INL/MIS-22-66708-Revision-0

Next Generation Nuclear Energy: Advanced Reactors and Integrated Energy Systems

April 2022

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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Next Generation Nuclear Energy: Advanced Reactors and Integrated Energy Systems

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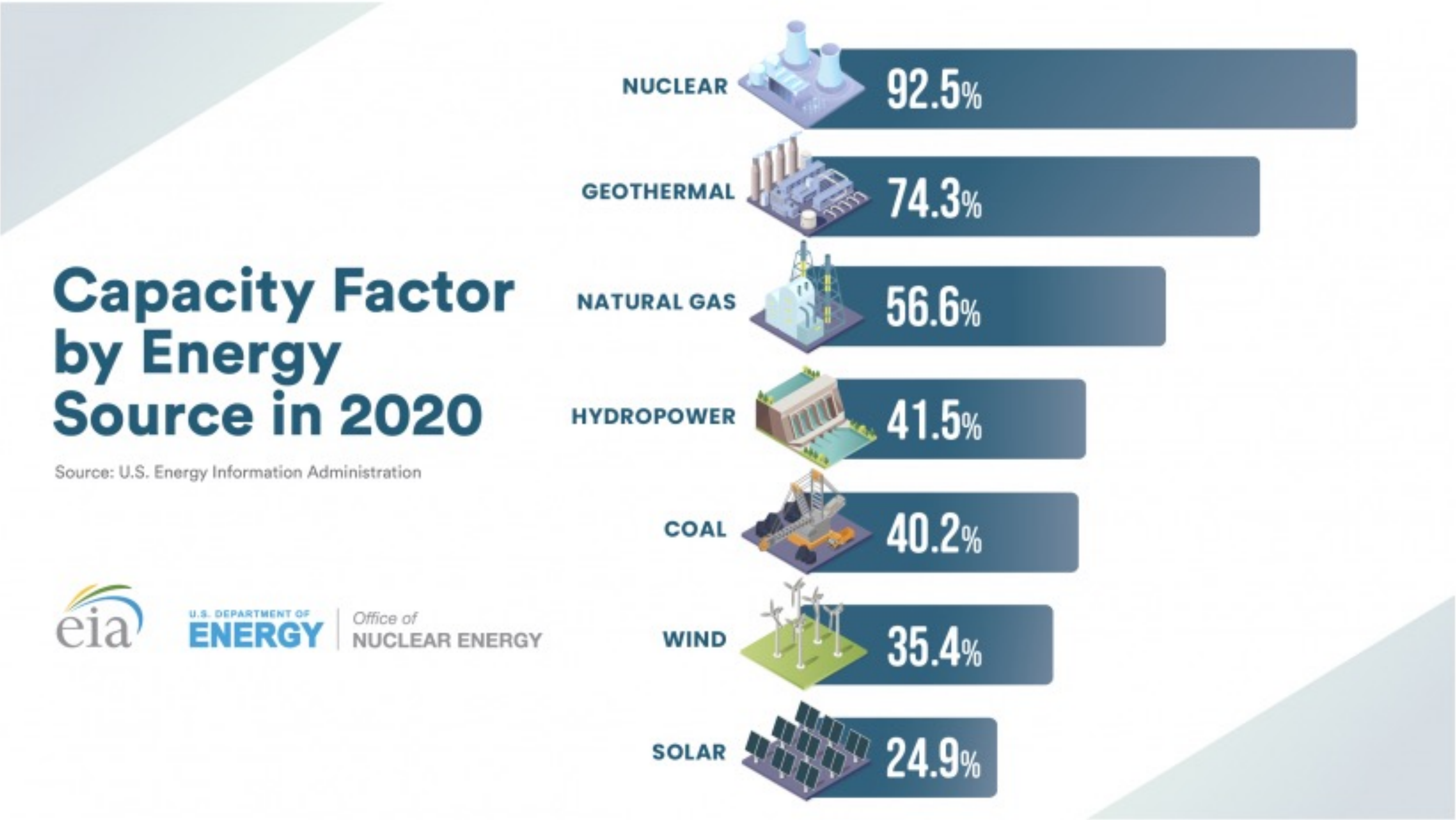
Presentation Overview

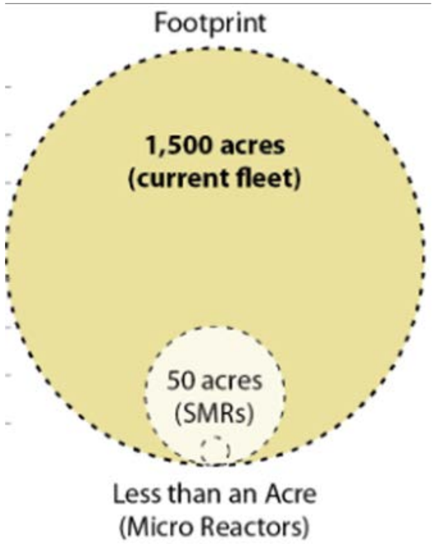
- Current state of nuclear energy as a part of a clean energy mix
  - Status of current fleet plants
  - New paradigms for operational flexibility
- Nuclear plant scale
  - Micro
  - Small
  - Large
- Advanced reactor concepts
  - Gas cooled (helium)
  - Fast spectrum, liquid metal cooled
  - Molten salt
- Novel deployment opportunities: Beyond the grid
- Demonstration and deployment timelines

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



energy.gov/nuclear

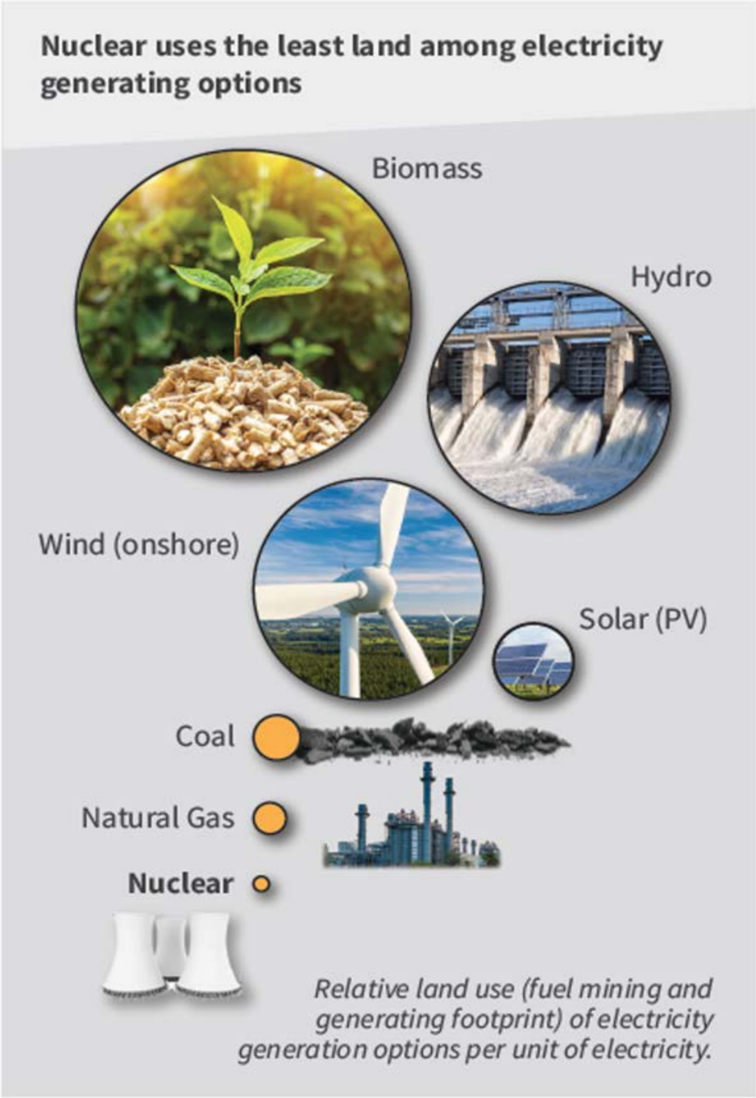
Nuclear energy and deployment flexibility



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

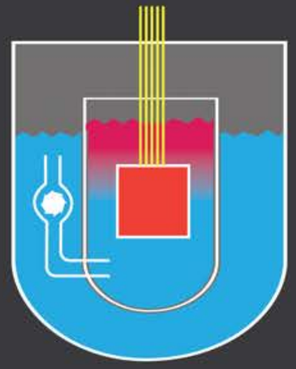
SMALL
1 MW to 20 MW
Micro-reactors
Can fit on a flatbed truck. Mobile. Deployable.

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

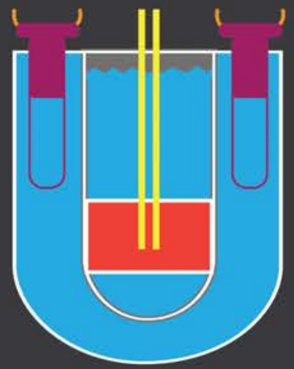
LARGE
300 MW to 1,000 + MW
Full-size Reactors
Can provide reliable, emissions-free baseload power

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

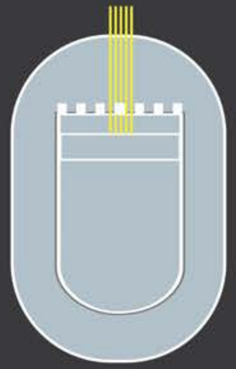
TYPES



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.



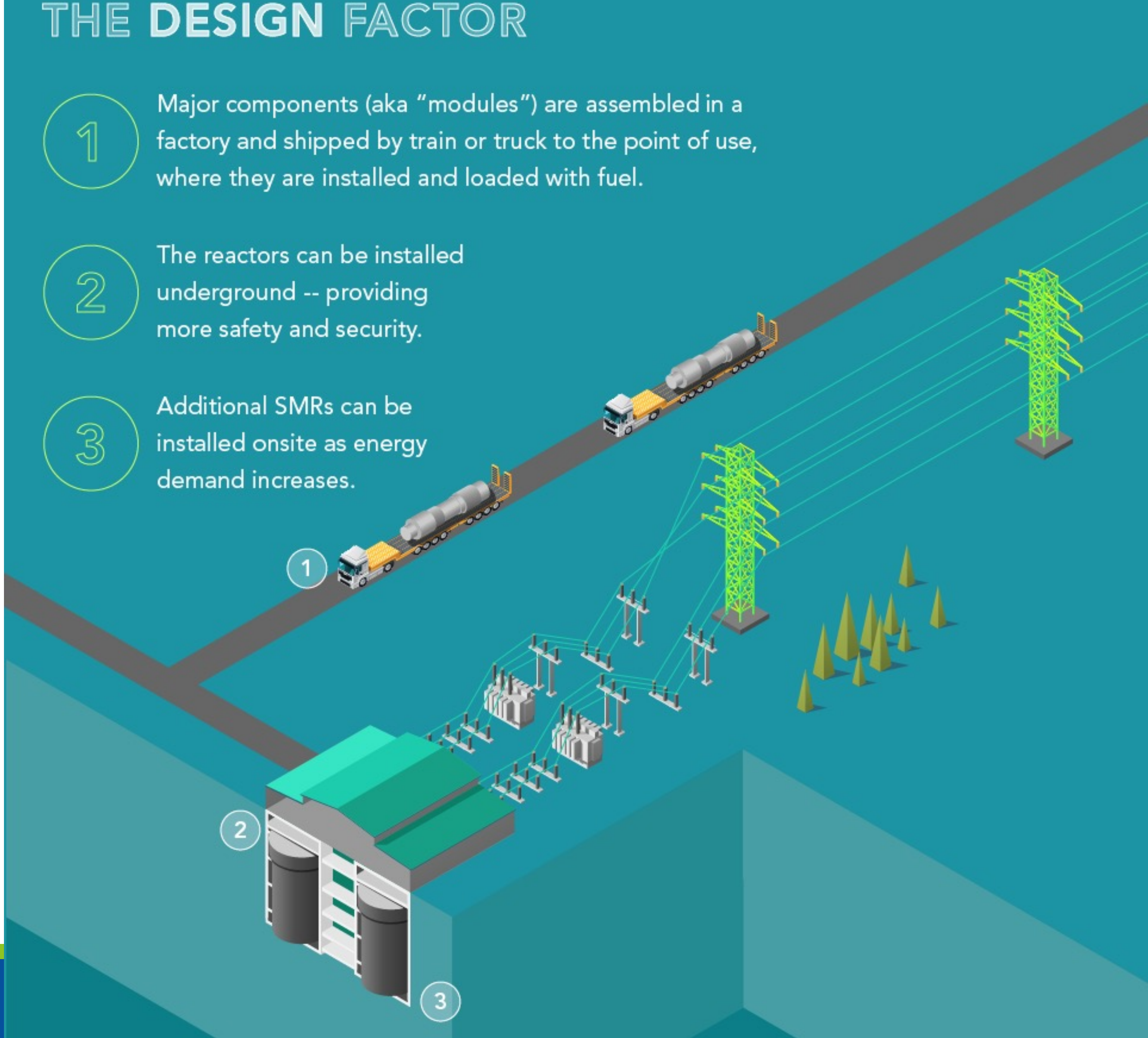
LIQUID METAL FAST REACTORS - Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.



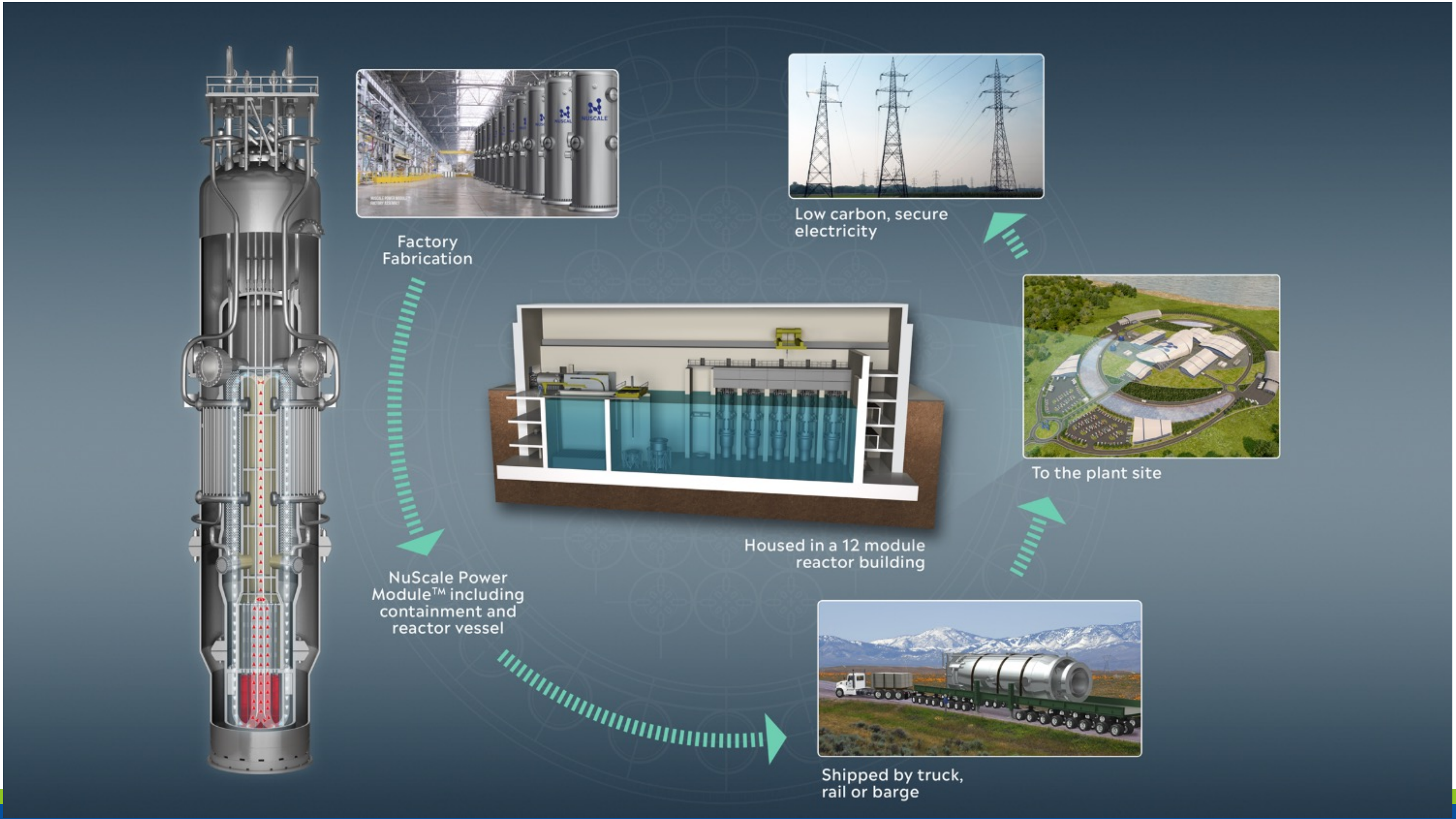
GAS-COOLED REACTORS – Use flowing gas as a coolant. Operate at high temperatures to efficiently produce heat for electric and non-electric applications.

Small modular reactors

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

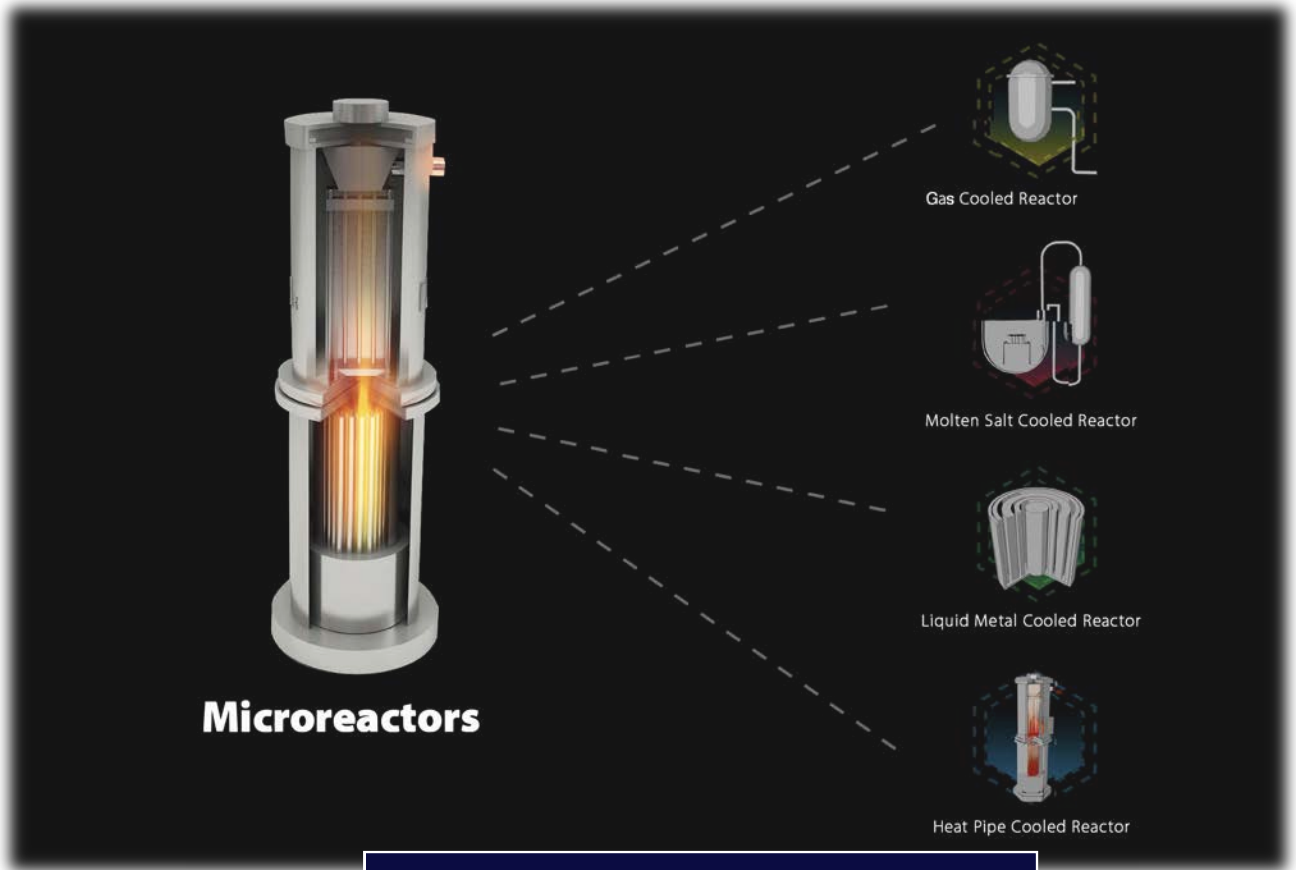


NuScale Power: A new approach to construction and operation



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

Advanced reactors: Summary of the U.S. landscape

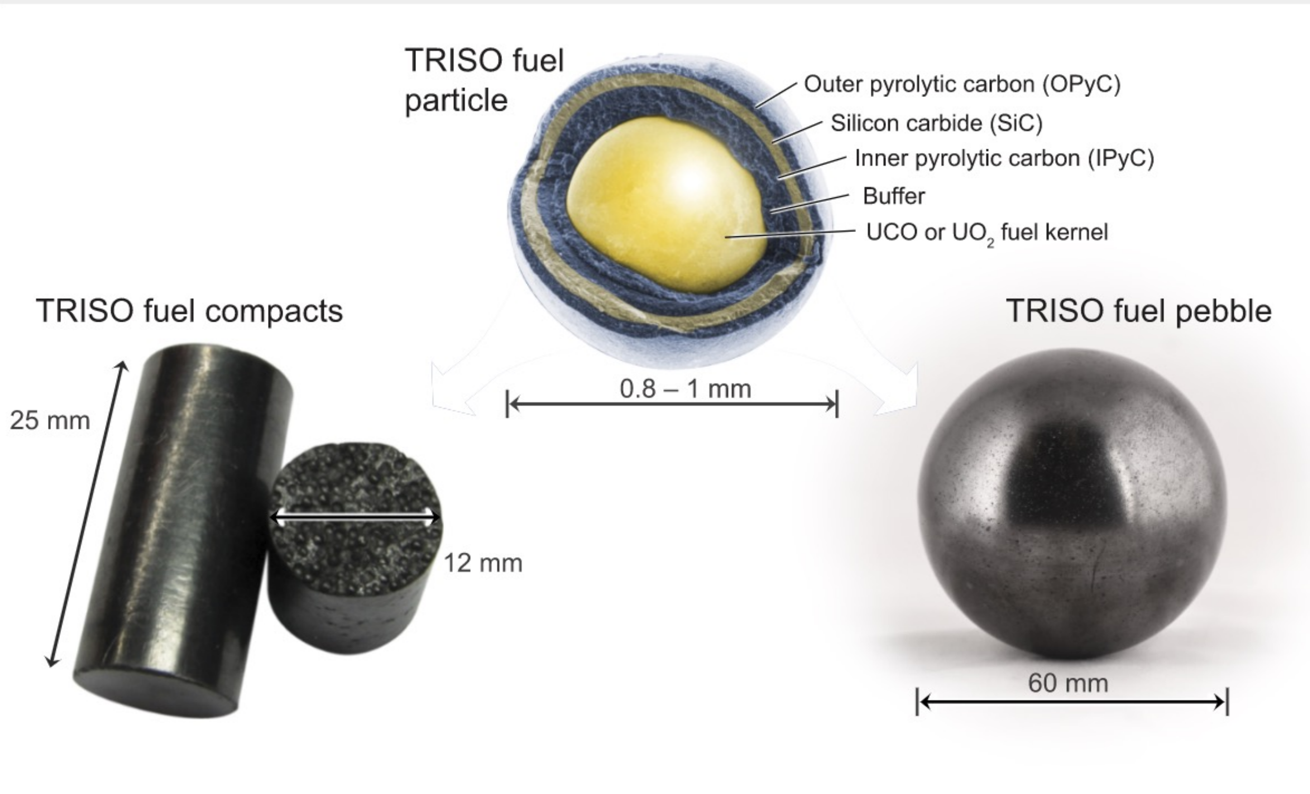
- Dozens of U.S. companies are working on advanced nuclear projects for a wide array of capabilities to meet the energy needs of the future
  - Light water-cooled advanced small modular reactors
  - Advanced sodium-, gas-, lead-, molten salt-cooled reactors
  - Significant levels of private sector investment
- Motivation for advanced reactor development
  - Potential for improved safety and operational capability
  - Various options for future commercial, limited-grid and remote applications
  - Potential for improved nuclear resource utilization and reduced nuclear waste
  - Flexible operation to support the national grid of the future containing many energy-source options

Reference: T. Beville, Overview of Advanced Reactor Demonstration Program, NRC Advanced Reactor Stakeholder Public Meeting, January 21, 2021.

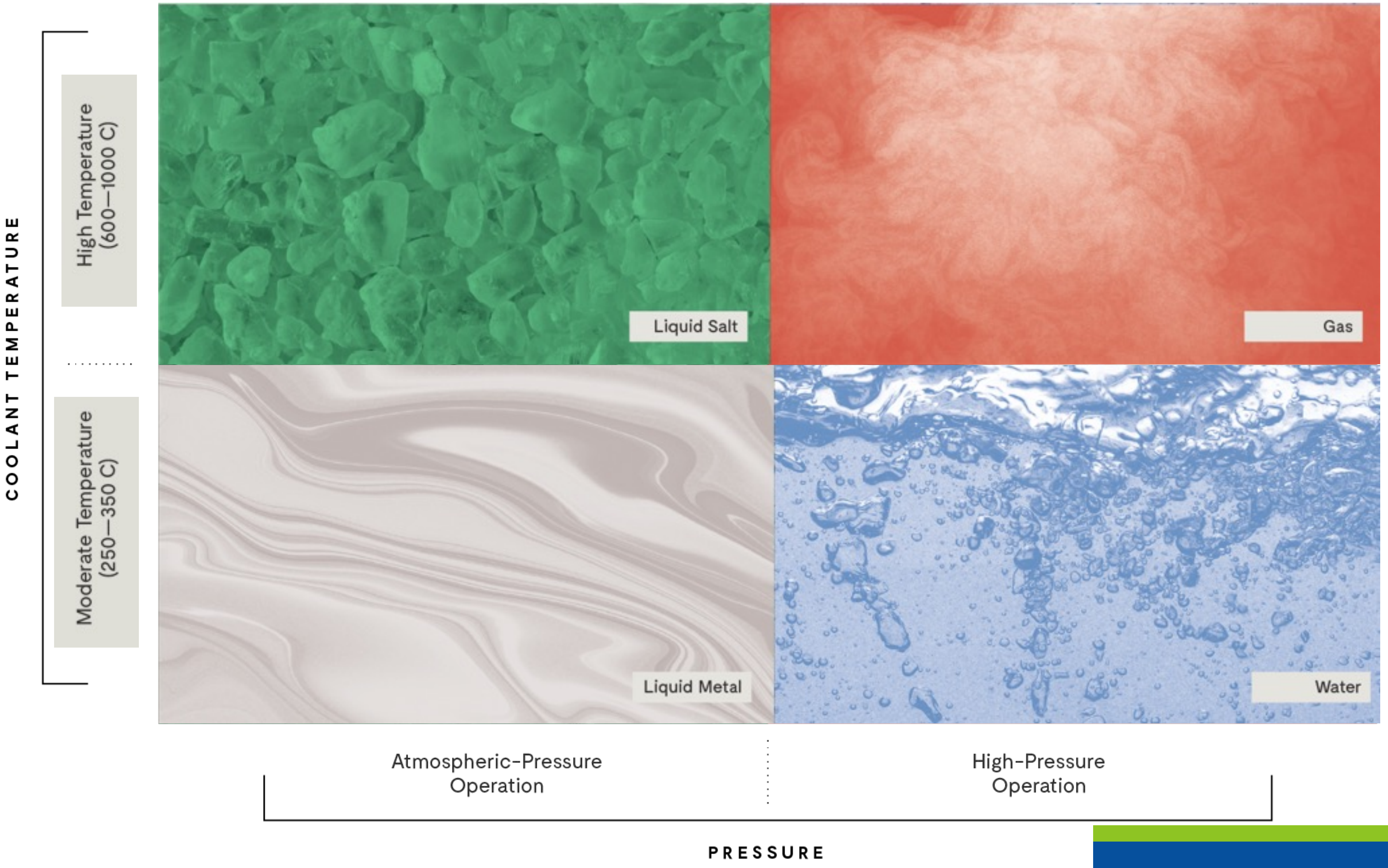
Advanced safety approaches

- "Passive/inherent safety"
  - High thermal mass: no added coolant required
  - Natural circulation: no pumping power required
  - Fail-safe valves: no backup power required
  - "Walk-away-safe": plant shuts down on its own in emergency scenarios, driven by laws of physics

- Limit impacts to site boundary through novel fuel designs
  - TRISO fuel – contains fission products around each fuel element
  - Keep fuel cool without power supply using passive safety approaches
  - Molten salt fuel – contains fission products in liquid or removes and stores continuously; online refueling



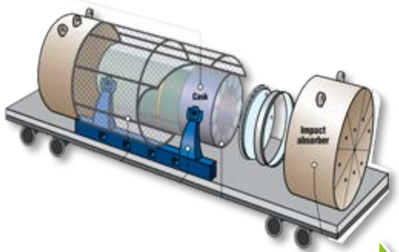
Reactor coolant choices



Vision for advanced reactor demonstrations and deployment – opportunities ahead of us

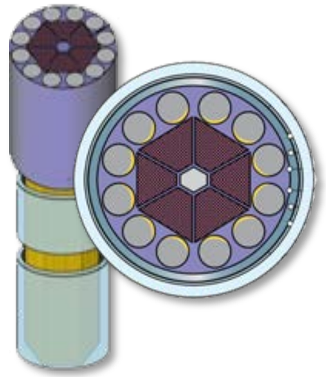
Demonstrate First Microreactors in Early 2020s

- Resolve key advanced reactor issues
- Open new markets for nuclear energy
- Provide a “win” to build positive momentum
- Civilian and federal apps.



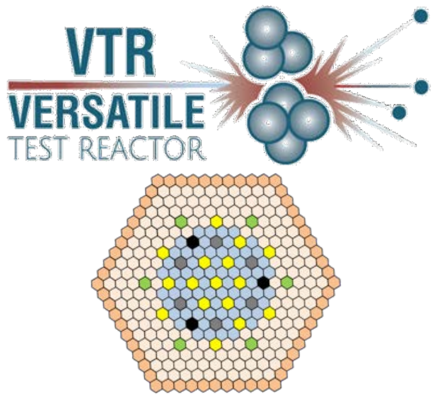
Microreactors Deployed

- Support deployment for remote site power and process heat customers
- RD&D to enable broader deployment



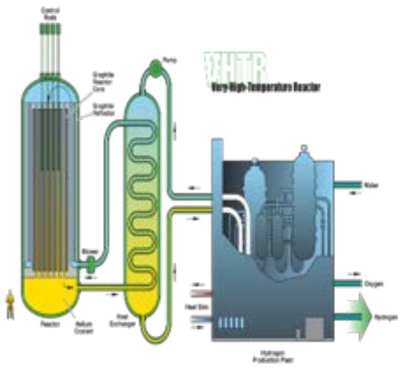
Versatile Test Reactor (VTR) Operating

- Establish fast-spectrum testing and fuel development capability
- Support non-LWR advanced reactor demonstrations



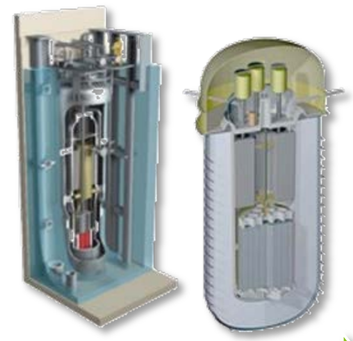
Advanced Reactor Demonstrations

- DOE-NE Advanced Reactor Demonstration Program
- Demonstrate two advanced reactors



SMR Operating

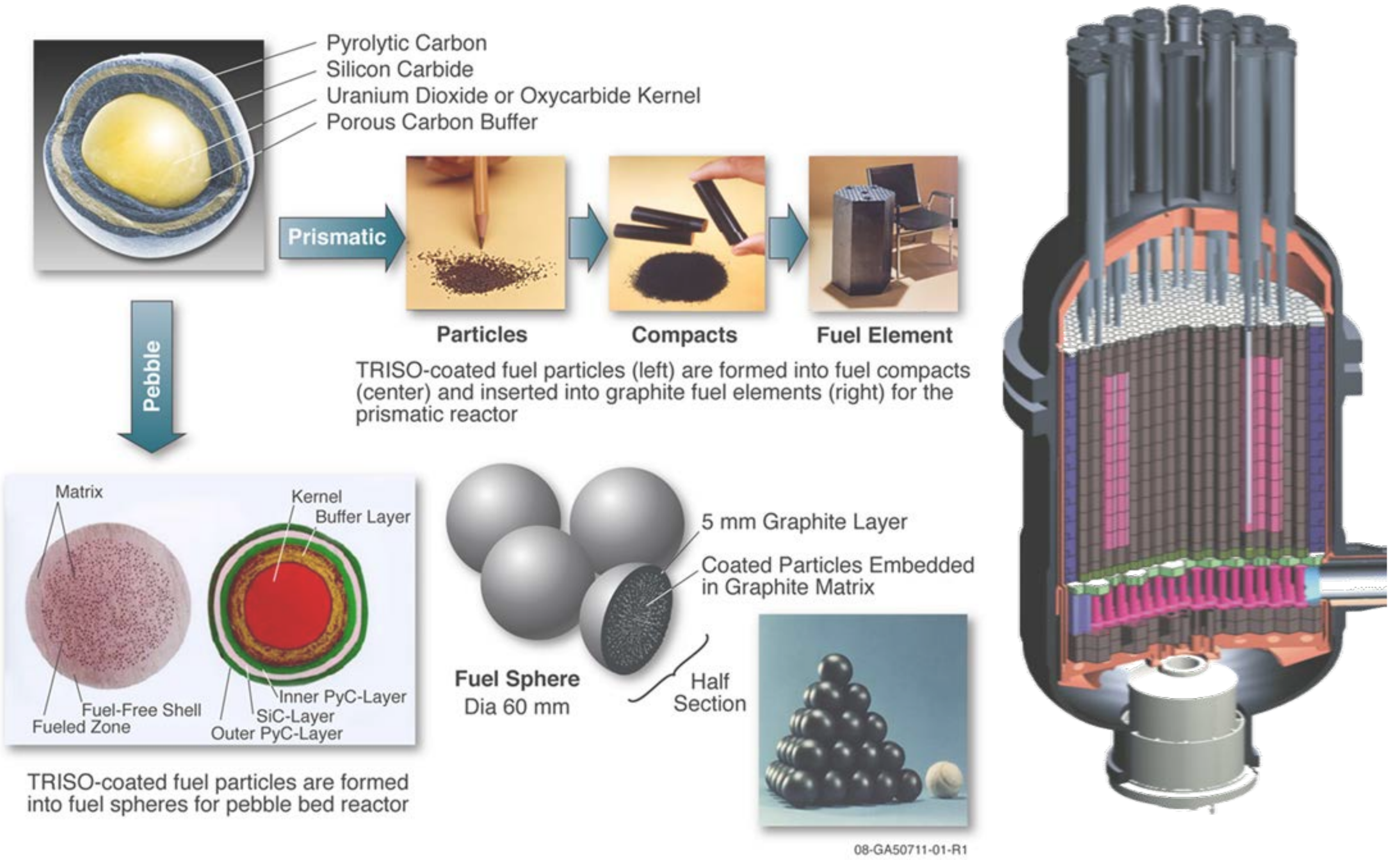
- Enable deployment through siting and technical support
- 2029 - First NuScale module (UAMPS) to commence commercial operation



2025 **2028** **2029**

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



Information courtesy G. Strydom, HTGR National Technical Director

Example: X-energy—Xe-100

- 200 MWth (80 MWe) per unit
- Modular, scalable to a 4-pack for 320 MWe
- Helium coolant: 750^{o}C, 7 MPa
- Steam secondary: 565^{o}C, 16.5 MPa
- Fuel: 220,000 Graphite Pebbles with TRISO Particles
- High temperature tolerant graphite core structure
- ASME compliant reactor vessel, core barrel & steam generator
- Designed for a 60-year operational life
- Flexible application – electricity and/or process heat
- Base load or load following
- Online refueling (95% plant availability)
- Safety perimeter: 400 yards

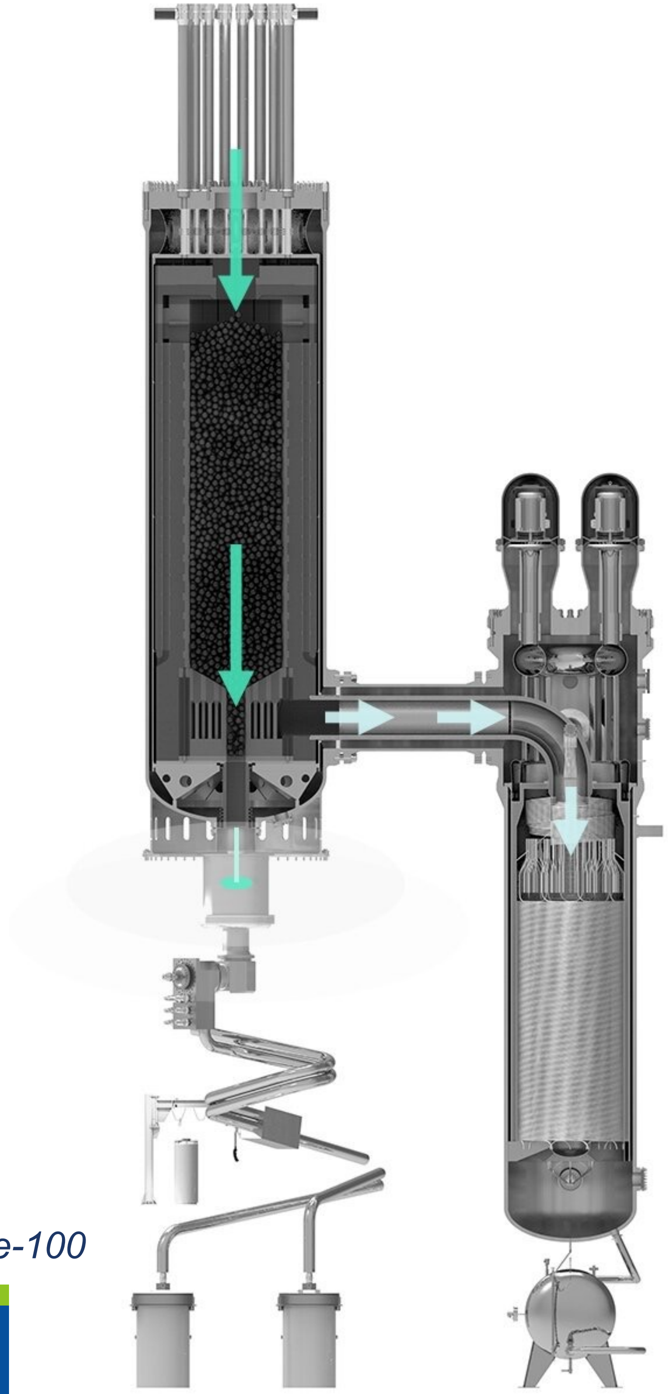
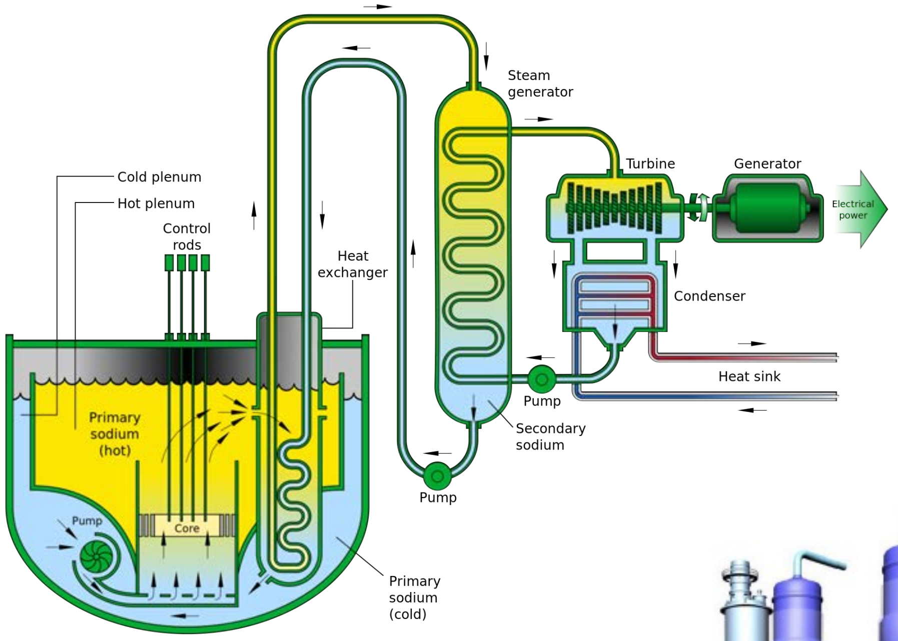
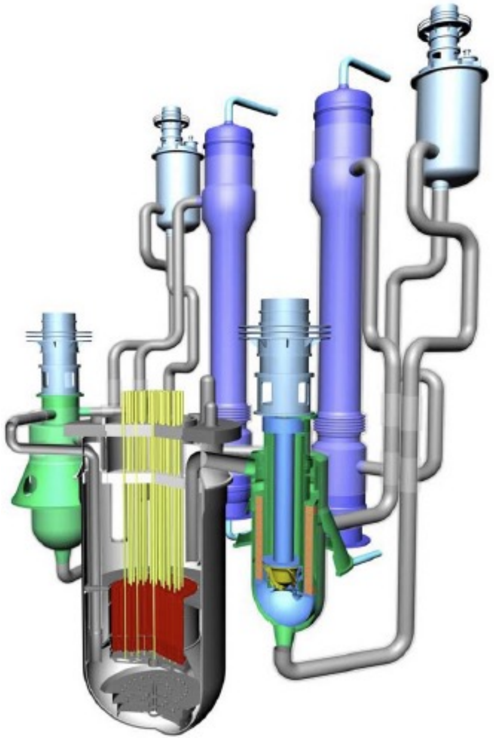


Image source: X-energy.com/reactors/xe-100

Liquid Metal Fast Reactor





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

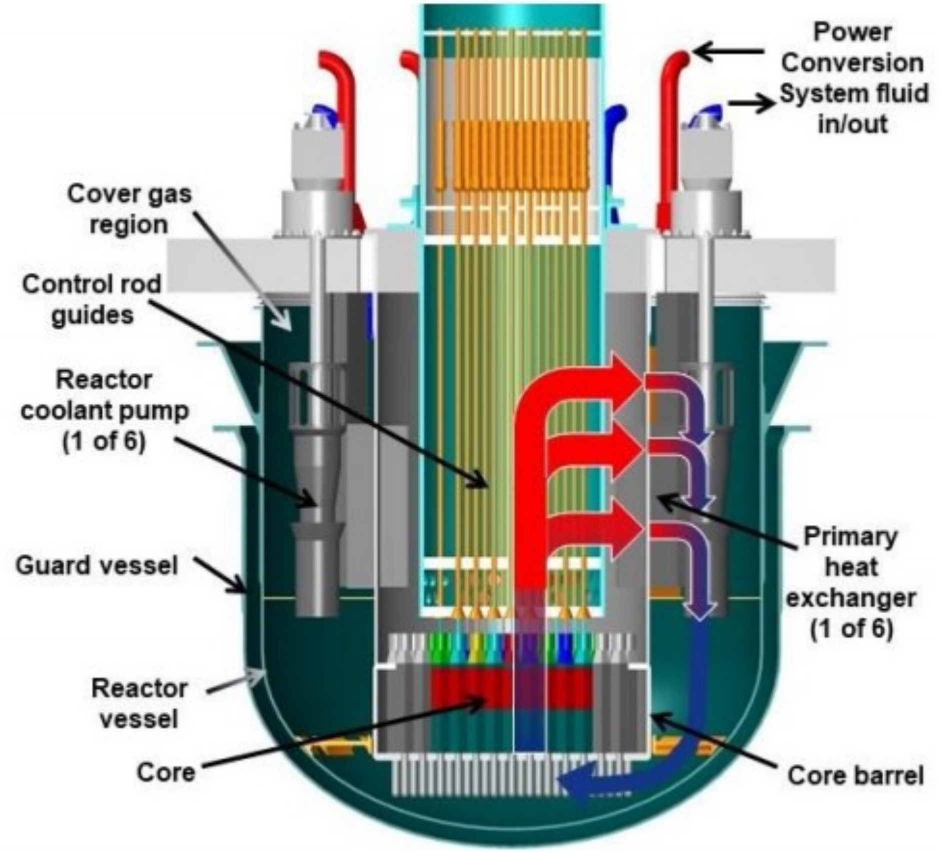
- Liquid metals as a primary coolant, allow higher power density
- Leading coolants considered in the U.S. include sodium, lead
  - Sodium: Chemically reactive w/water, air; SS compatible
  - Lead: Non-reactive w/water, air; corrosive
  - Coolant temperature ~550°C
  - Operate near atmospheric pressure
- 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 Hitachi—Natrium

- Sodium-cooled fast reactor
- 345 MWe, plus molten salt storage for up to 500 MWe for 5.5 hrs
  - Na-salt heat exchanger to isolate thermal storage from nuclear island
- Metal fuel
- ~500^{o}C operating temperature
- Targeted power costs of $50-55MWh for first demonstrations and $40/MWh or less with storage system
- Ramp rate target of 8-15% per minute
- 80% reduction in nuclear concrete relative to large-scale LWRs

Reference: Natriumpower.com

Example: Westinghouse Lead Fast Reactor



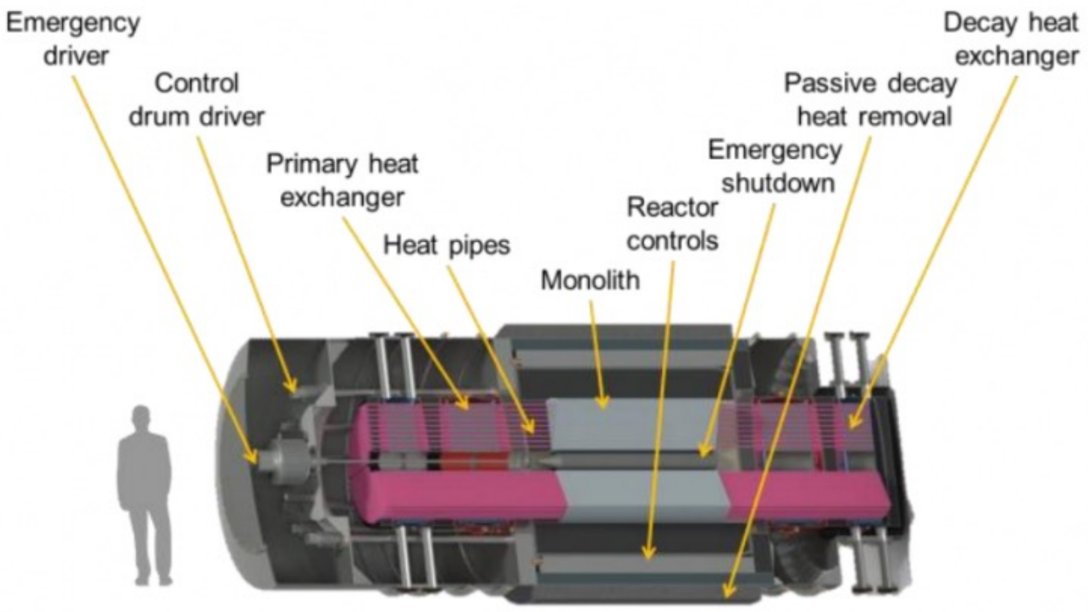
- 450 MWe, lead-cooled
- Passively safe, compact, scalable
- Flexible output, support for non-electric applications
- Could incorporate thermal energy storage
- sCO_2 Brayton cycle
- Potential use of Westinghouse EnCore Fuel (advanced technology/accident-tolerant fuel)
  - Chromium-coated fuel cladding (phase 1)
  - SiC cladding (phase 2)

Image source: Westinghouse LFR Fact Sheet, available at https://www.westinghousenuclear.com/new-plants/lead-cooled-fast-reactor

Example: Westinghouse eVinci^{TM} MicroReactor

- Transportable energy generator
- Fully factory built, fueled and assembled
- Delivers combined heat and power – 1 MWe to 5 MWe
- 40-year design life with 3+ year refueling interval
- Target less than 30 days onsite installation
- Autonomous operation
- Power demand load following capability
- High reliability and minimal moving parts
- Near zero Emergency Planning Zone with small site footprint
- Green field decommissioning and remediation
- Solid core
- Heat removal via sodium heat pipes

- Heat pipes:
  - No reactor coolant pumps
  - Inherently adjust heat load
  - Higher temperature operation



Molten Salt Reactors

General characteristics

- Molten salts have high heat capacity
- Allow for low pressure operation
- Large margin to boiling
- High operating temperature: ~700^{o}C

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 Molten Chloride Fast Reactor

- Fuel dissolved in a molten chloride salt coolant
- High operating temperature
- Stable, inherently safe
- Net breed and burn, batch refueling with DU or NatU make-up feed
- Passive decay heat removal

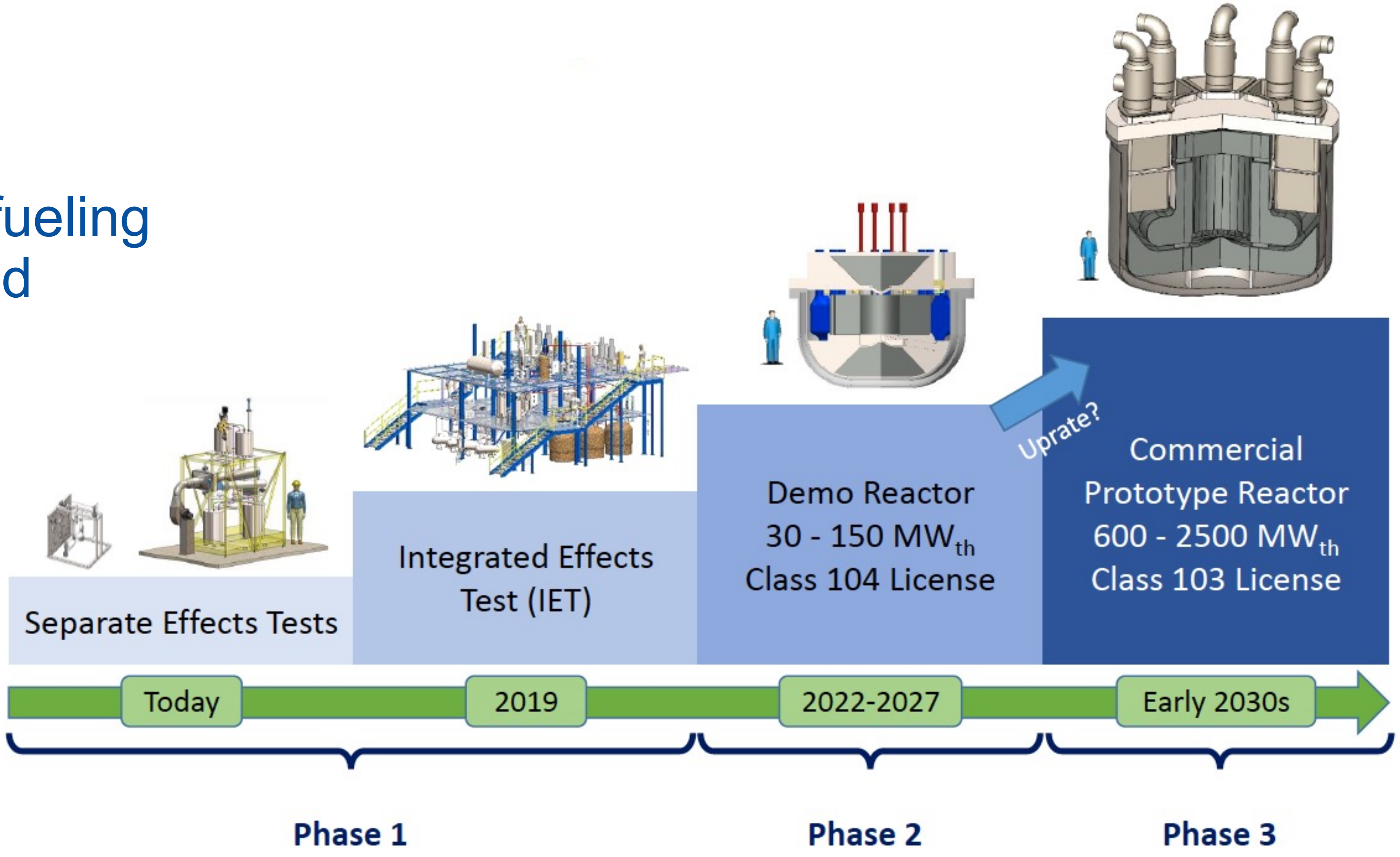


Image source:
K. Kramer, 2018 ETEC Nuclear Suppliers Workshop,
DOI: 10.13140/RG.2.2.18467.09768

Example: Kairos Power FHR (solid fuel)

- Low-pressure fluoride salt coolant
- TRISO fuel
- Steam cycle
- 140 MWe, 45% net efficiency
- Reactor outlet 650^{o}C
- Nitrate "solar" intermediate salt
- 585^{o}C main/reheat temperature
- Online refueling
- Single or multi-module deployment
- Passive cooling upon loss of power

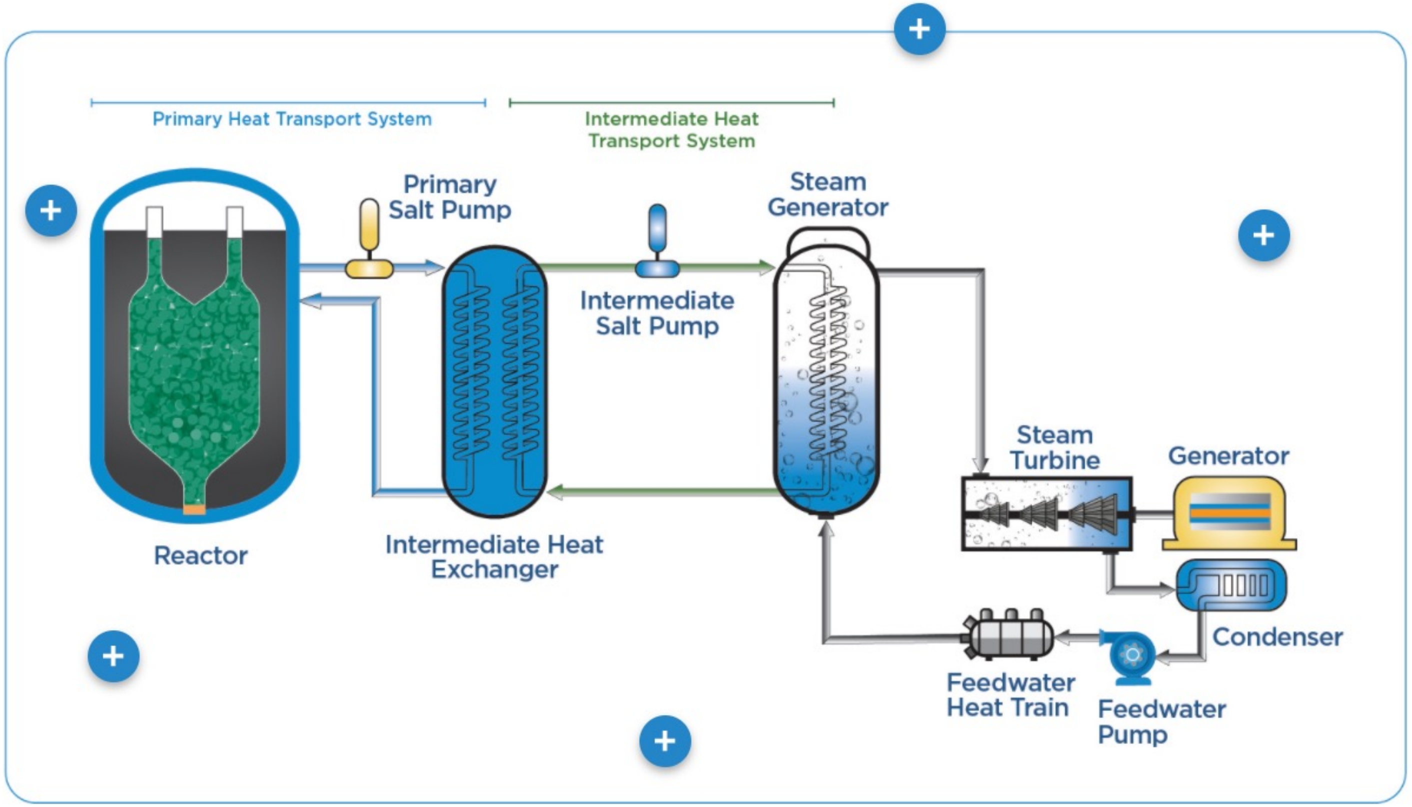


Image reference: Kairos Power, https://kairospower.com/technology/

US DOE Advanced Reactor Demonstration Program

- Established in fiscal year (FY) 2020 budget language ($230 million (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
- Overall FY21 budget for ARDP activities $250 M

ARDP program elements

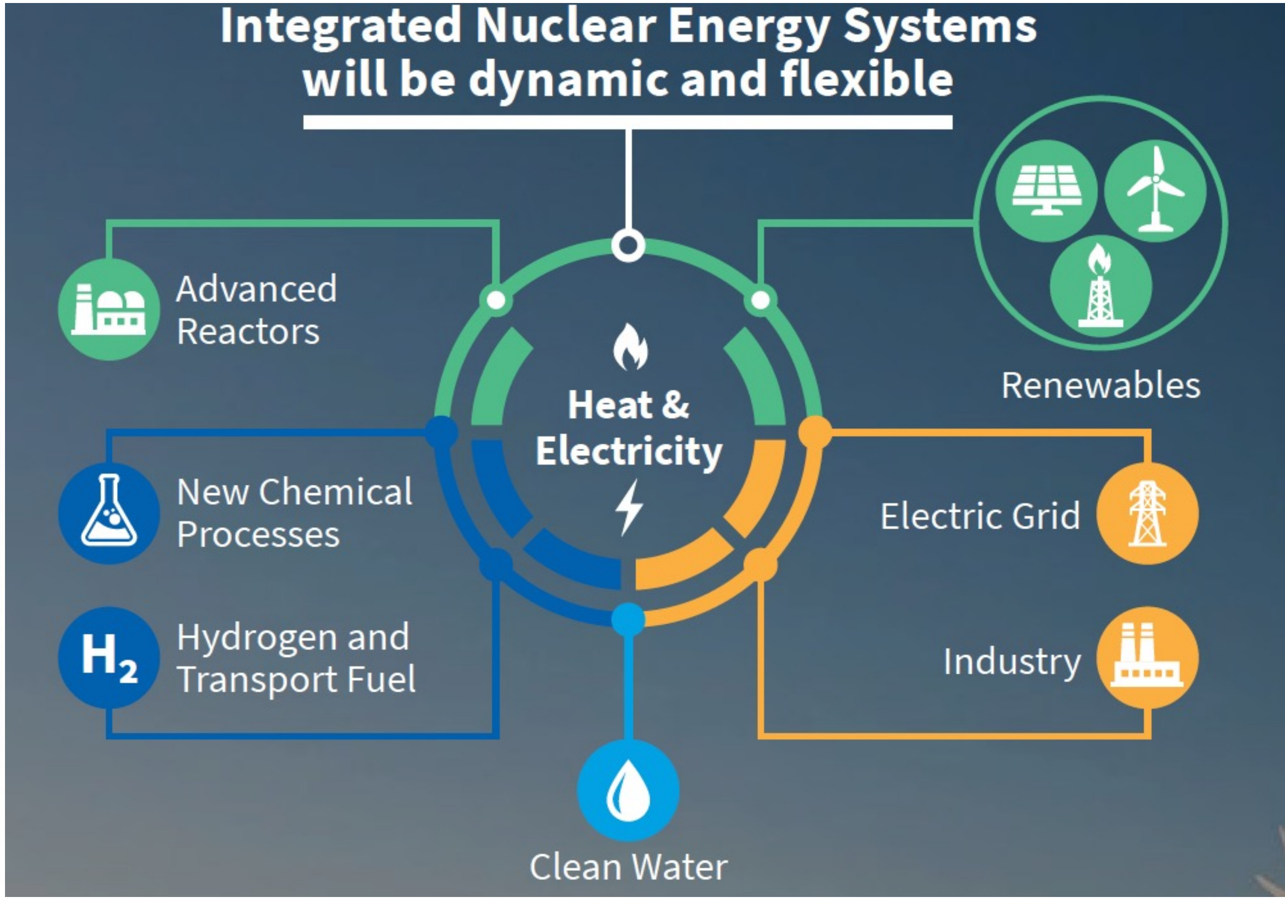
- **Advanced Reactor Demonstrations (Demos)**
  - Cost-shared partnerships with industry (up to 50 percent (%) government, not less than 50% industry) to build two advanced demonstration reactors with significant improvements compared to current generation of operational reactors
  - Demos to be constructed and operational in a 5-7 year window after award
  - $160 M appropriated for fiscal year (FY) 2020 ($80 M per award)
  - $160 M appropriated for FY 2021 ($80 M per award)
- **Risk Reduction (RR) for Future Demonstrations**
  - Cost-shared research and development (R&D) activities with industry (up to 80% government, not less than 20% industry) to address technical risks in advanced reactor designs to support potential future advanced reactor demonstrations
  - $30 M appropriated for FY 2020 (up to 5 awards)
  - $40 M appropriated for FY 2021 (To be distributed among awards based on agreed-upon cost requirements)

ARDP program elements

- **Advanced Reactor Regulatory Development**
  - National laboratory-led R&D to resolve technical challenges with licensing advanced reactors
  - Supporting efforts with NRC and industry stakeholders to develop cross-cutting advanced reactor licensing frameworks Licensing Modernization Project (LMP)
  - Technology-Inclusive Content of Application Project (TICAP)
  - Focused R&D to address technology-specific regulatory challenges for NE advanced reactor campaigns
  - $15 M appropriated for FY 2020; $15 M for FY 2021
- **Advanced Reactor Safeguards**
  - Applies laboratory R&D to address near term challenges that advanced reactor vendors face in meeting domestic requirements for U.S. builds.
  - Project focus areas: Materials Accountancy, Physical Protection, Gen-IV and IAEA Interface
  - $5 M appropriated for FY 2020; $5 M for FY 2021

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
  - 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
  - https://x-energy.com/
- Site selection for demonstrations in process; both currently considering Energy Northwest sites in Washington state



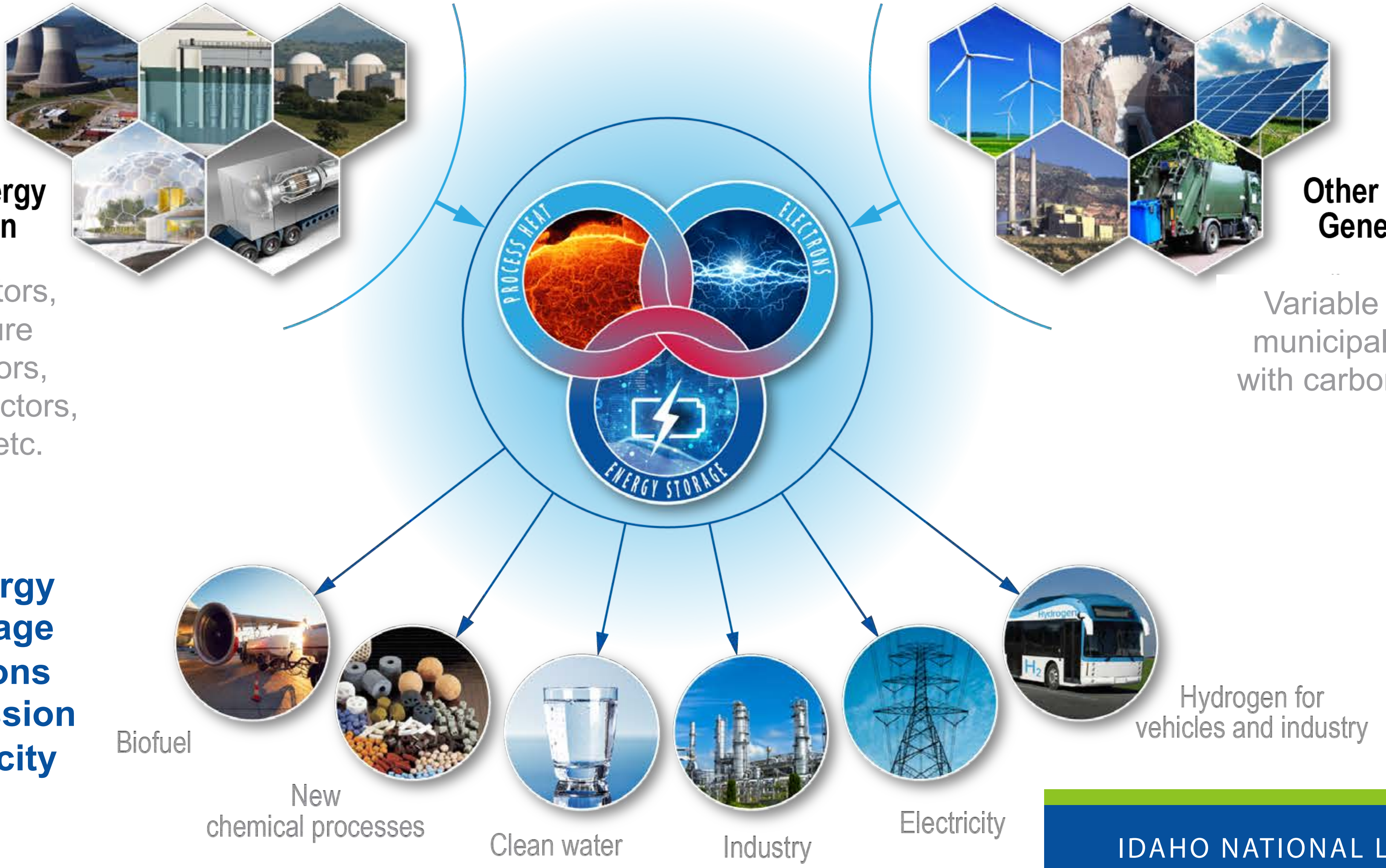
INTEGRATED ENERGY SYSTEMS

Maximizing the contribution of carbon-free energy generation for electricity, industry, and transportation – while supporting a resilient grid and converting valuable resources to higher value products

Future clean energy systems – transforming the energy paradigm

Nuclear Energy Generation

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



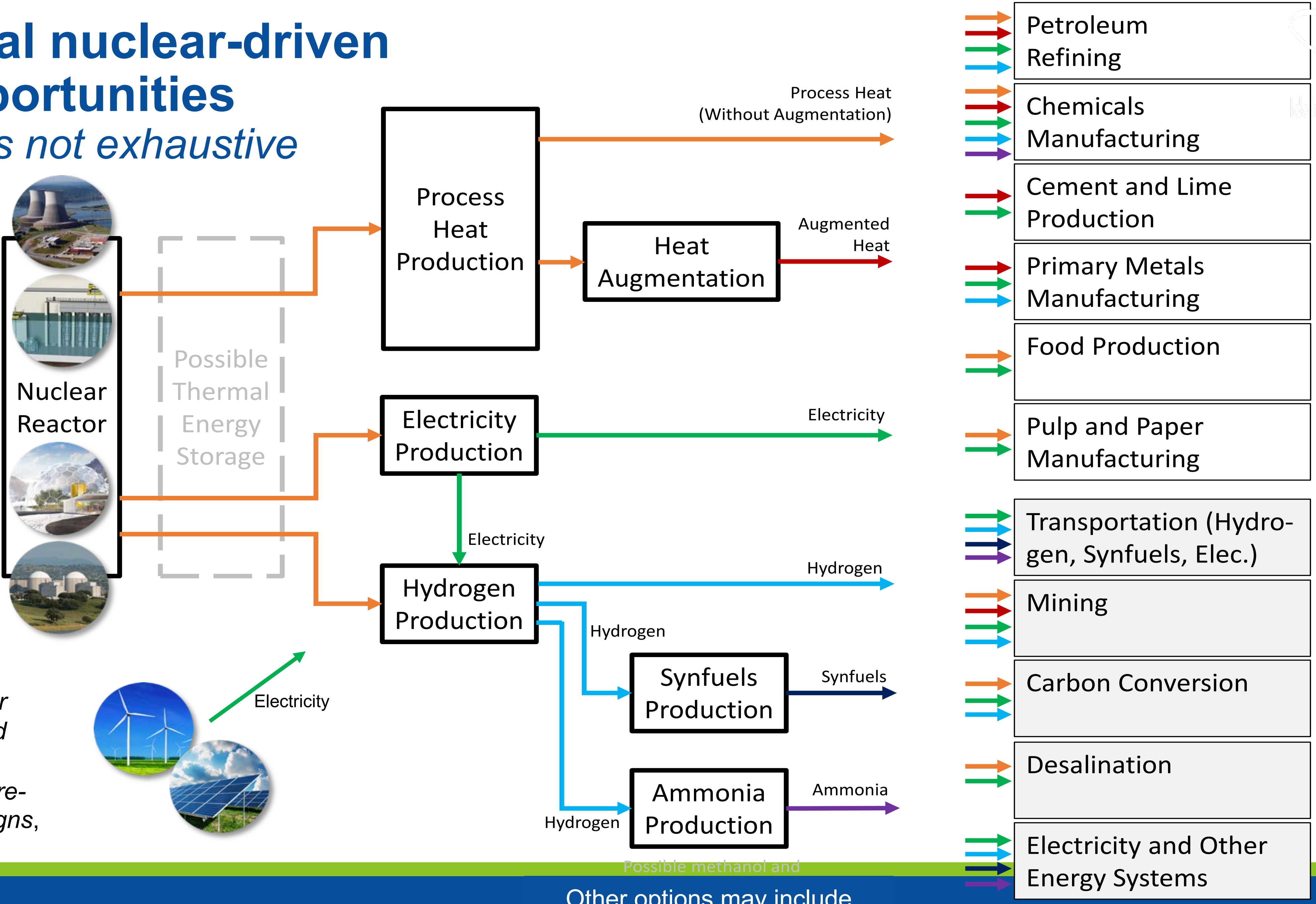
Other Energy Generation

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

Integrated energy systems leverage the contributions from nuclear fission beyond electricity

Potential nuclear-driven IES opportunities

Examples not exhaustive

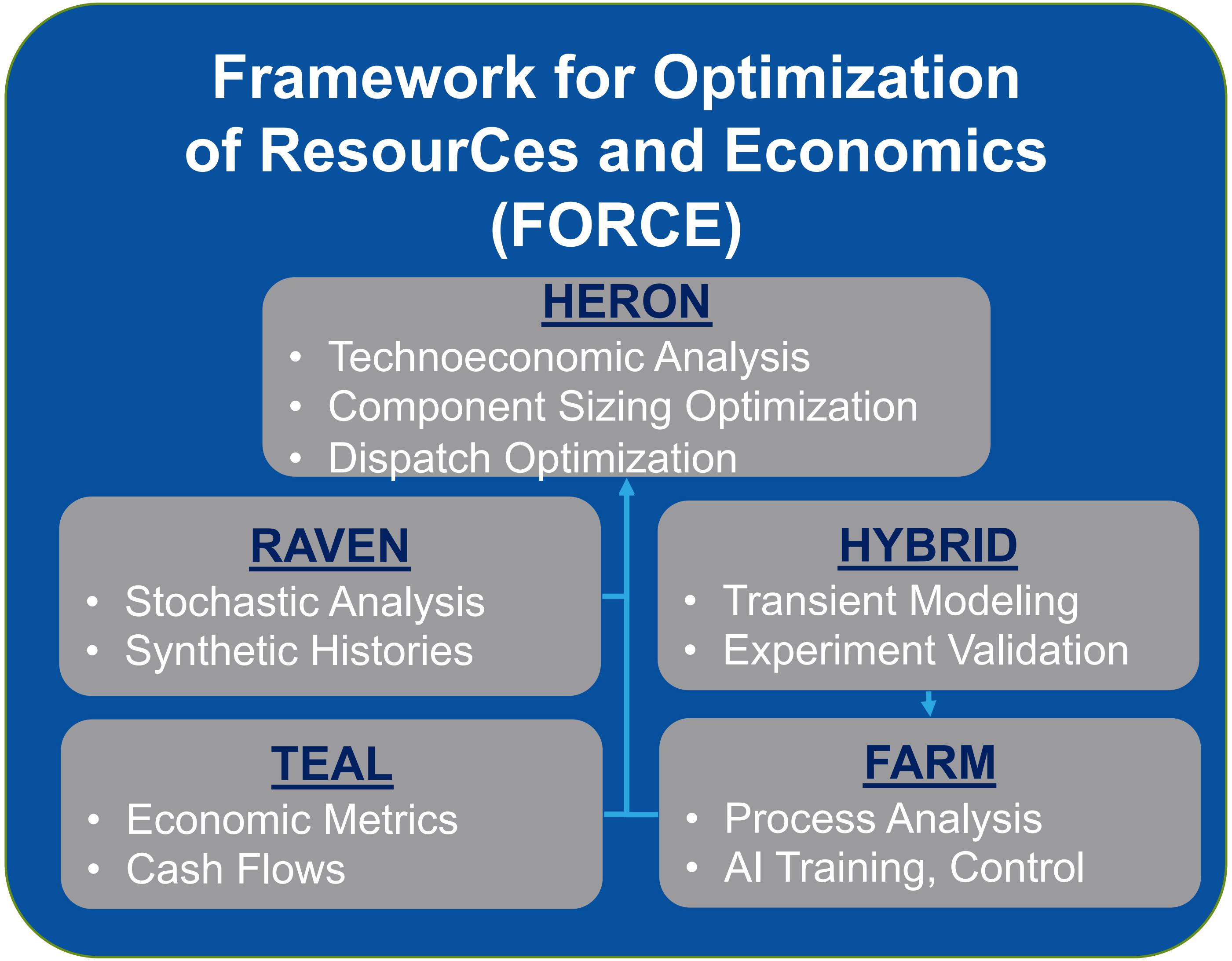


Source: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, April 2021

Other options may include methanol, synthetic methane

Integrated energy systems analysis and optimization

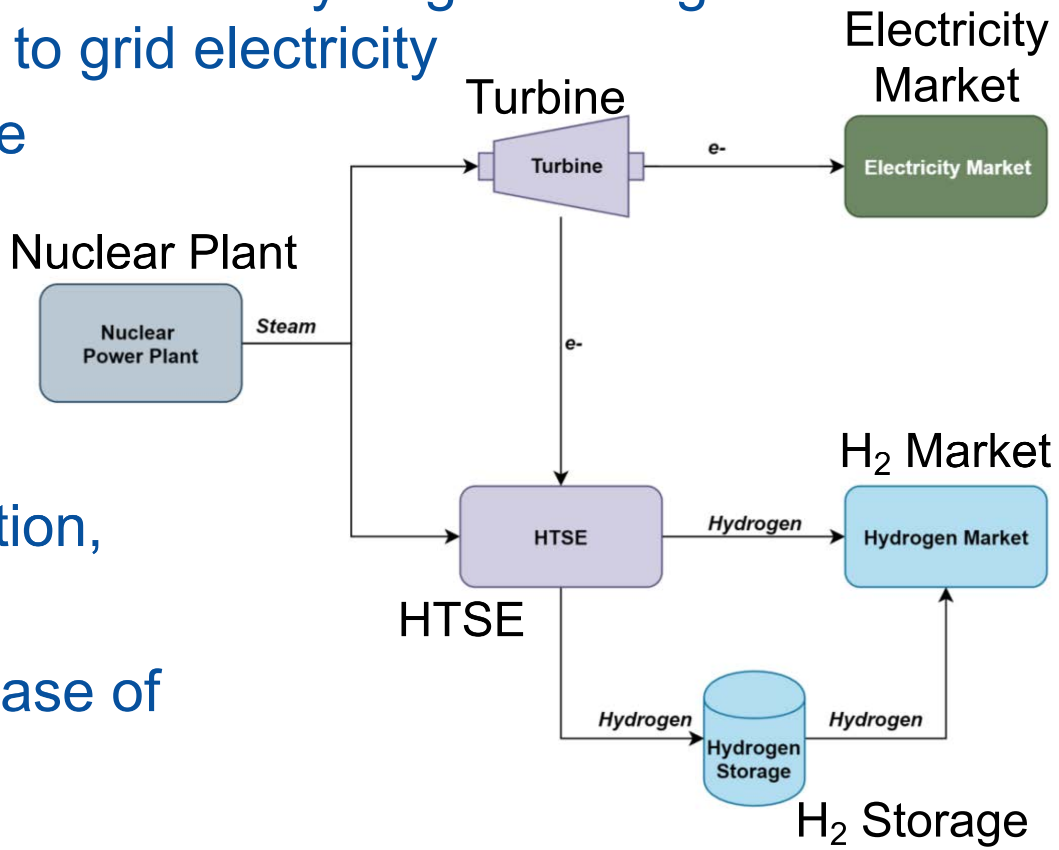
- **Technoeconomic assessment**
  - Portfolio Optimization
  - Dispatch Optimization
  - Process Model Simulation
  - Economic Analysis
  - Supervisory Control
  - Stochastic Analysis
  - Workflow Automation



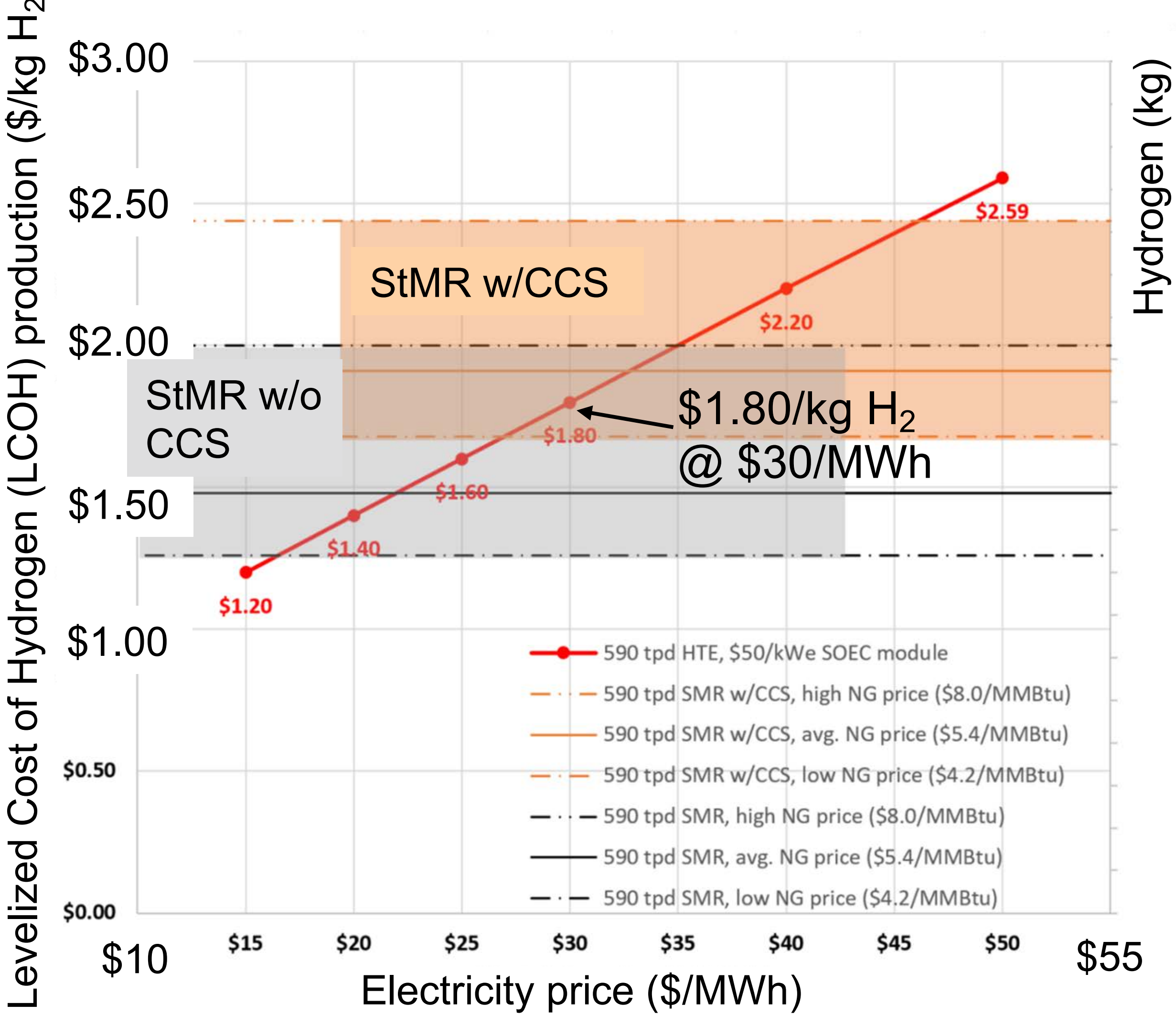
For more information and to access opensource tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.

Example: Disruptive potential of nuclear produced hydrogen

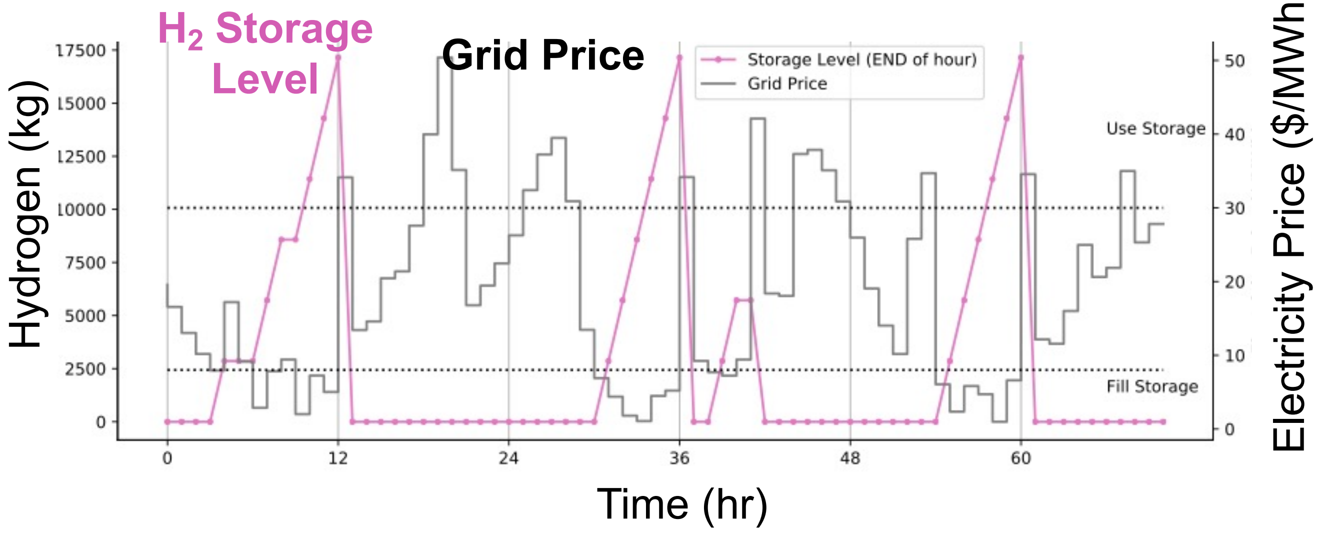
- Collaboration between INL, ANL, NREL, Constellation (Exelon), and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing → hydrogen is more profitable
  - High grid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

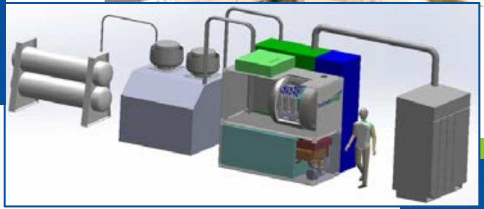
Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

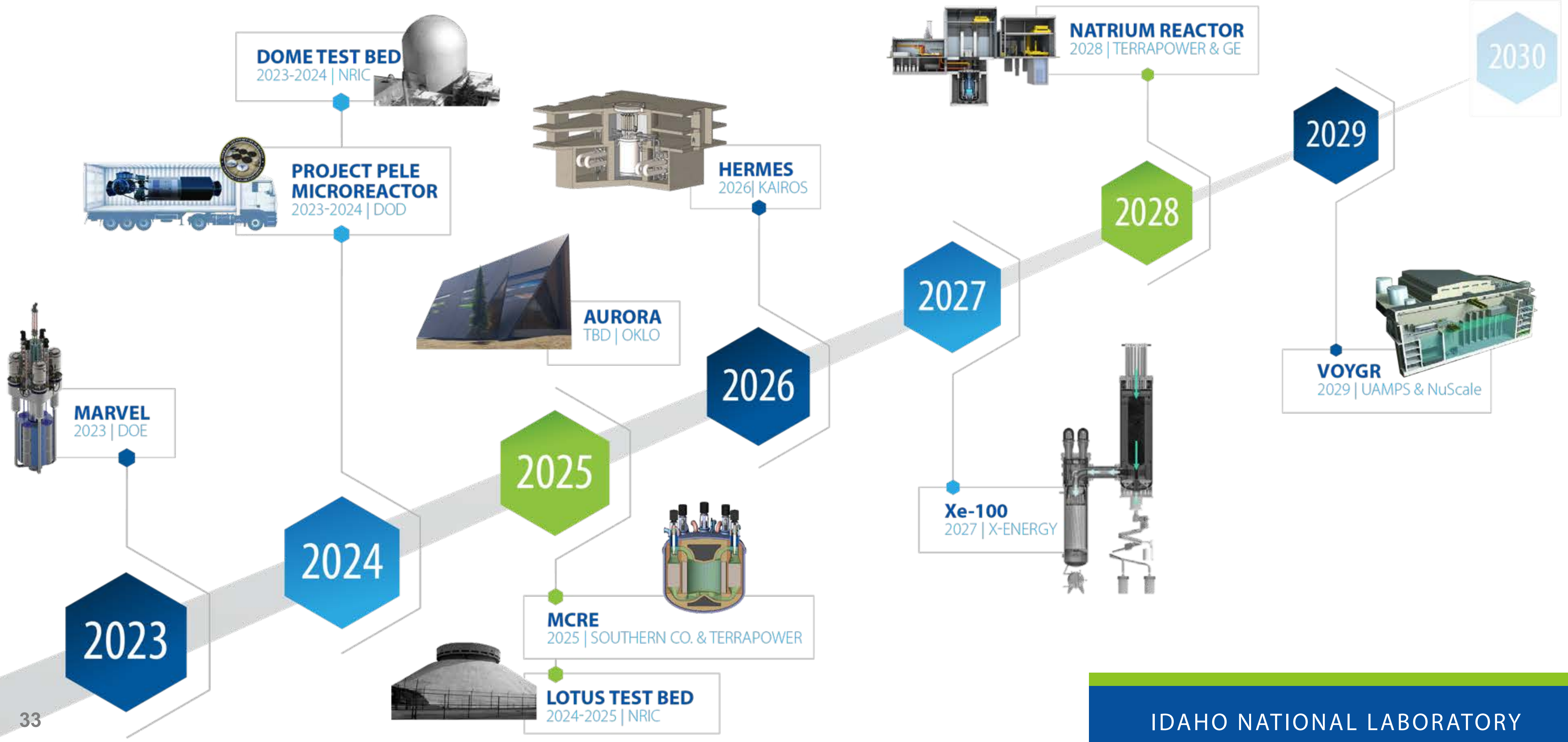
Thermal & Electrical Integration at Prairie Island NPP HTSE/SOEC

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

FuelCell Energy at INL, SOEC



Accelerating advanced reactor demonstration & deployment



National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure

NRIC National Reactor Innovation Center

- 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

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

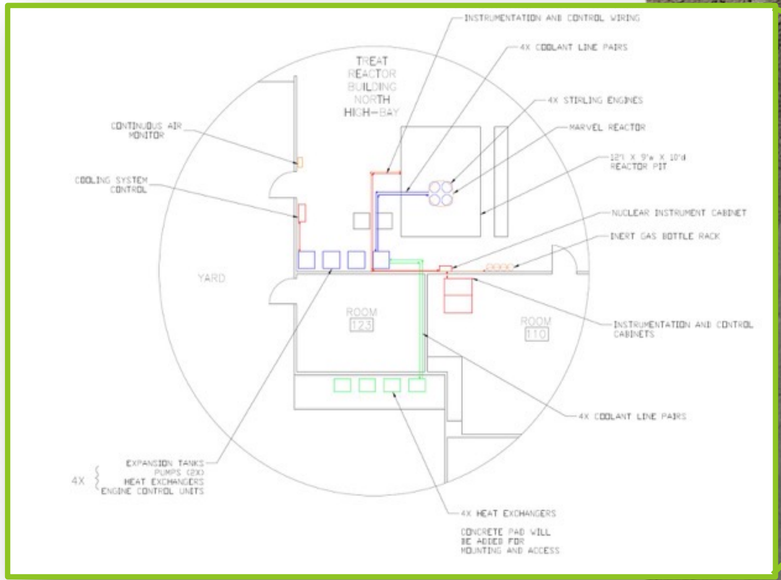
 For more information on NRIC and to download resources, see https://nric.inl.gov/.

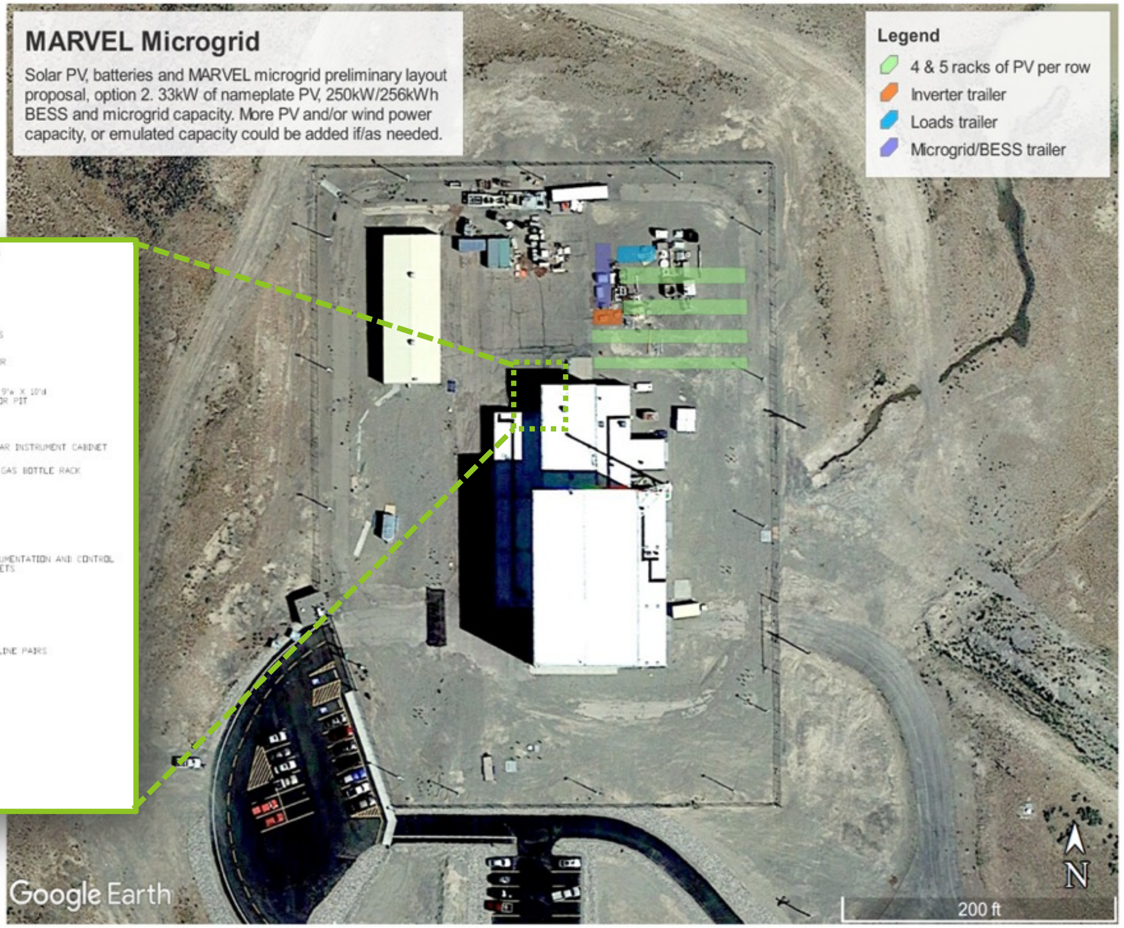
Microreactor integration with a microgrid

Microreactor Applications Research Validation and Evaluation (MARVEL) Objective:

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

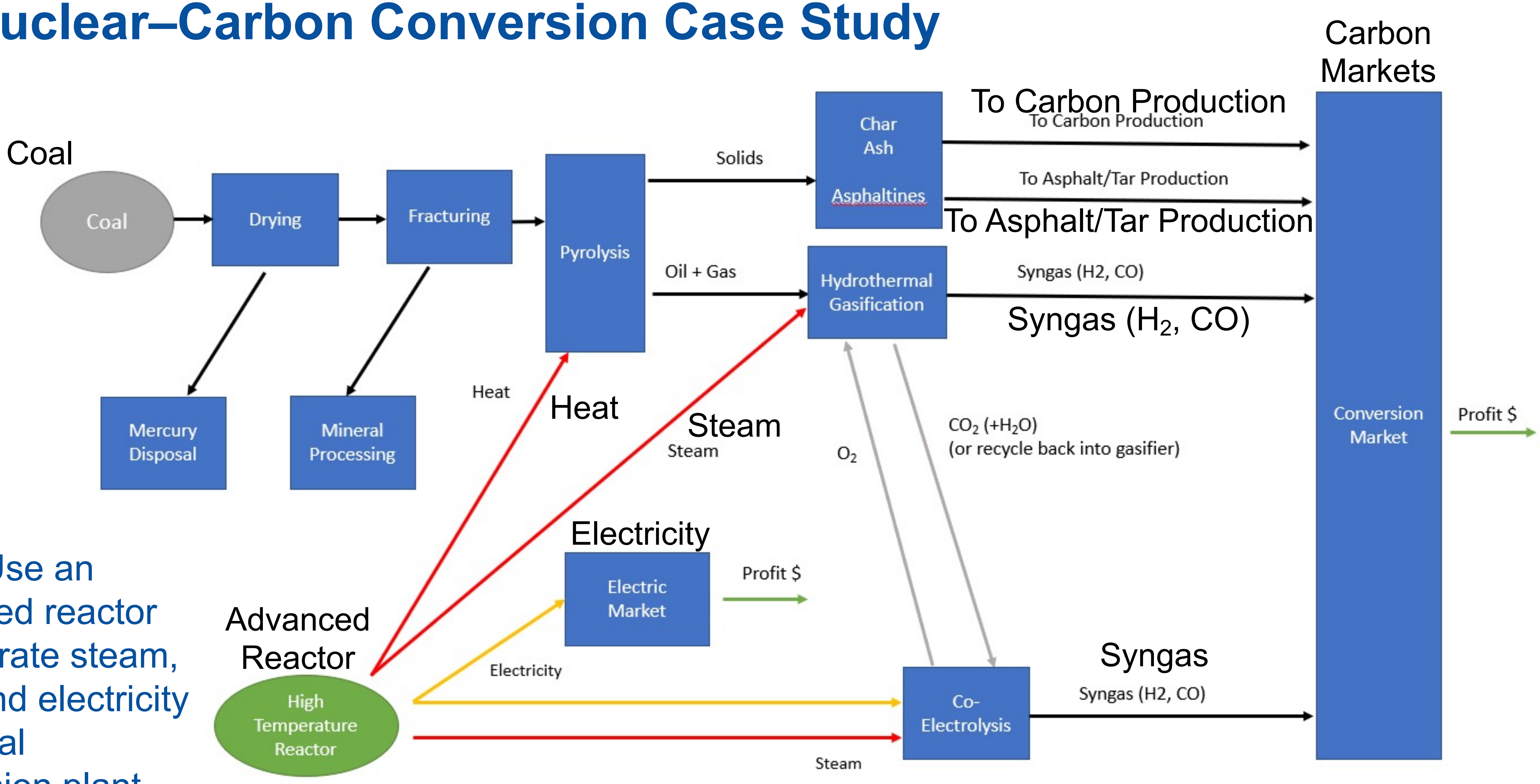
Demonstrate nuclear microgrid operations and provide opportunity to demonstrate operation with coupled energy users, such as hydrogen production and desalination.





MARVEL Construction: Dec 2022
MARVEL Criticality: Dec 2023

Nuclear–Carbon Conversion Case Study

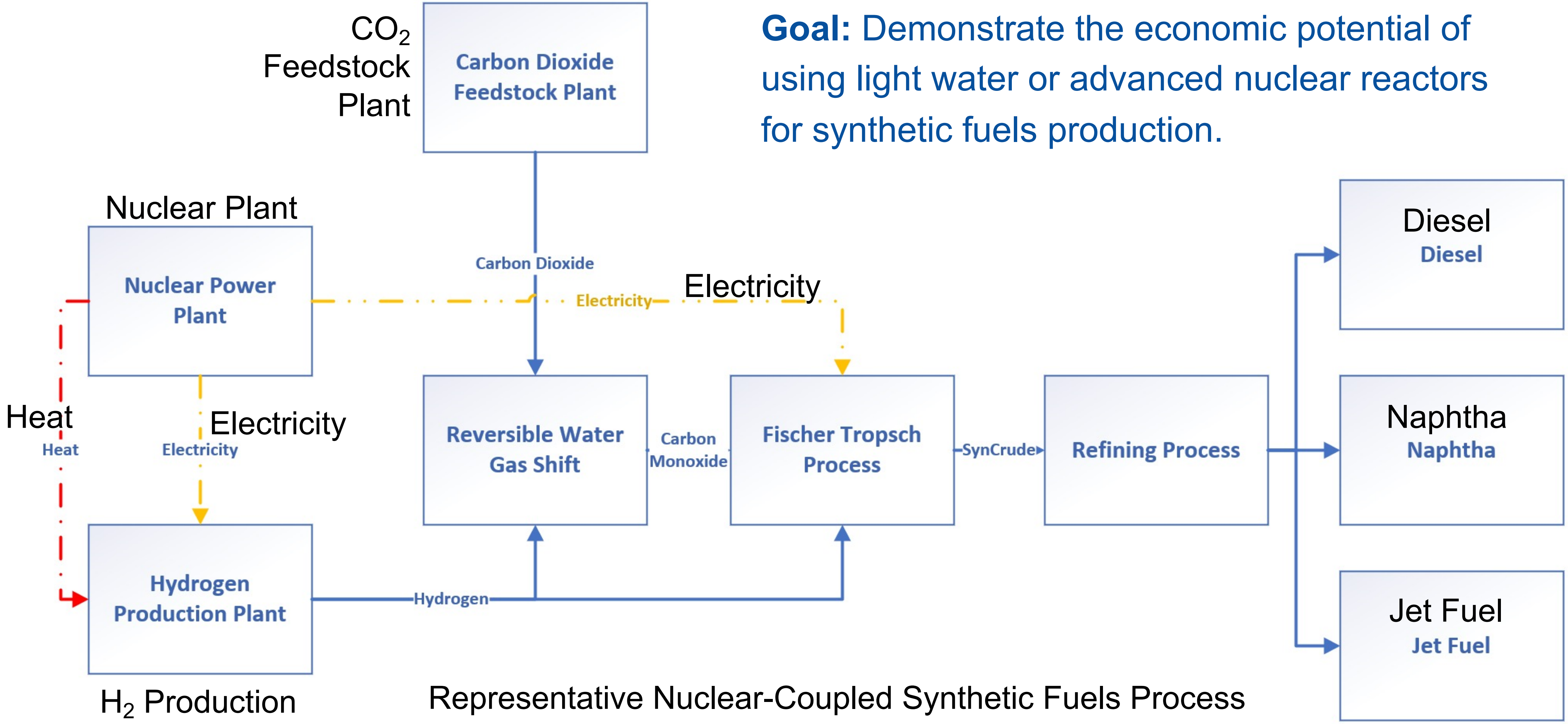


Representative Coal Conversion Process

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

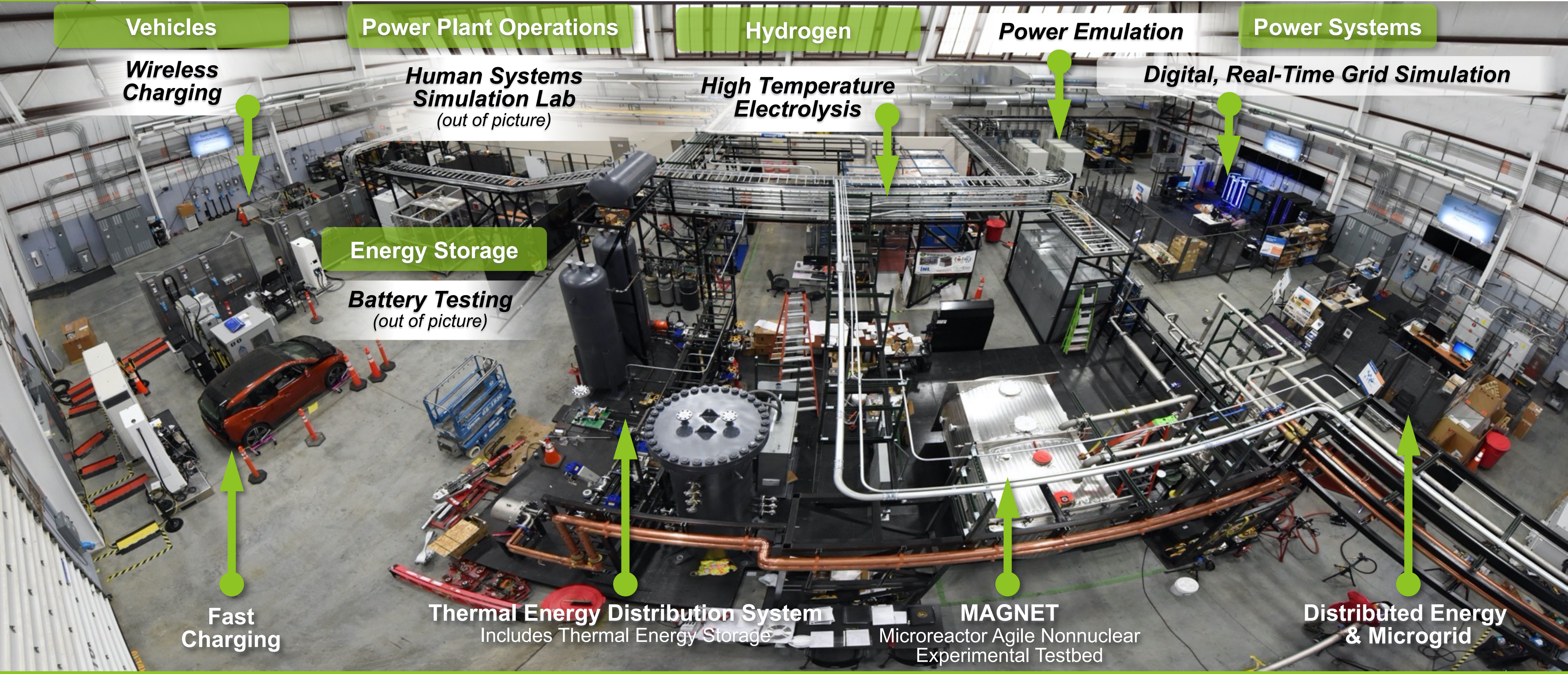
Nuclear Synthetic Fuels Production

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



Representative Nuclear-Coupled Synthetic Fuels Process

Dynamic Energy Transport and Integration Laboratory (DETAIL)



Idaho National Laboratory

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- 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