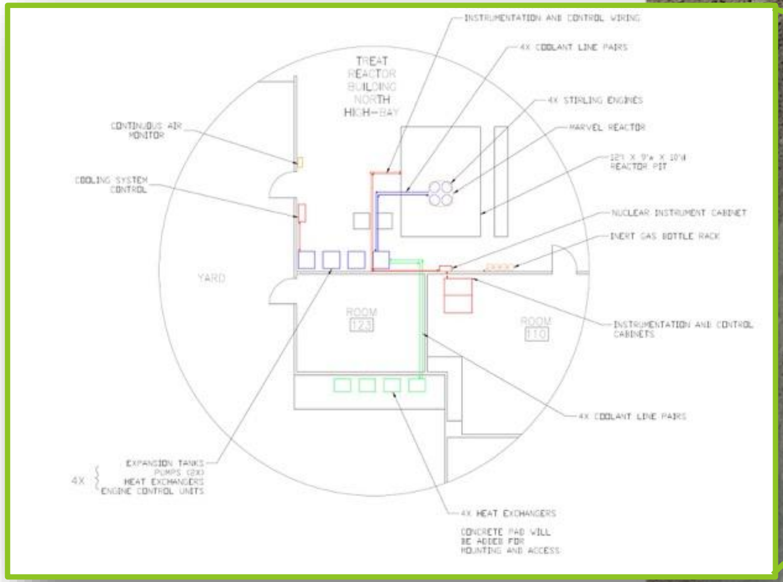
Microreactor integration with a microgrid

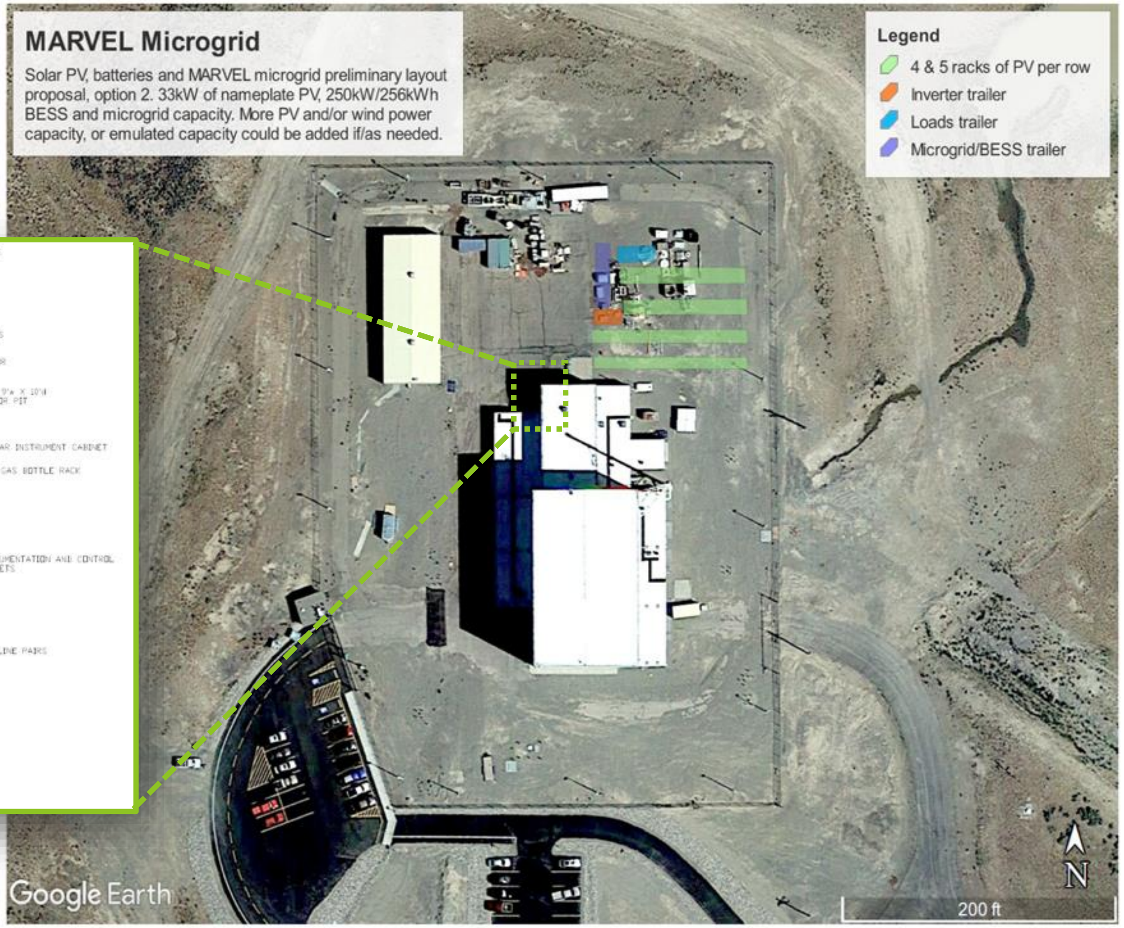
MARVEL

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

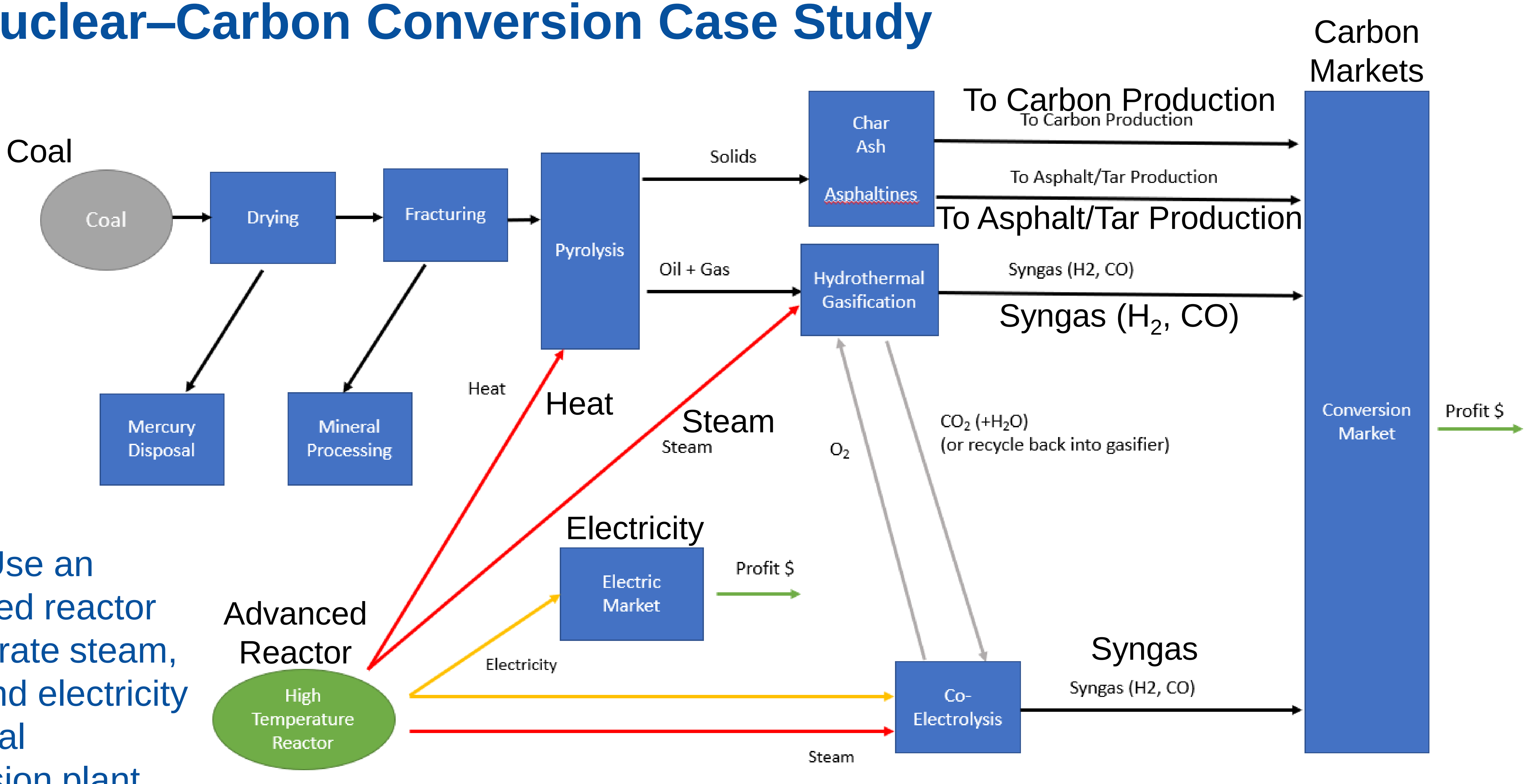
- Goal: Demonstrate two advanced reactors by 2025
- Strategy:
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components
- Capabilities:
  - NRIC DOME (Demonstration 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

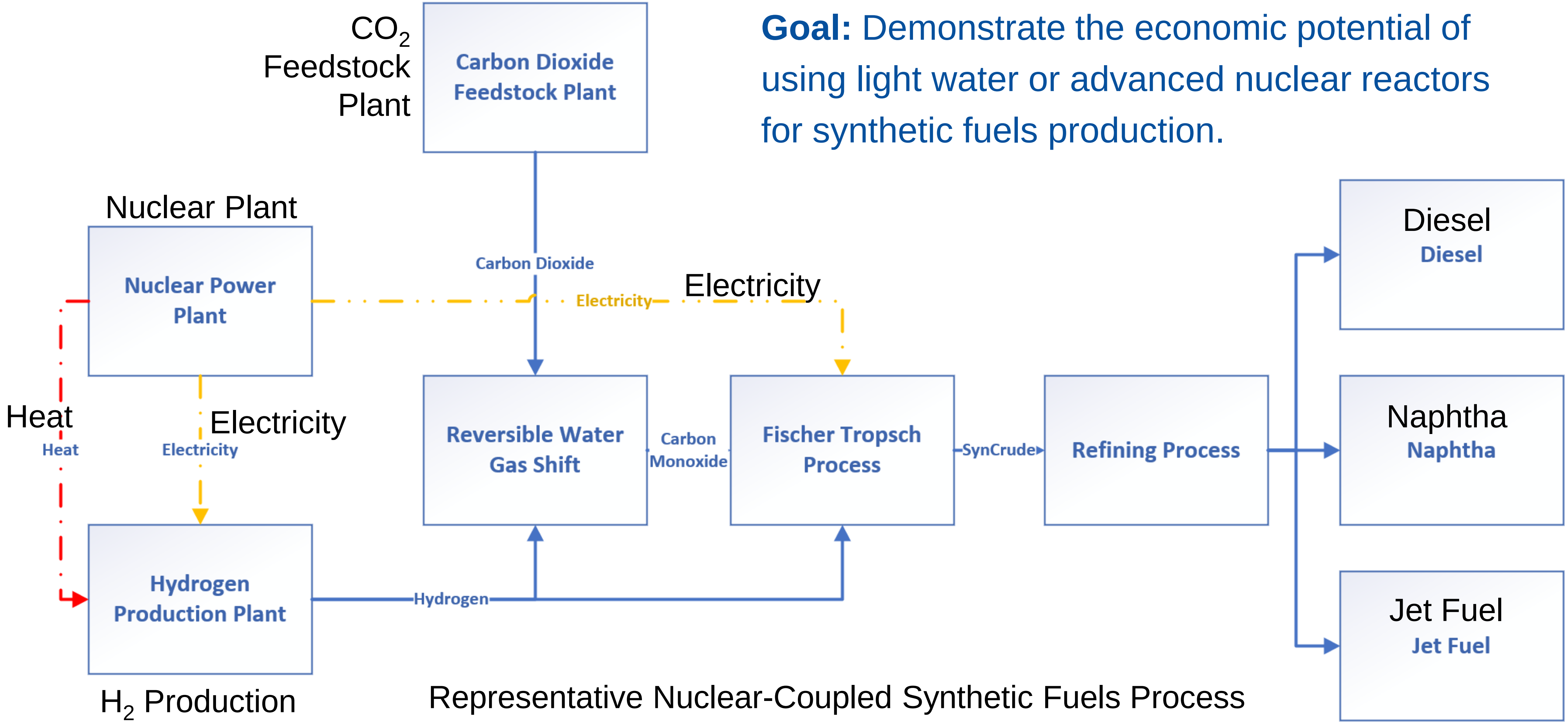


Goal: Use an advanced reactor to generate steam, heat, and electricity for a coal conversion plant.

Representative Coal Conversion Process

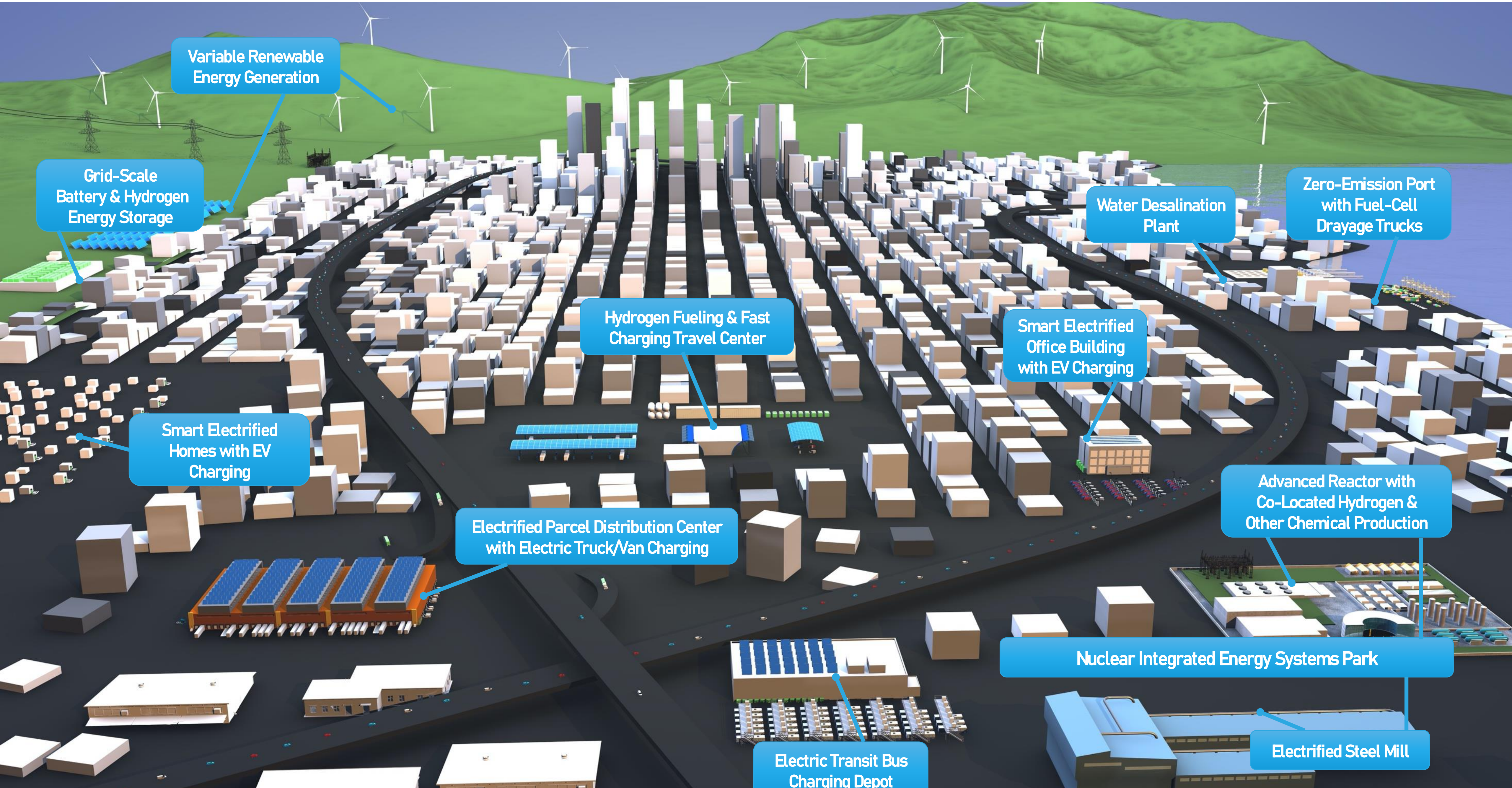
Nuclear Synthetic Fuels Production

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



Idaho National Laboratory

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- National Reactor Innovation Center (NRIC): https://nric.inl.gov
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- 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