INL/MIS-23-75216-Revision-0

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

November 2023

Changing the World's Energy Future

Shannon M Bragg-Sitton

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

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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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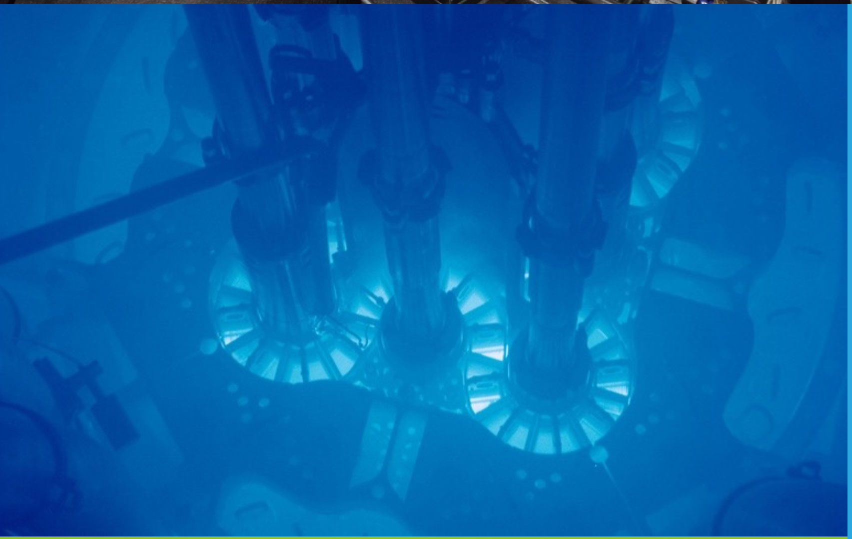

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September 2023

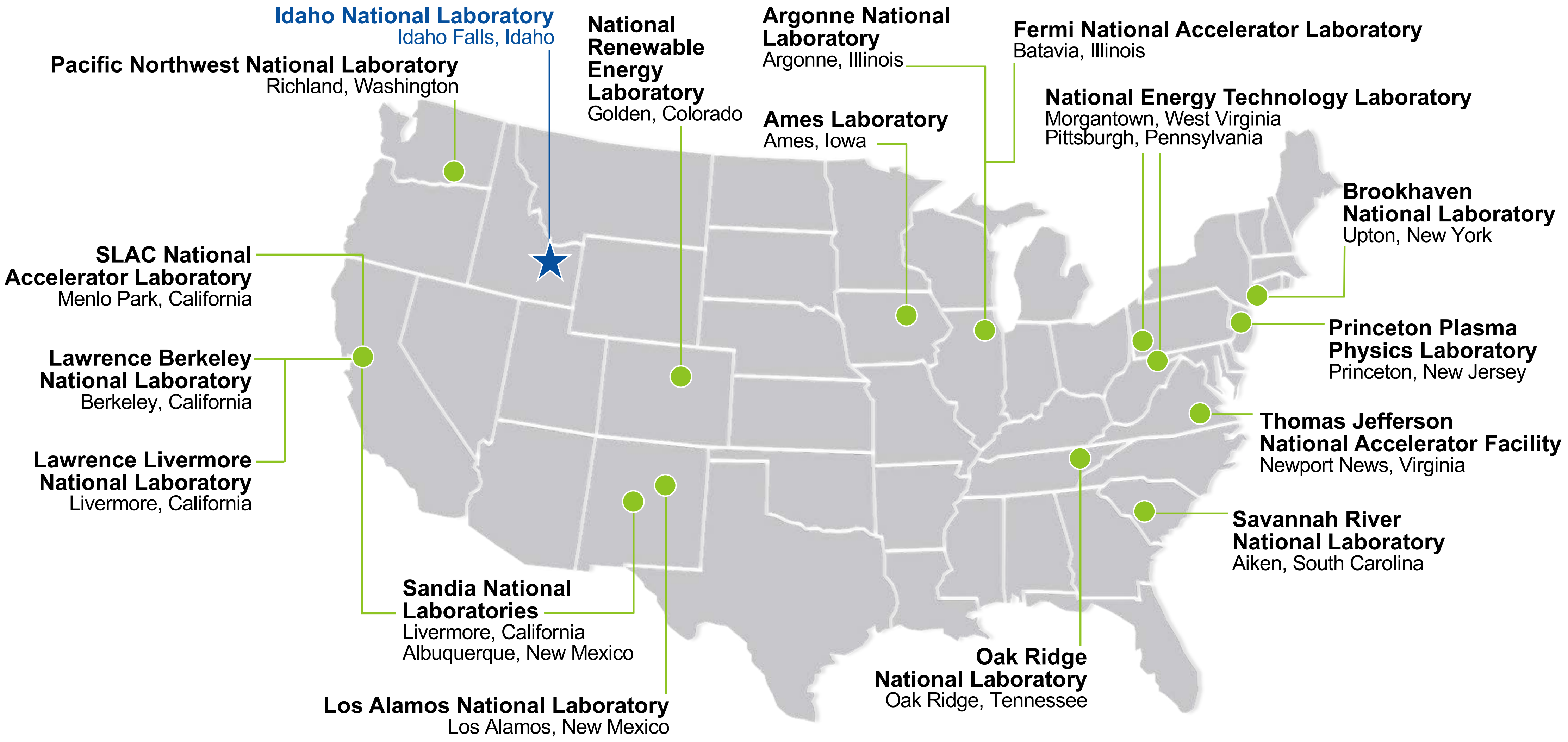
Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

INL Idaho National Laboratory

Presentation Overview

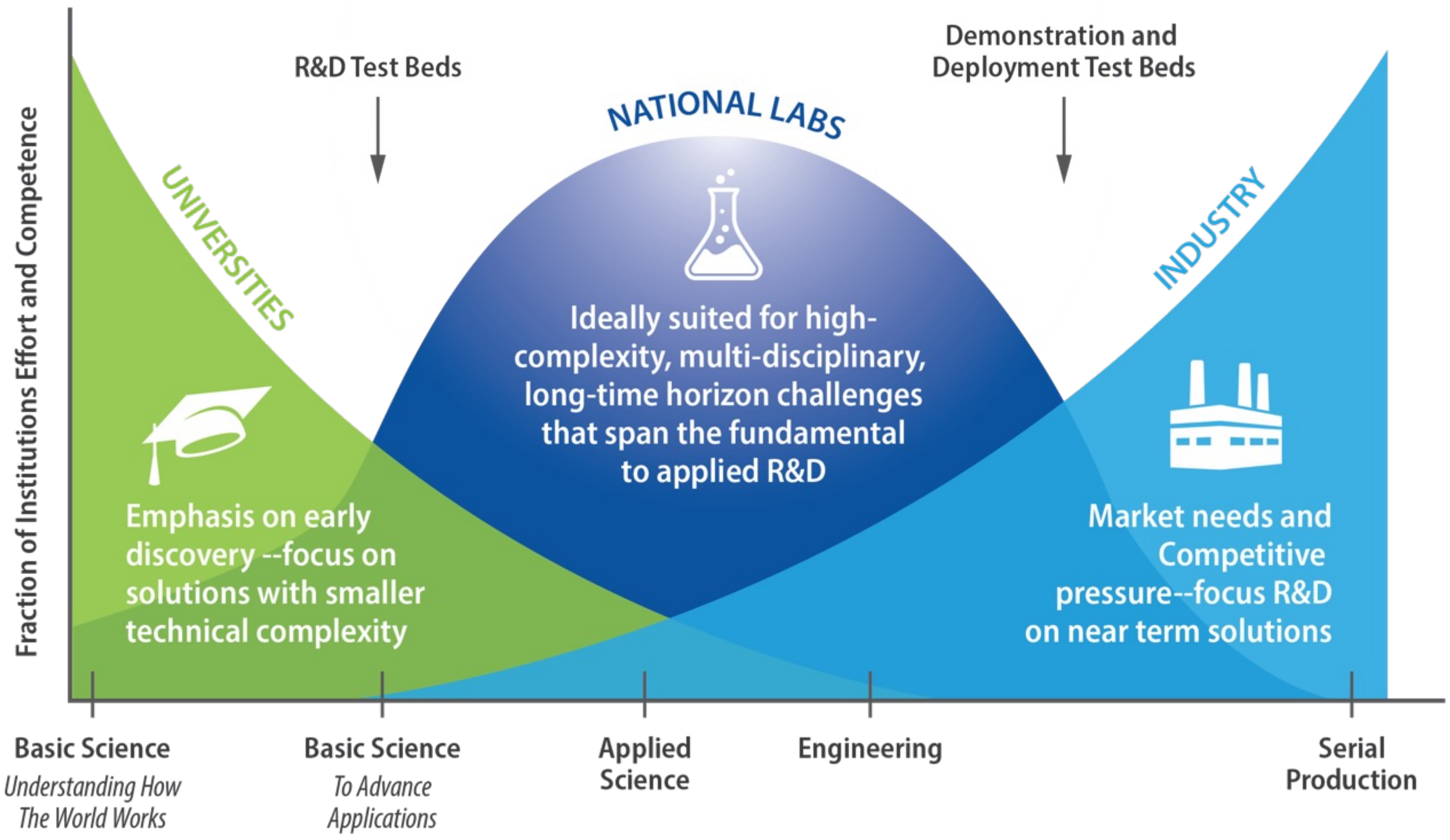
- Brief introduction to Idaho National Laboratory
- Current state of energy in the U.S.
- Nuclear energy options
  - Nuclear plant scale
    - Large (~GW systems)
    - Small (~100s MW)
    - Micro (~few to 10s MW)
  - Advanced reactor concepts
    - Gas cooled (helium)
    - Fast spectrum, liquid metal cooled
    - Molten salt
- Novel deployment opportunities: Moving beyond the grid
- Demonstration and deployment timelines

DOE National Laboratories

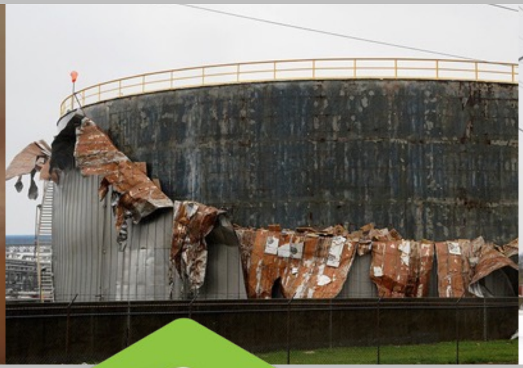


DOE laboratories span the spectrum from basic to applied science & technology

DOE labs support the entire technology lifecycle



Addressing the world's most pressing challenges through research, development, and demonstration


VISION

To change the world's energy future and secure our nation's critical infrastructure.

MISSION

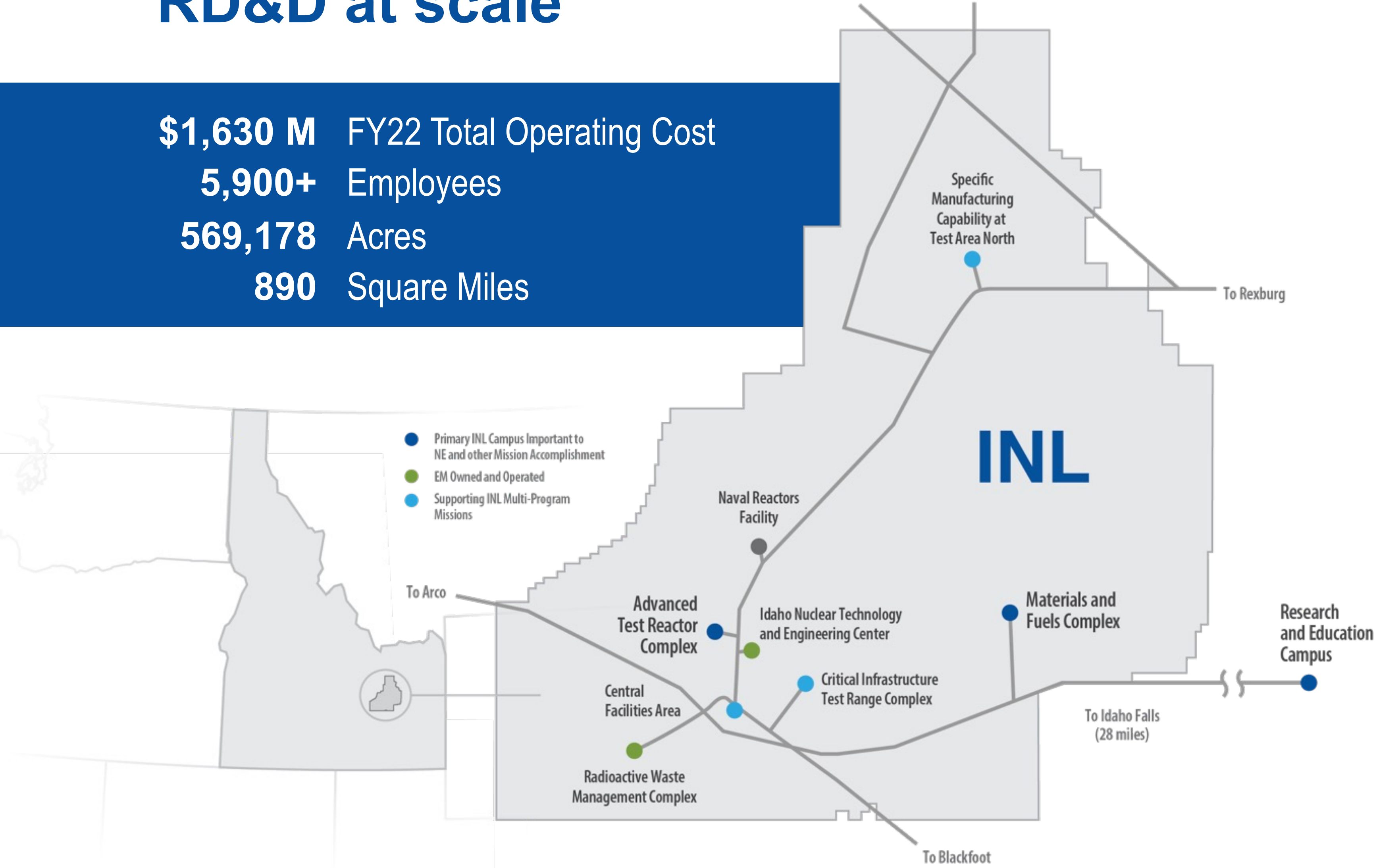
Discover, demonstrate and secure innovative nuclear energy solutions, clean energy options and critical infrastructure.

VALUES

Excellence, Inclusivity, Integrity, Ownership, Teamwork, Safety

Unique INL site, infrastructure, and facilities enable energy and security RD&D at scale

$1,630 M	FY22 Total Operating Cost
5,900+	Employees
569,178	Acres
890	Square Miles



4 Operating reactors

22 Hazard Category II & III non-reactor facilities/ activities

49 Radiological facilities/activities

17.5 Miles railroad for shipping nuclear fuel

44 Miles primary roads (125 miles total)

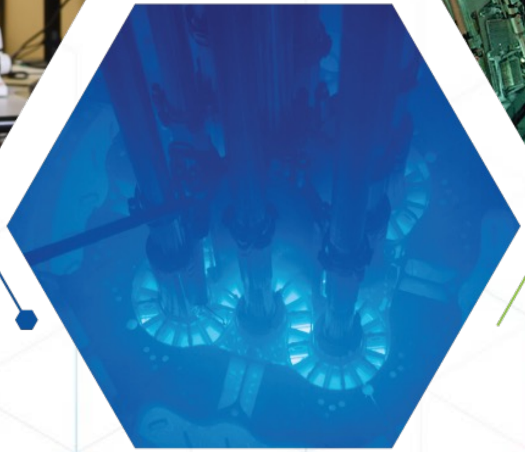
9 Substations with interfaces to two power providers

128 Miles high-voltage transmission & distribution lines

3 Fire Stations

INL Mission Directorates—
Creating a secure, resilient, net-zero energy future

Advanced Test
Reactor Complex



Nuclear Science
& Technology

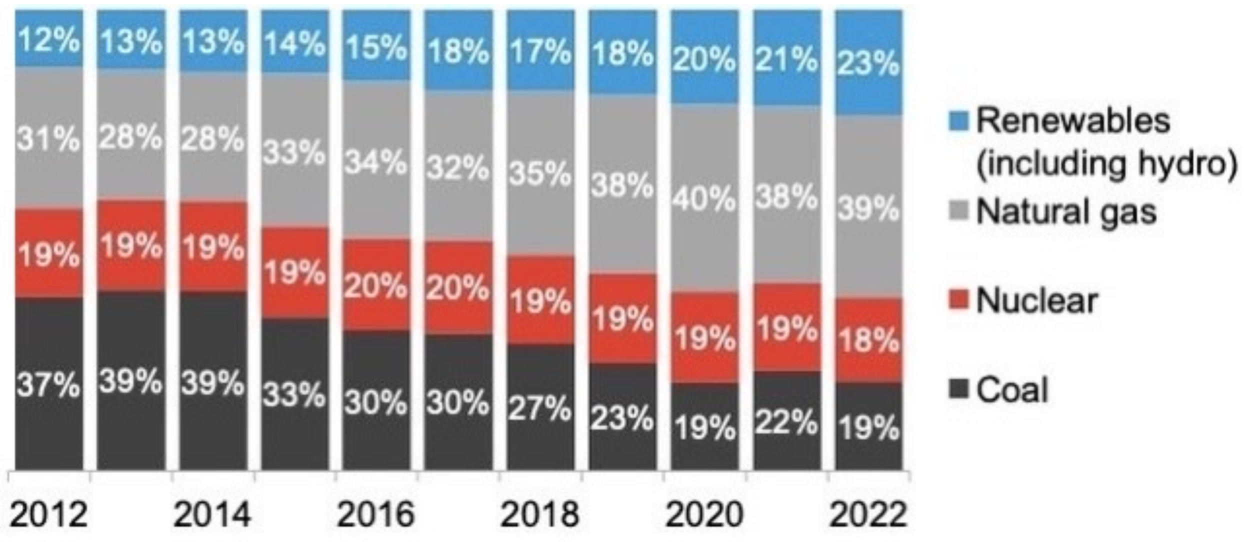
Energy &
Environment Science
& Technology

Materials and
Fuels Complex

National & Homeland
Security Science
& Technology

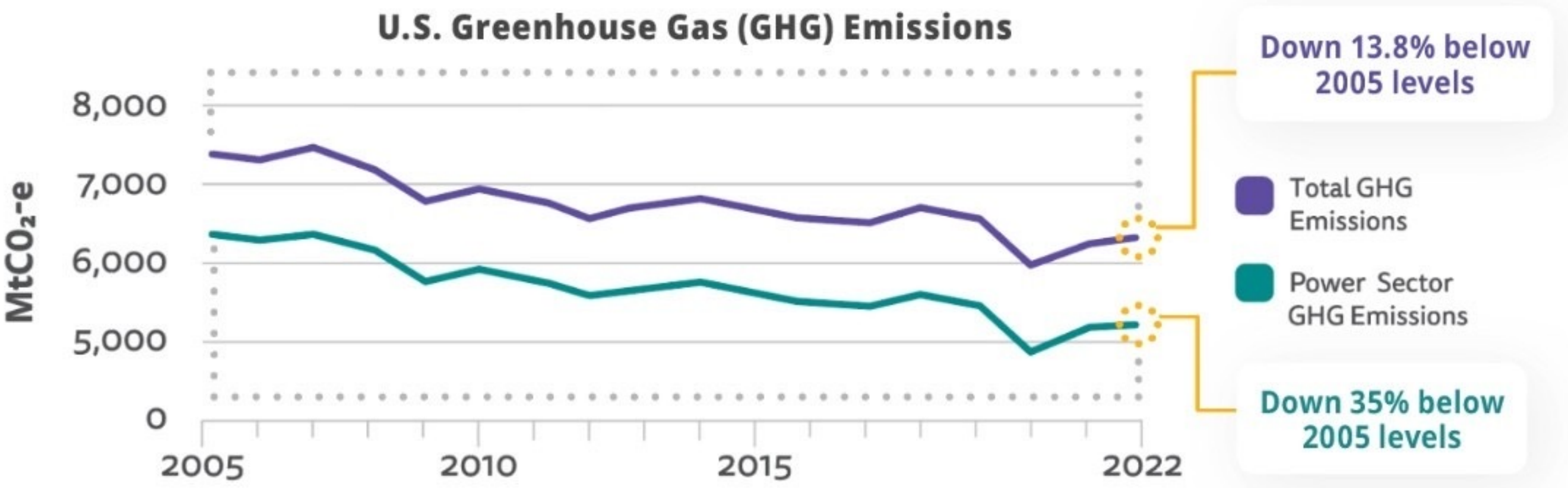
Addressing the global challenge: Climate change

U.S. electricity generation and emissions, World Economic Forum



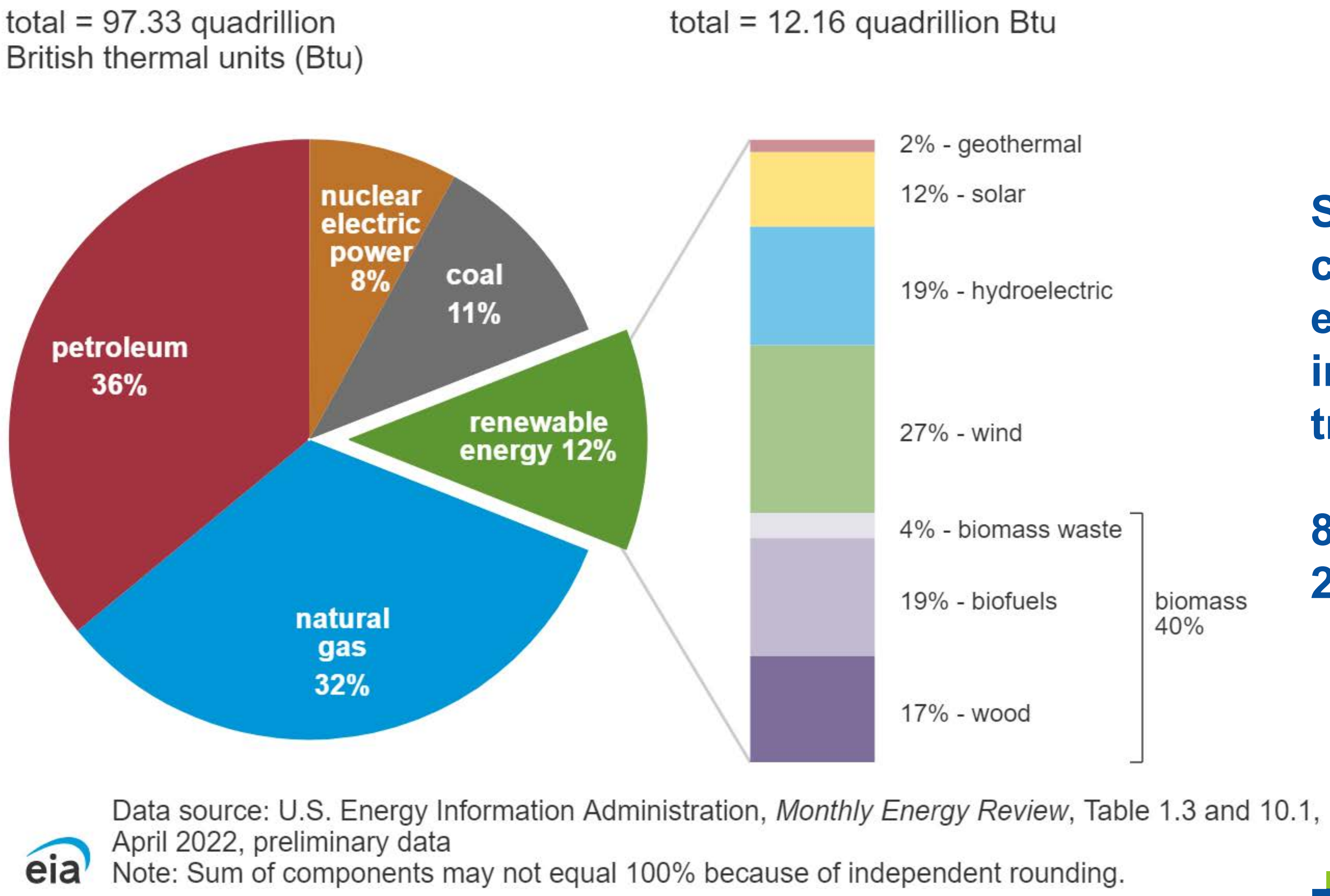
The U.S. achieved a record of 41% electricity from low-carbon sources in 2022—with the remainder from natural gas and coal.

More than $1 trillion was invested in the global energy sector in 2022, with $141 billion of that being spent in the U.S.



Data available at: https://www.weforum.org/agenda/2023/03/us-electricity-energy-carbon-renewables/

U.S. primary energy consumption by energy source, 2021



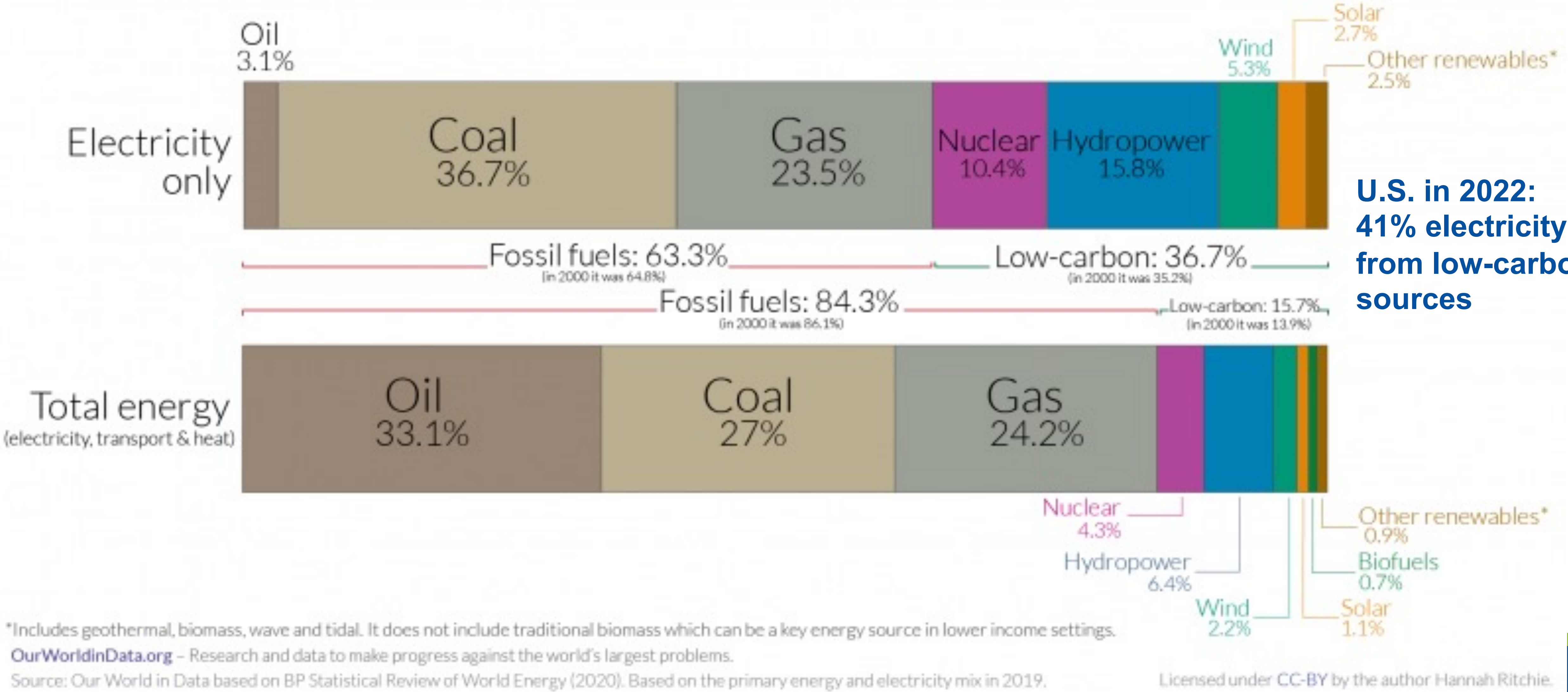
Summary of total energy consumption, including electricity, heating, industry, and transportation.

80% fossil fuels
20% non-fossil sources

Summary data available at https://www.e-education.psu.edu/ebf301/node/457

The global challenge: Decarbonizing electricity and total energy sources

(Data shown for 2019)



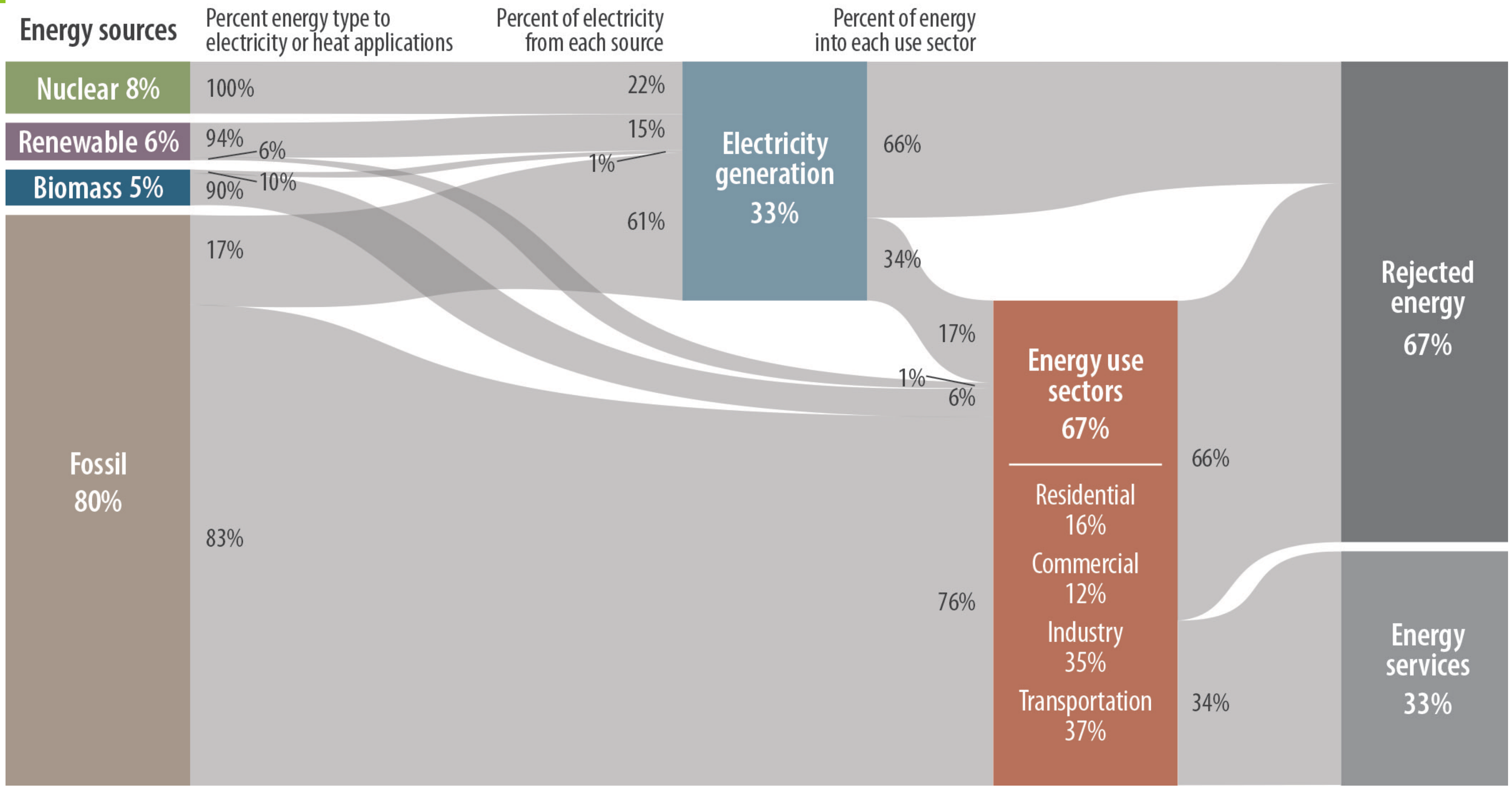
U.S. in 2022: 41% electricity from low-carbon sources

Today's electricity grid

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

We must consider the role(s) of all clean energy generation options as we look to future solutions to sustainably support growing energy demands— and we must look to non-emitting sources of heat in addition to electricity.

2018 energy sources and consumers, U.S.



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/

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.

The U.S. Department of Energy is doubling down on the commitment to clean energy

- *Energy Earthshots™ will accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. They will drive the major innovation breakthroughs that we know we must achieve to solve the climate crisis, reach our 2050 net-zero carbon goals, and create the jobs of the new clean energy economy.* (*https://www.energy.gov/policy/energy-earthshots-initiative*)

Hydrogen Shot ← **Goal: <$1/kg clean H_2 by 2031**
Clean H_2: <4 kg CO_2/kg H_2

Long Duration Storage Shot

Carbon Negative Shot

Enhanced Geothermal Shot

Floating Offshore Wind Shot

Goal: 85% lower industrial GHG emissions by 2035 → Industrial Heat Shot

Clean Fuels & Products Shot ← **Goal: >85% reduction in GHG emissions by 2035**

ENERGY earthshots U.S. DEPARTMENT OF ENERGY

Key challenges to deep decarbonization

- Providing clean, non-emitting electricity on a dispatchable basis

- Replacing the high-quality heat that is currently provided by fossil fuels

- Developing a non-emitting source for a key energy carrier (i.e., hydrogen) that can support applications across all energy use sectors

→Nuclear energy can meet these challenges!

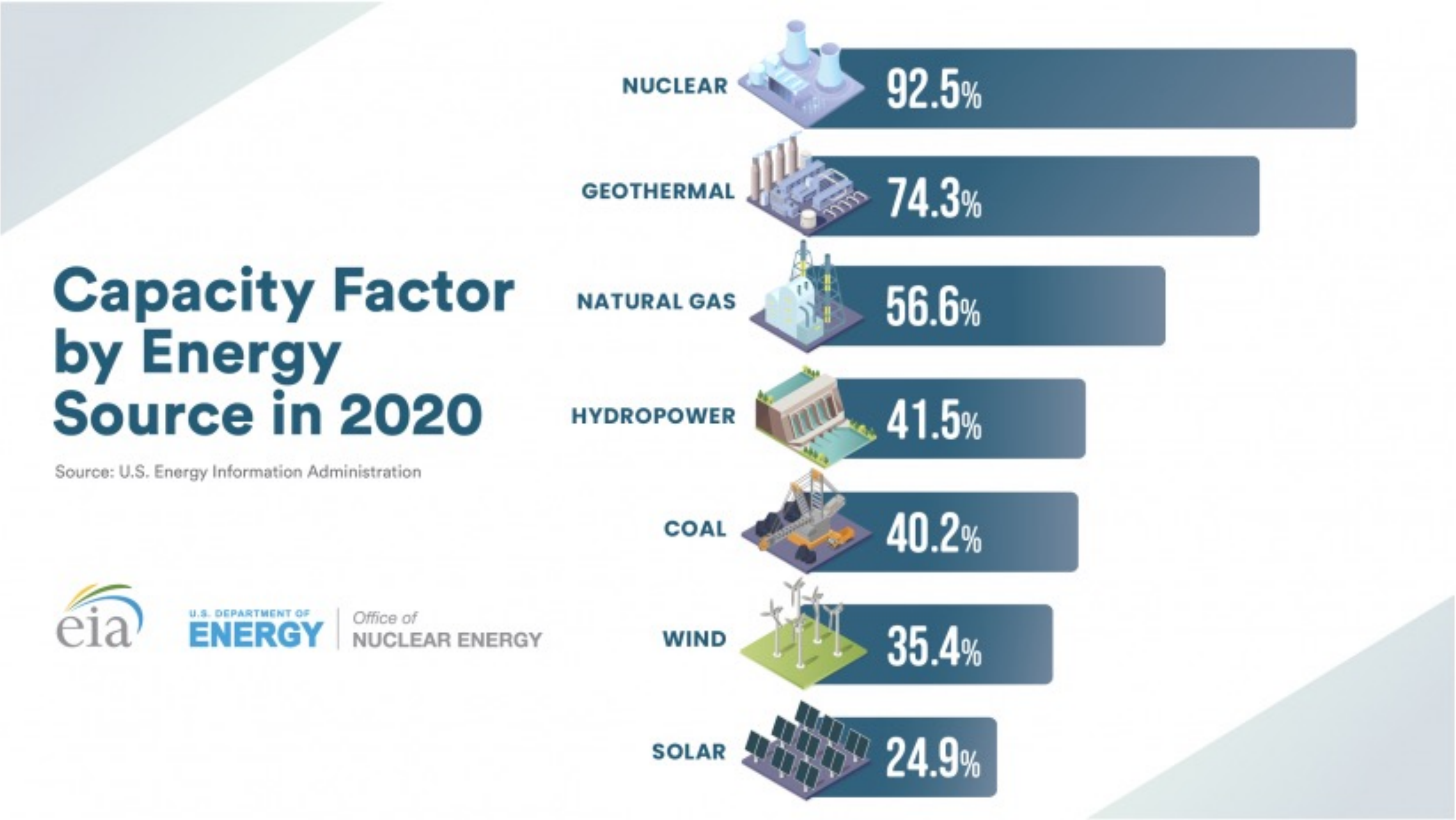
What is the status of nuclear energy?

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

- 93 operating reactors at 54 nuclear power plants in 28 states
- Water-cooled
- 18-24 month refueling cycle
- Built in the 1950s-80s, Plant Vogtle Unit 3 just added to the grid
- Reliable baseload electricity for the grid
- Large scale, ~1,000 MWe
- Custom built on site, ~1500 acres
- Emergency zone, 10 miles
- Fleet-wide capacity factor >93% (2021)

Applications:
Baseload electricity; 24/7

Nuclear energy is the workhorse of the U.S. grid

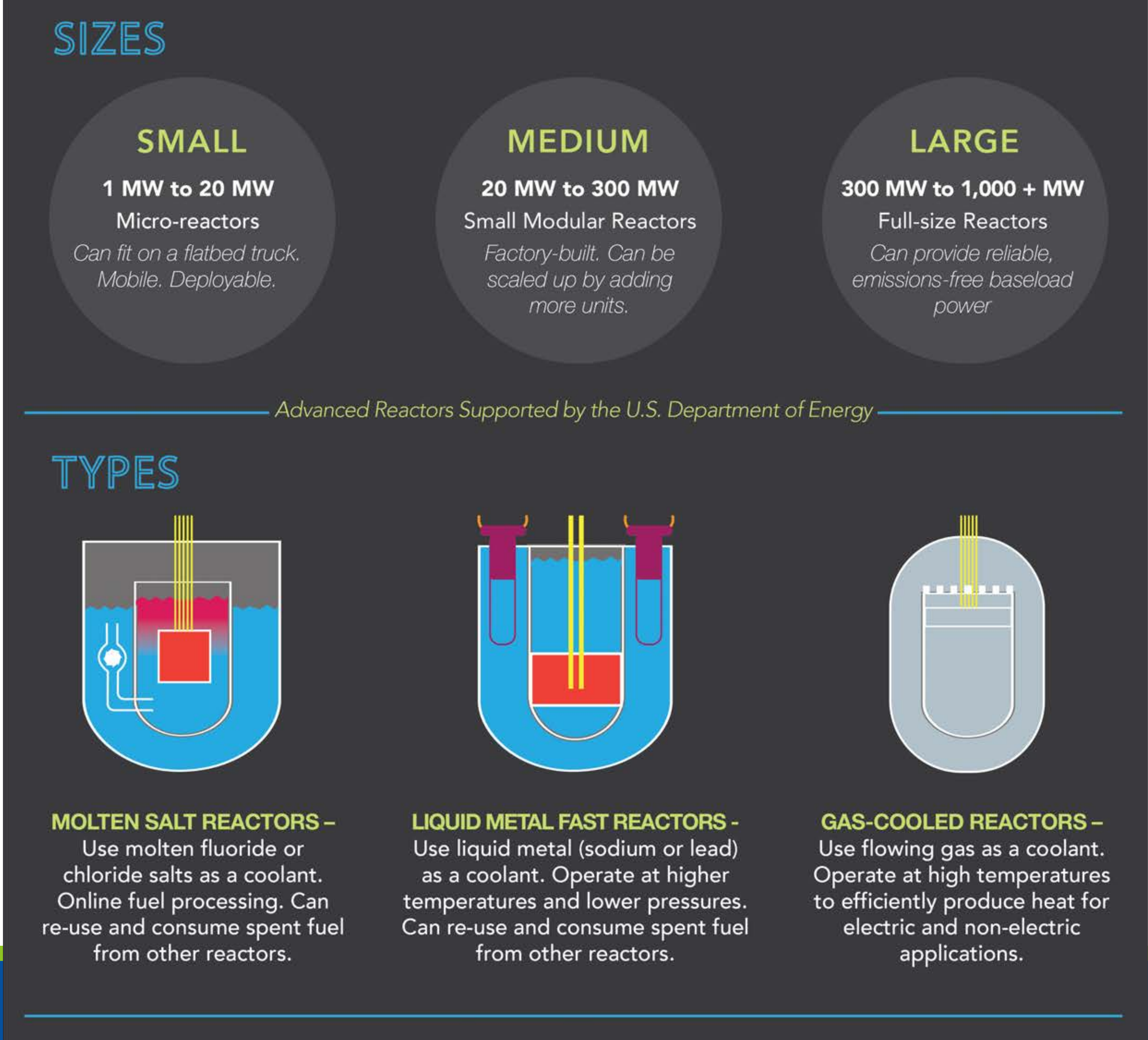


Advanced Reactor Design Concepts

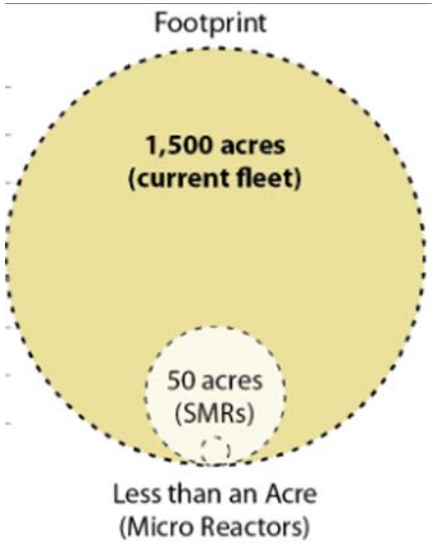
Key Benefits

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

70+ private sector designs under development



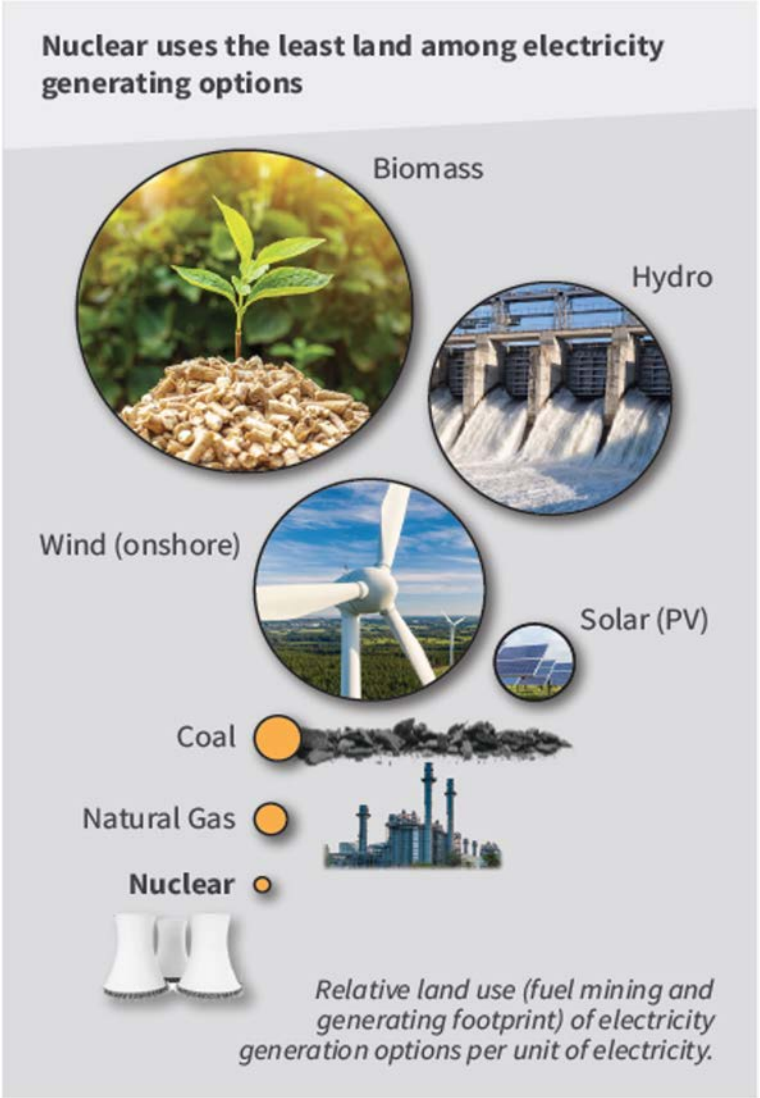
Deployment flexibility



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.

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

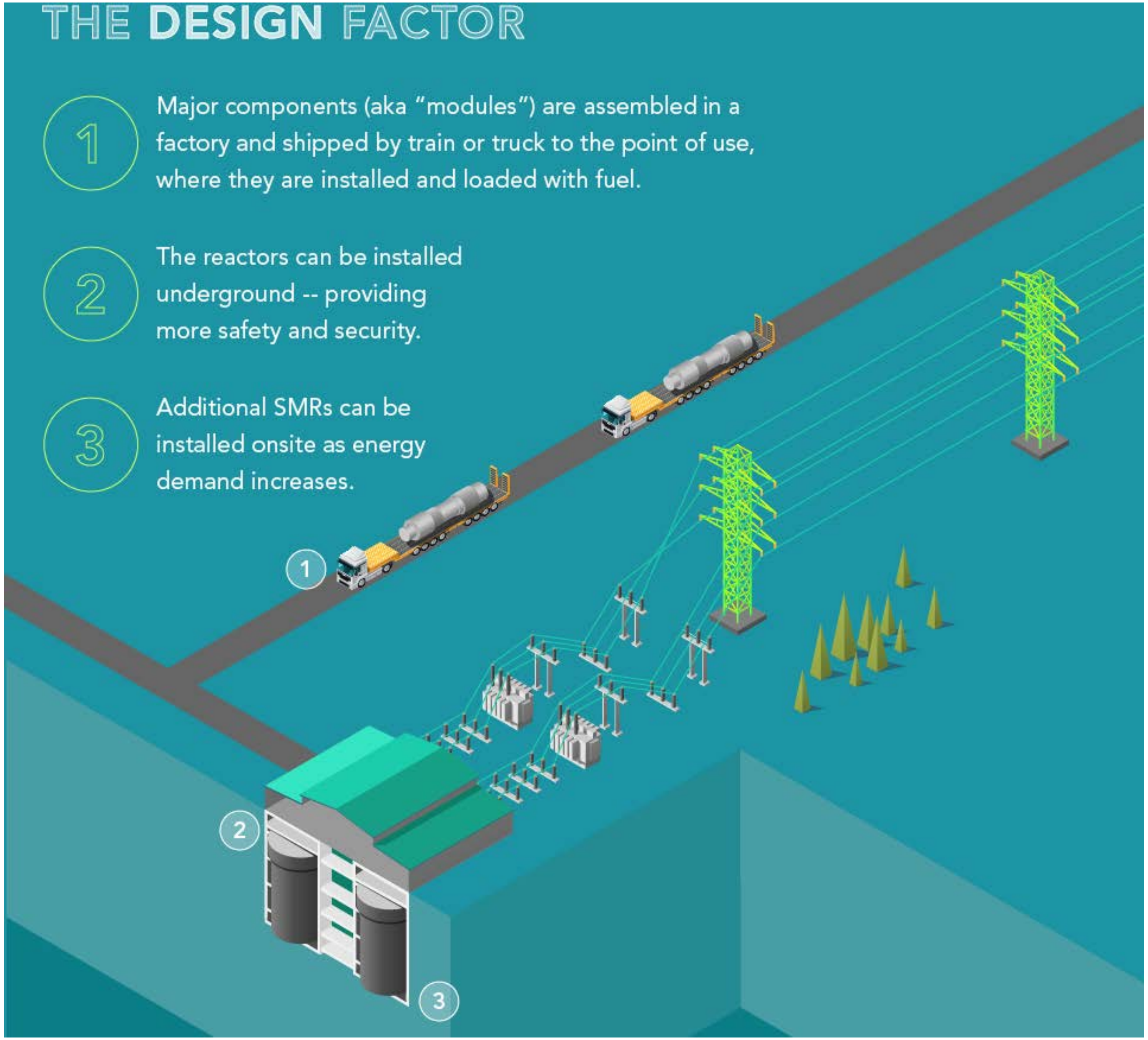
IES Integrated Energy Systems



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

Small modular reactors

- ~50-300 MWe
- Less site preparation
- Factory built, assembled on site
- Flexible operation (electricity, heat, steam)
- More deployment options
- Scalable—add modules as demand increases
- Passive, physics-based safety
- Emergency zone ~0.2 mi
- Opens up new business opportunities



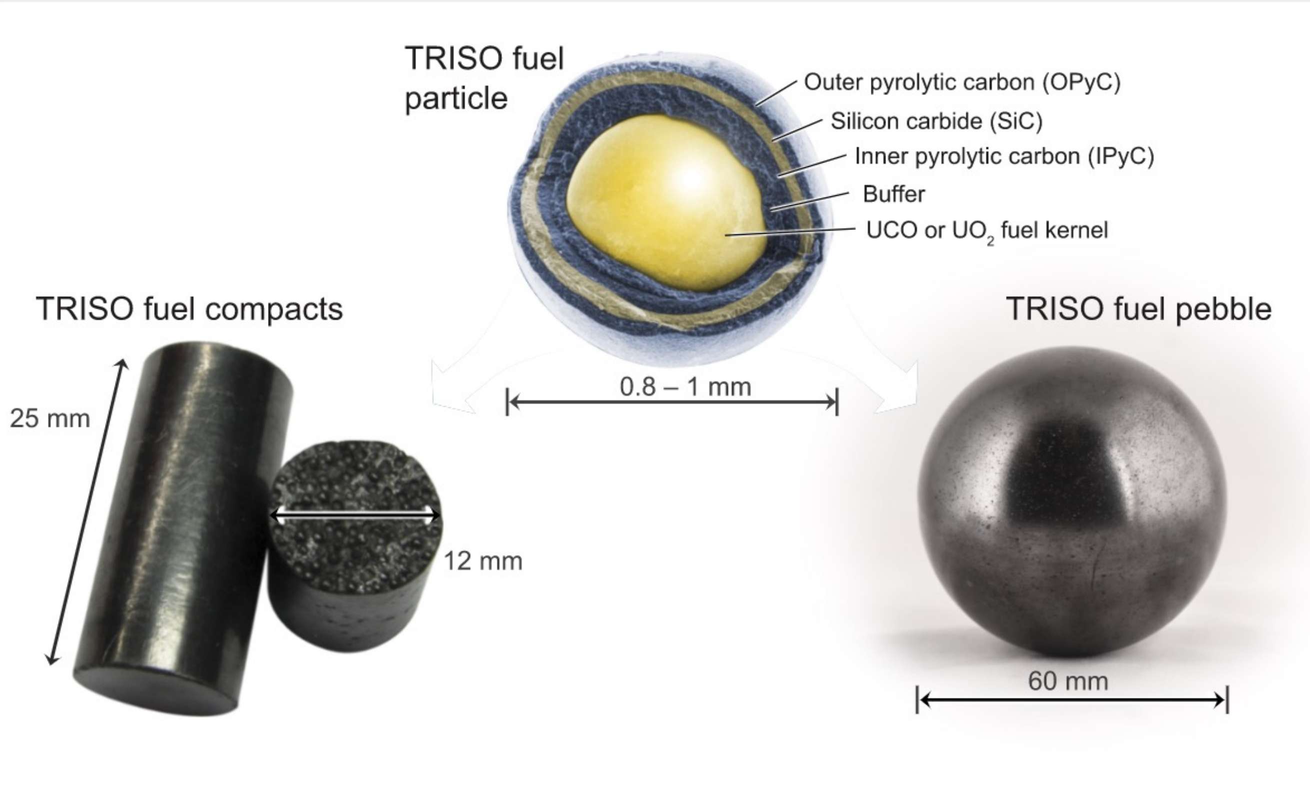
Microreactors

- Simple design
- <20 MWe, compact size
- Minimal site preparation
- Factory fabricated, assembled
- Fast on-site installation
- Flexible operation (electricity, heat, steam)
- Scalable—add modules as demand increases
- Passive, physics-based safety
- Emergency zone <1 acre
- Provide energy to remote locations
- Long core lifetime (5-20 yrs)

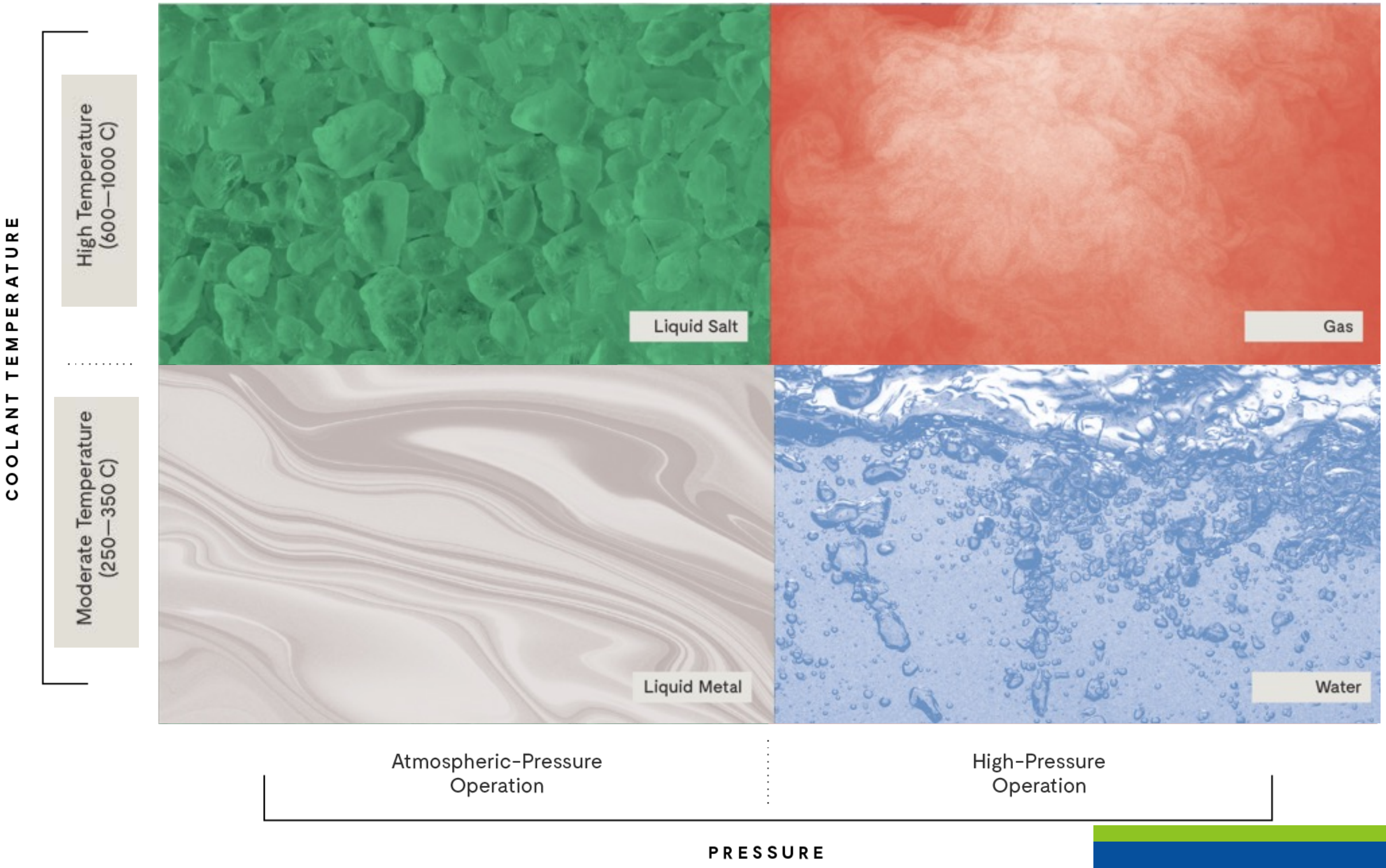
Advanced Safety Approaches

- "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

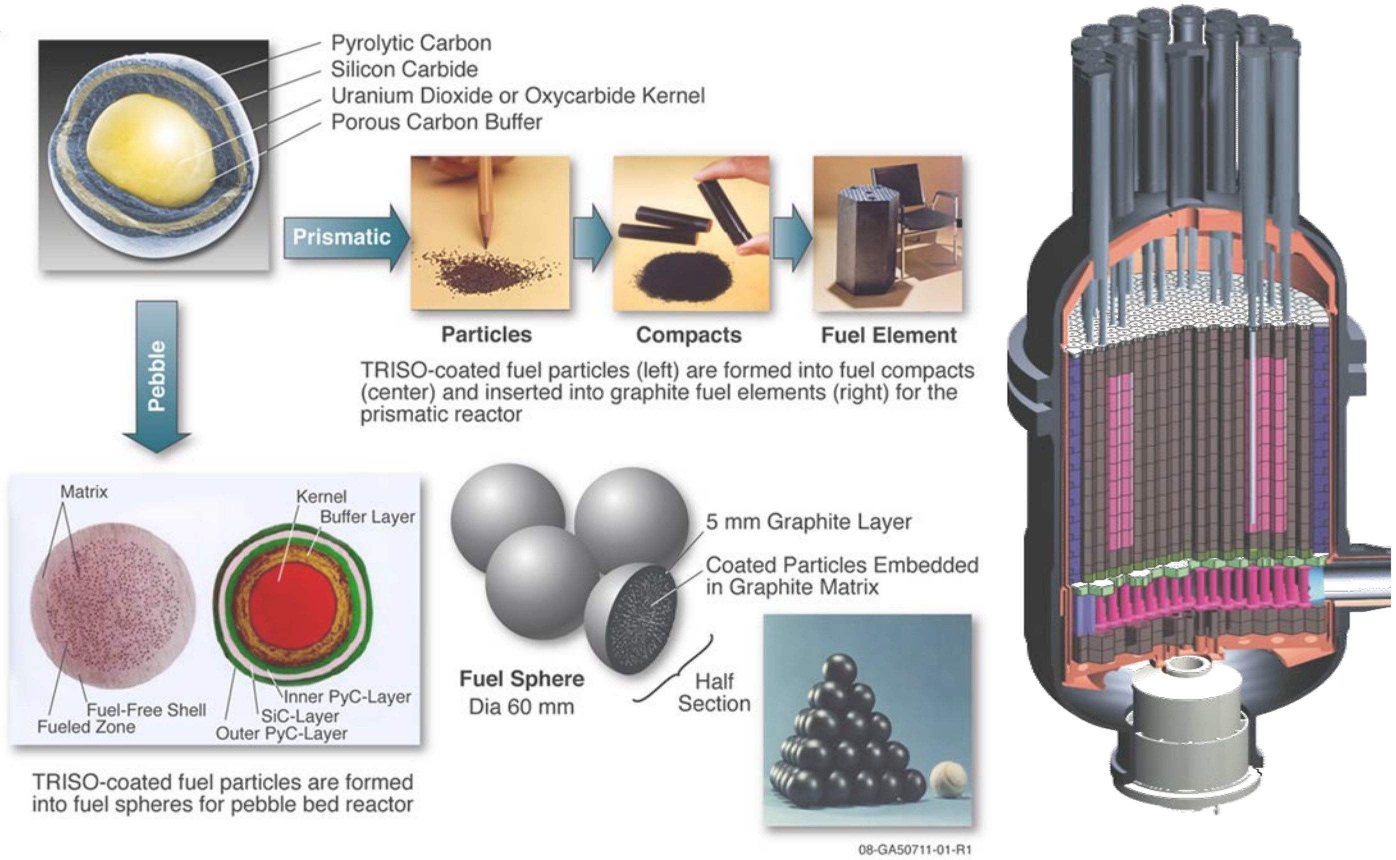


Reactor Coolant Choices



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°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

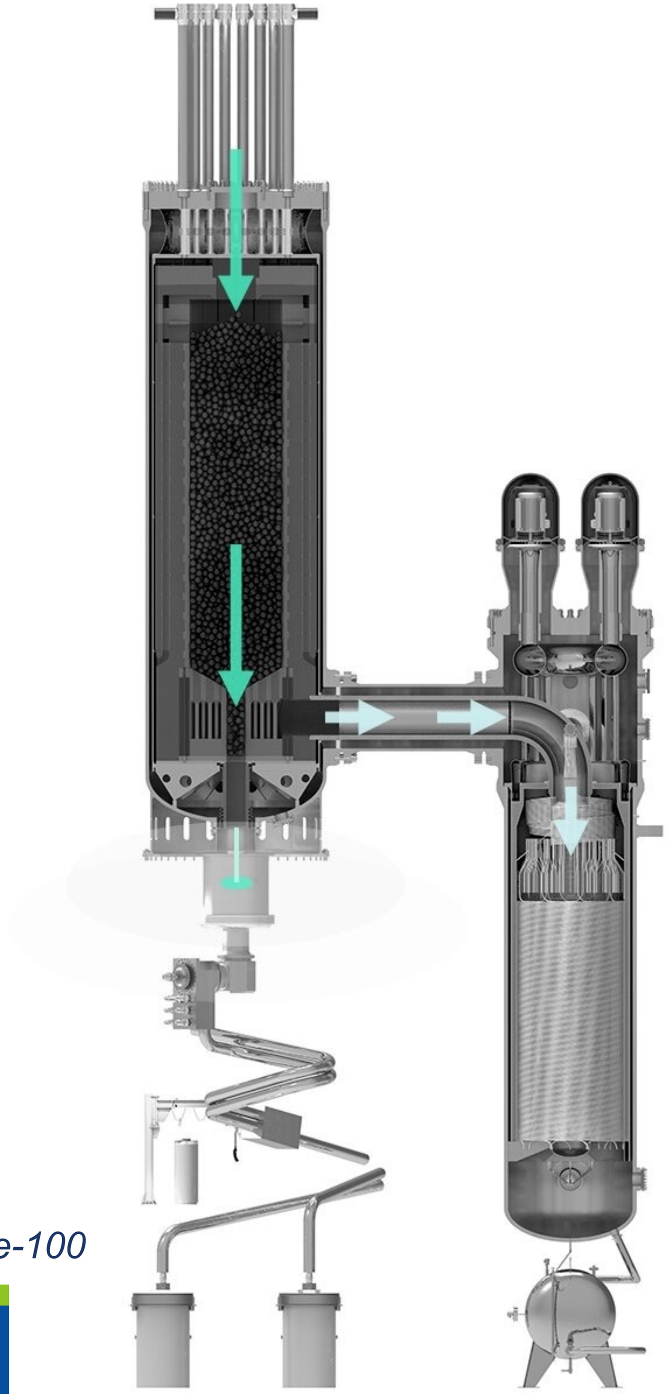
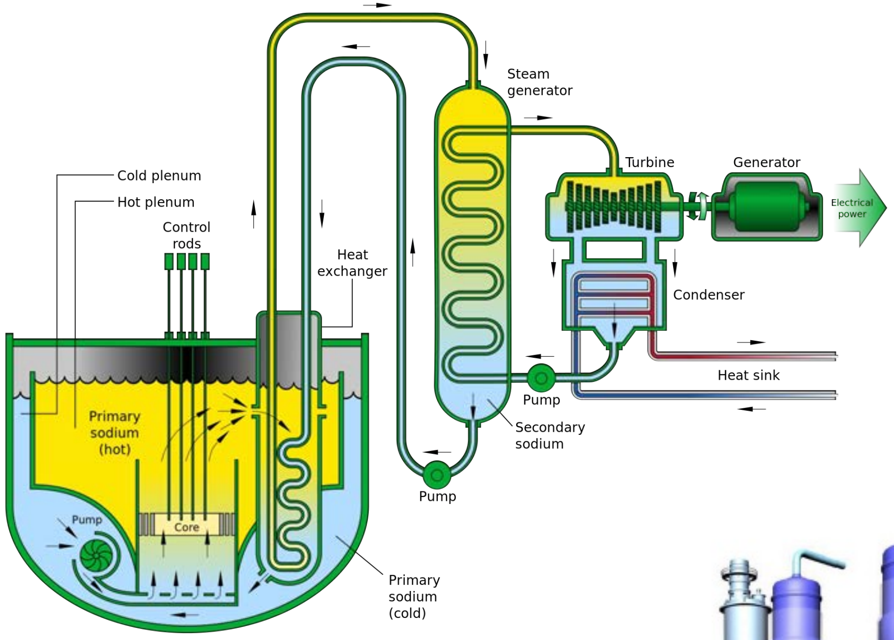
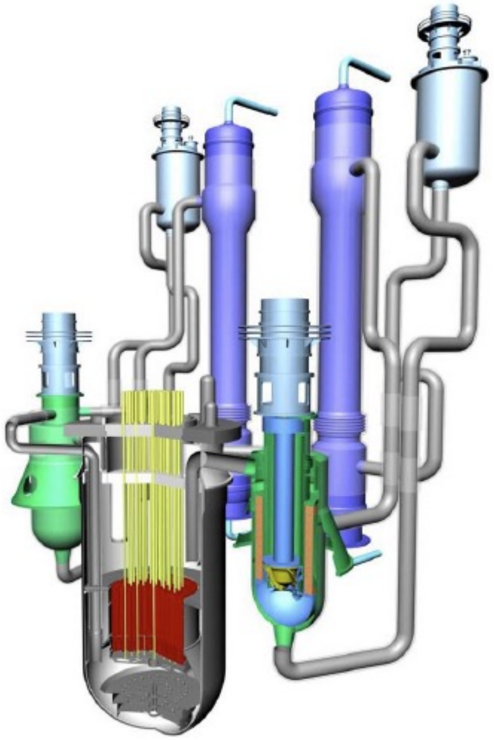


Image source: X-energy.com/reactors/xe-100

Liquid Metal Fast Reactor





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

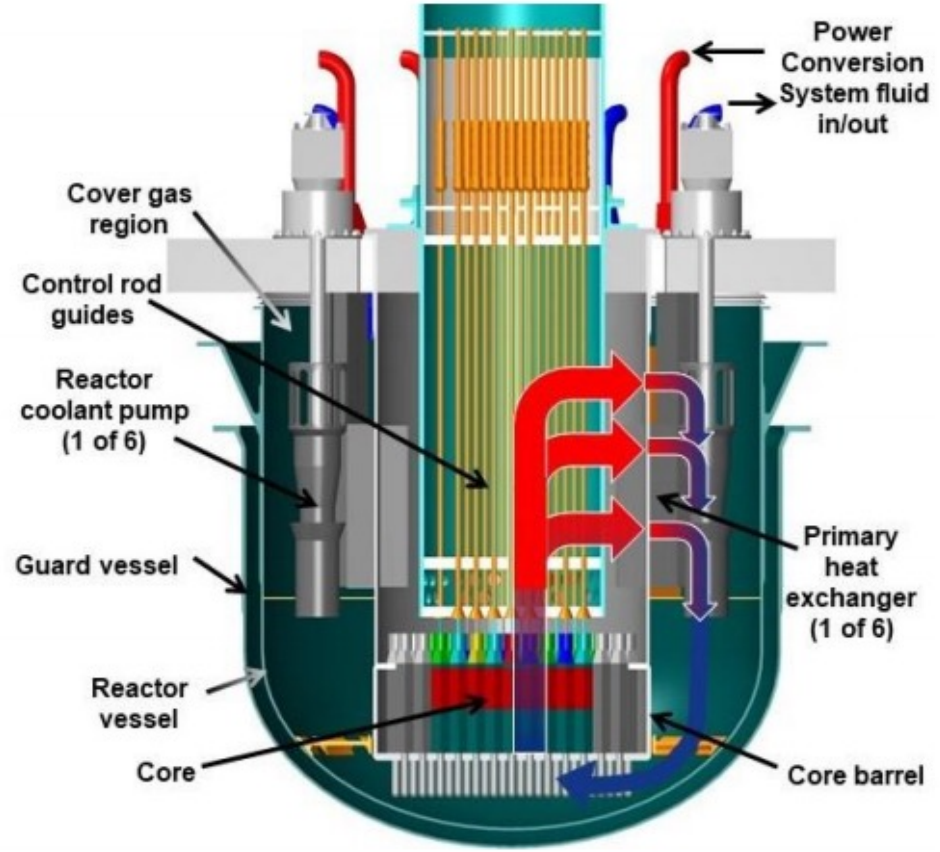
- Liquid metals as a primary coolant, allow higher power density
- Leading coolants considered in the U.S. include sodium, lead
  - Sodium: Chemically reactive w/water, air; SS compatible
  - Lead: Non-reactive w/water, air; corrosive
  - Coolant temperature ~550^{o}C
  - Operate near atmospheric pressure
- 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
- ~500ºC 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



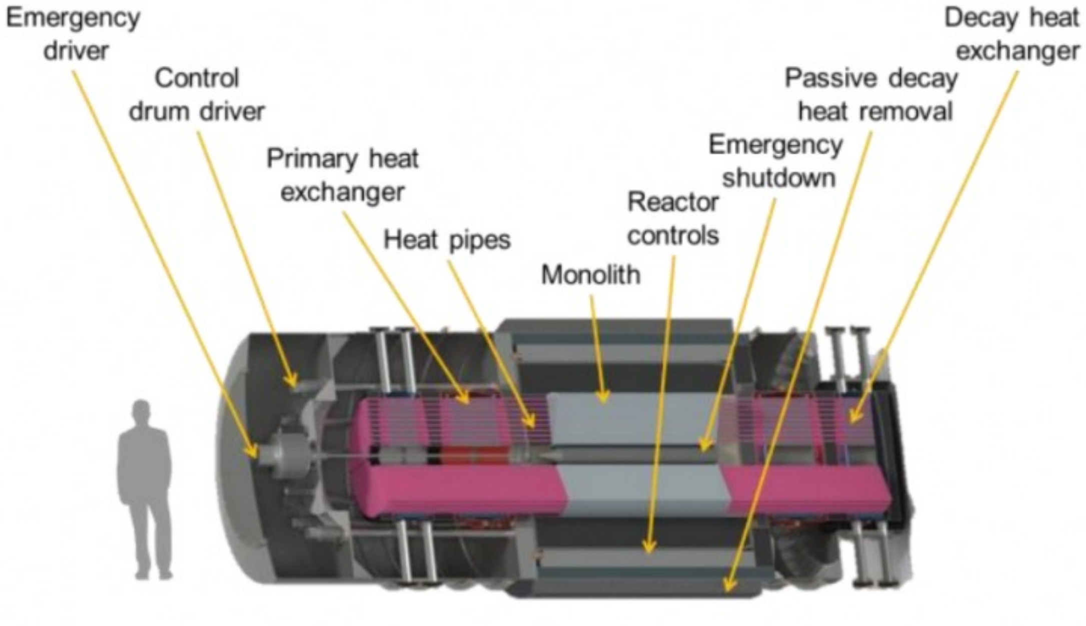
- 450 MWe, lead-cooled
- Passively safe, compact, scalable
- Flexible output, support for non-electric applications
- Could incorporate thermal energy storage
- sCO_2 Brayton cycle
- Potential use of Westinghouse EnCore Fuel (advanced technology/accident-tolerant fuel)
  - Chromium-coated fuel cladding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

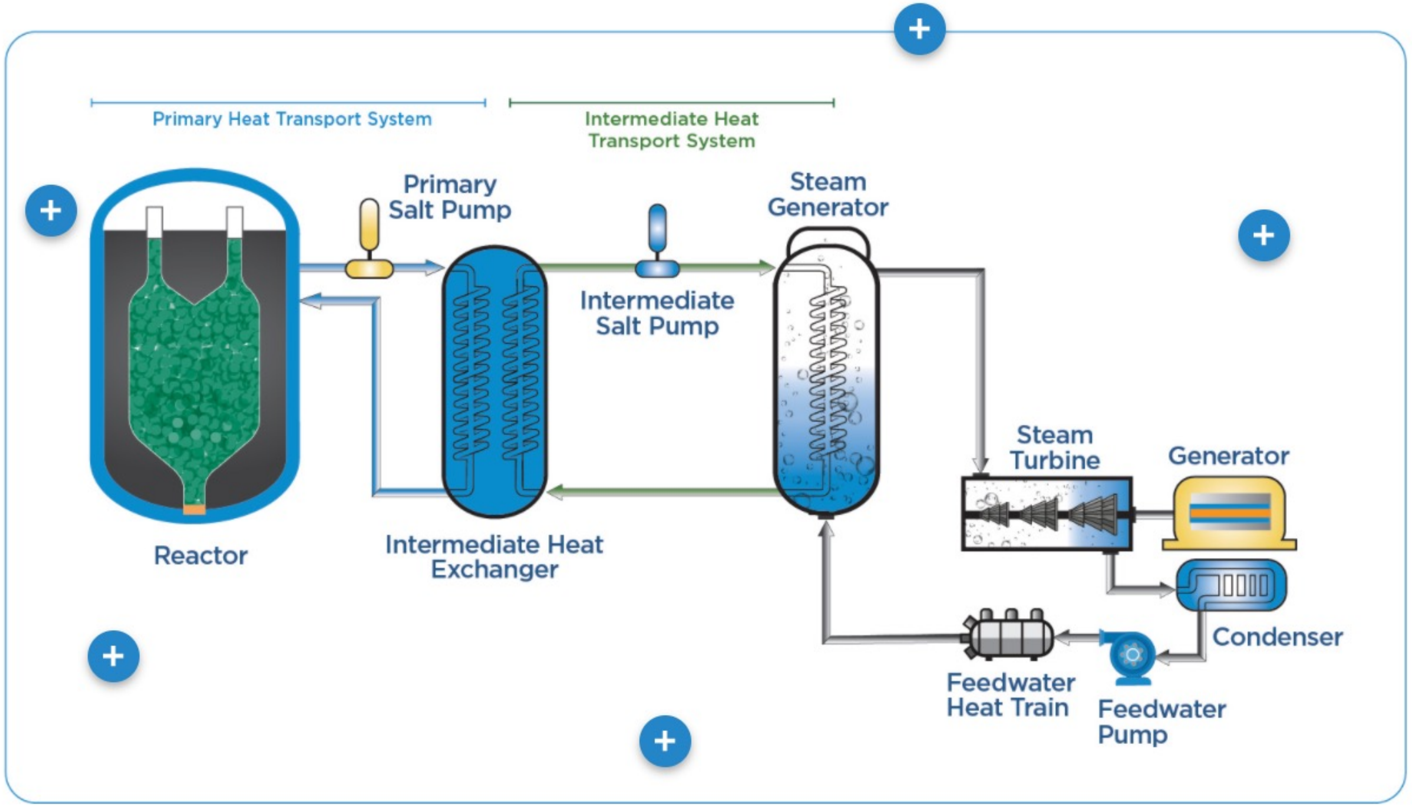


Image reference: Kairos Power, https://kairospower.com/technology/

Example: TerraPower Molten Chloride Fast Reactor (liquid fuel)

- 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

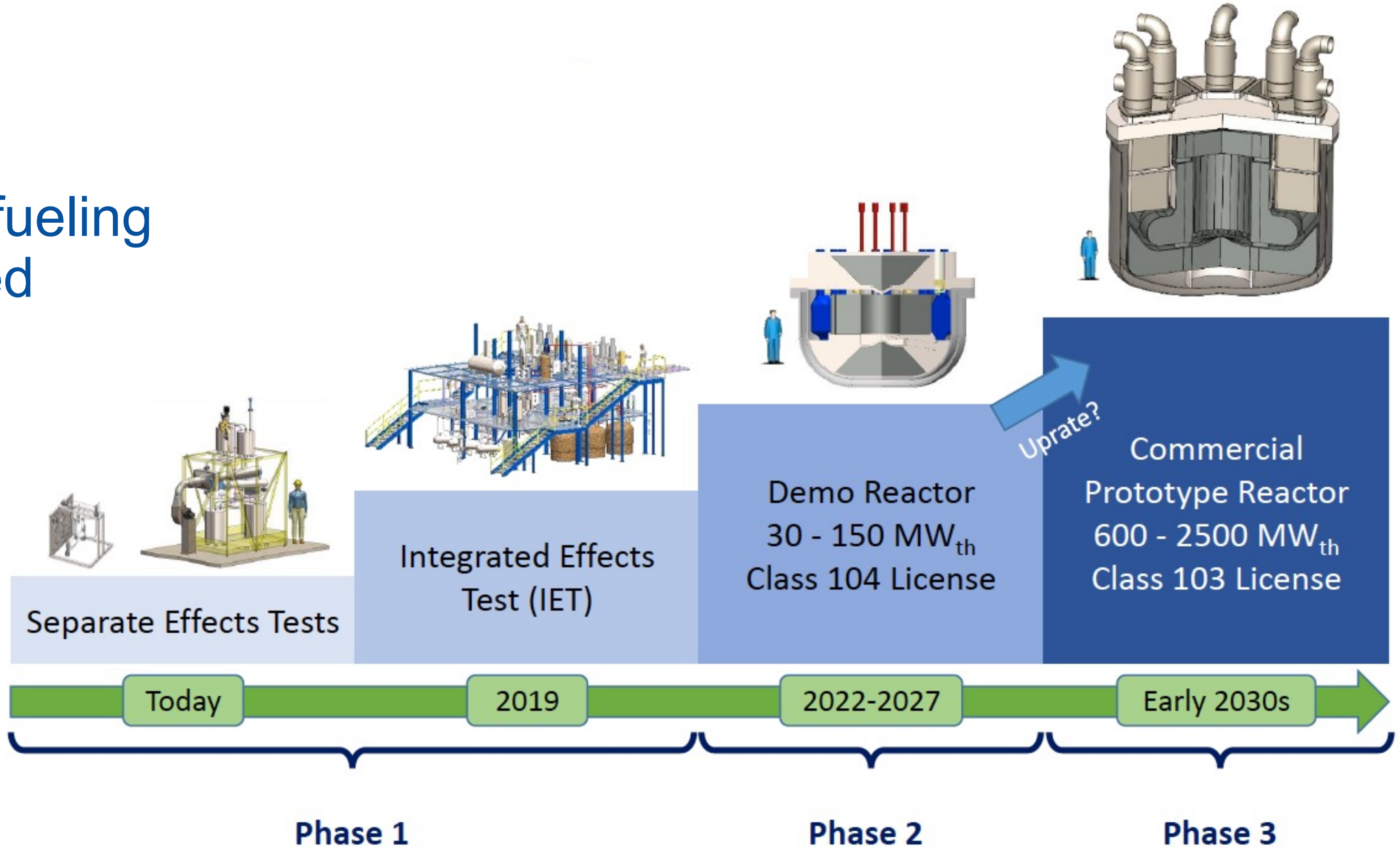
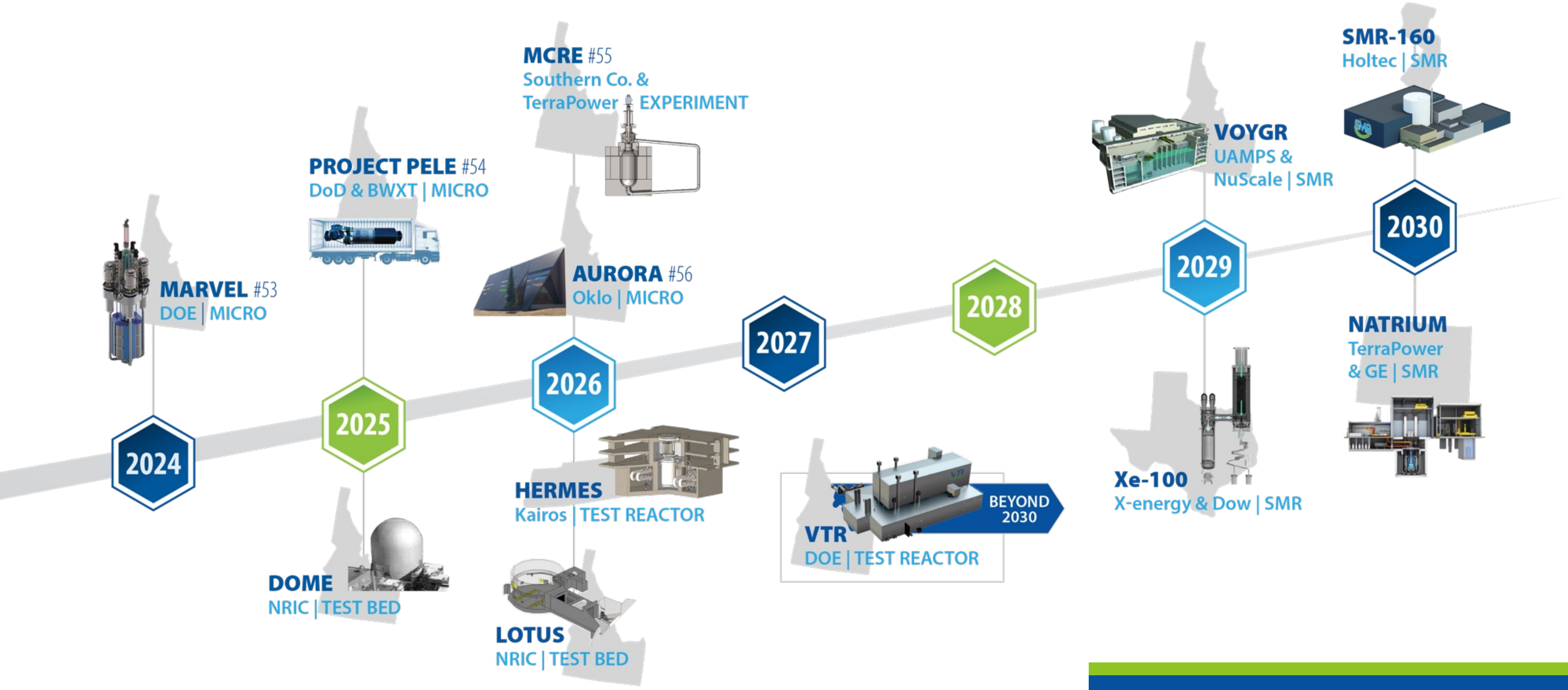


Image source:
K. Kramer, 2018 ETEC Nuclear Suppliers Workshop,
DOI: 10.13140/RG.2.2.18467.09768

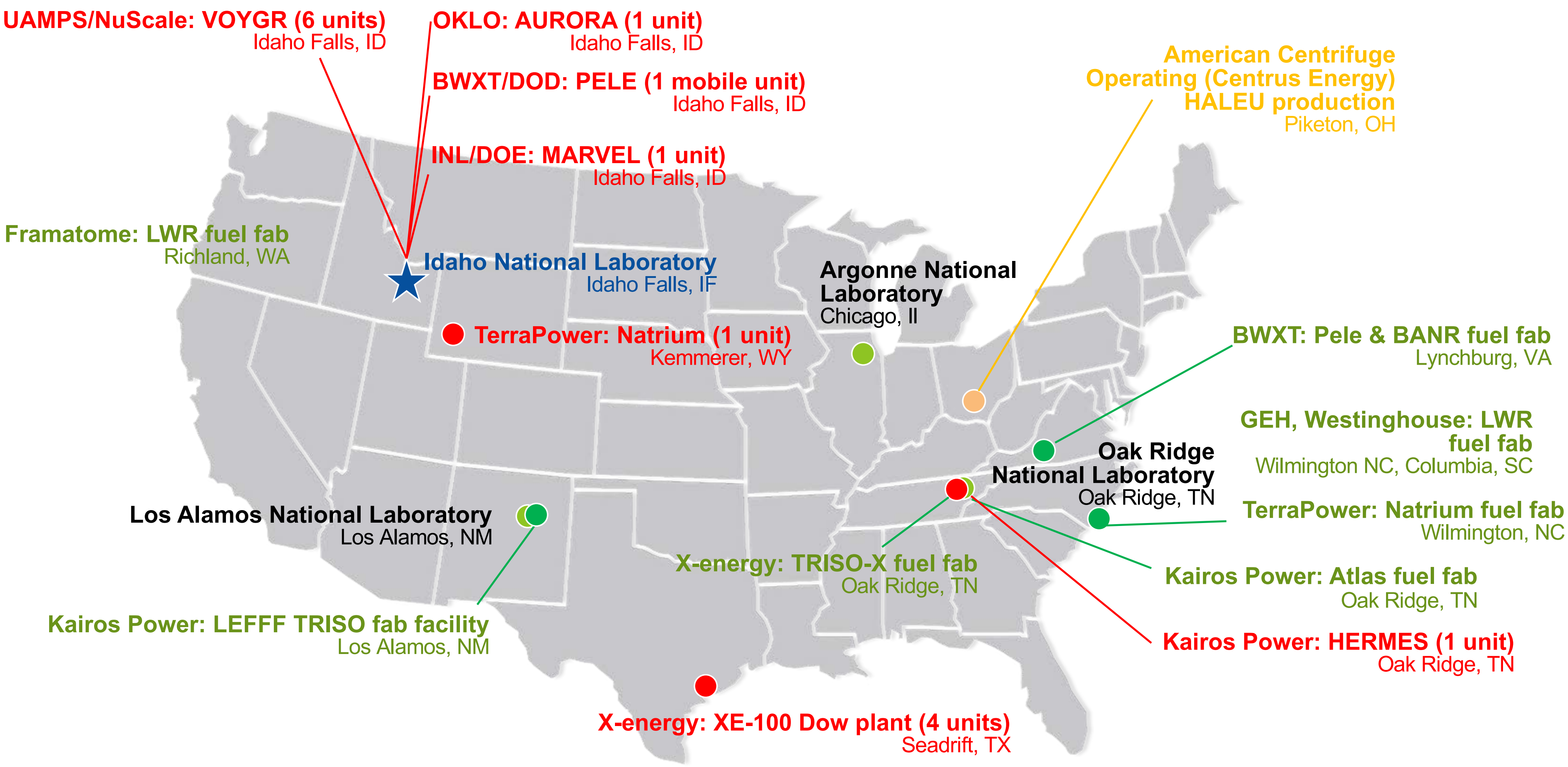
US DOE Advanced Reactor Demonstration Program

- 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

Accelerating advanced reactor demonstration & deployment



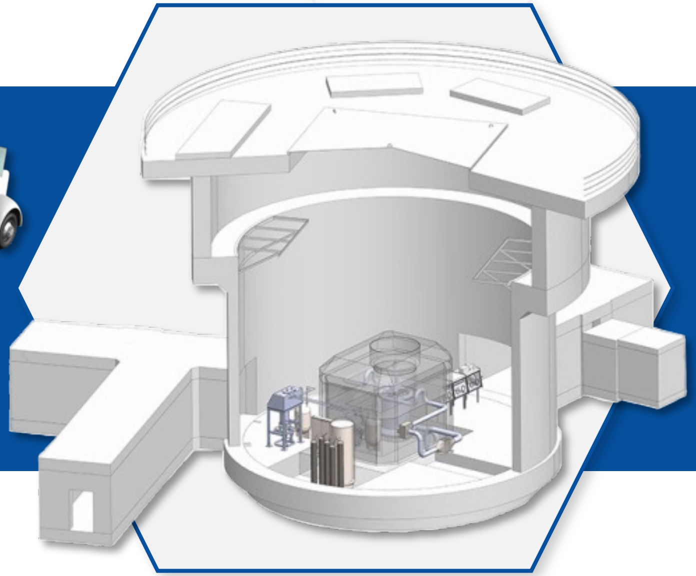
Advanced reactor projects and fuel fabrication facilities



Over the next three years, we will demonstrate the first new reactors on the INL site in over 40 years

Microreactor Application Research, Validation and EvaLuation Project
(MARVEL)

Department of Defense Strategic Capabilities Office Project Pele

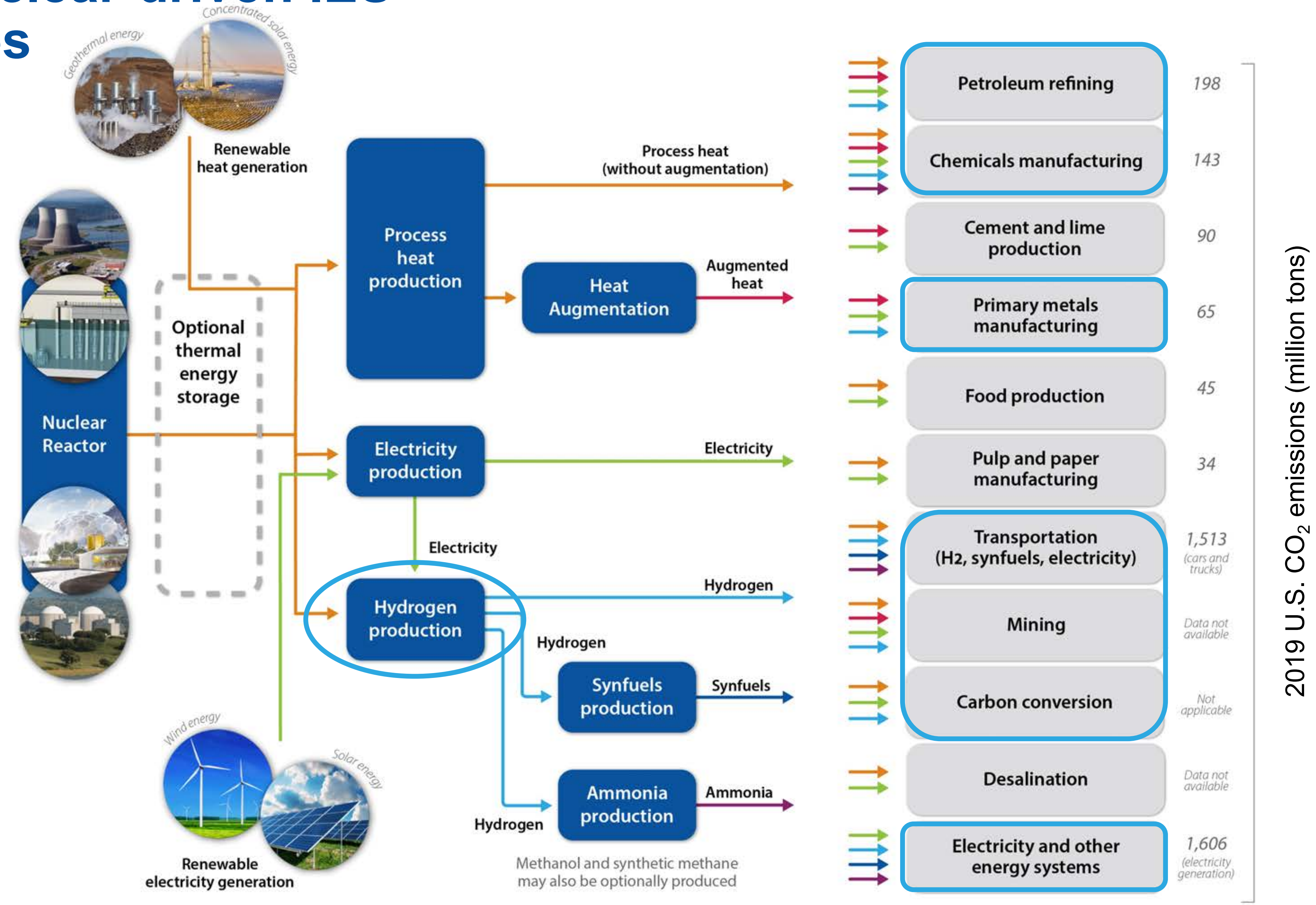


Molten Chloride Fast Reactor Experiment
(MCRE)

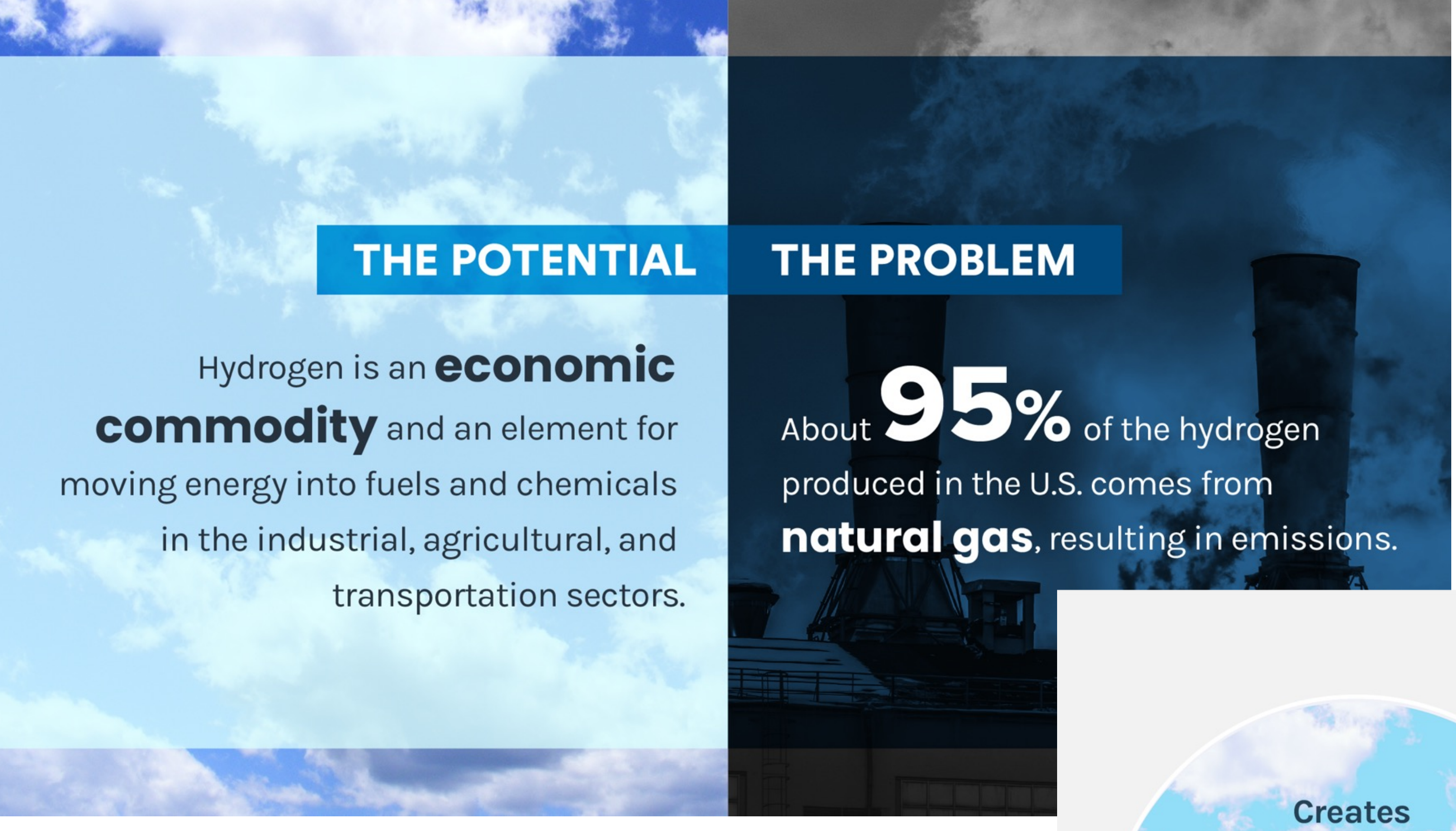
Using more of our clean energy options: Energy systems integration

Potential nuclear-driven IES opportunities

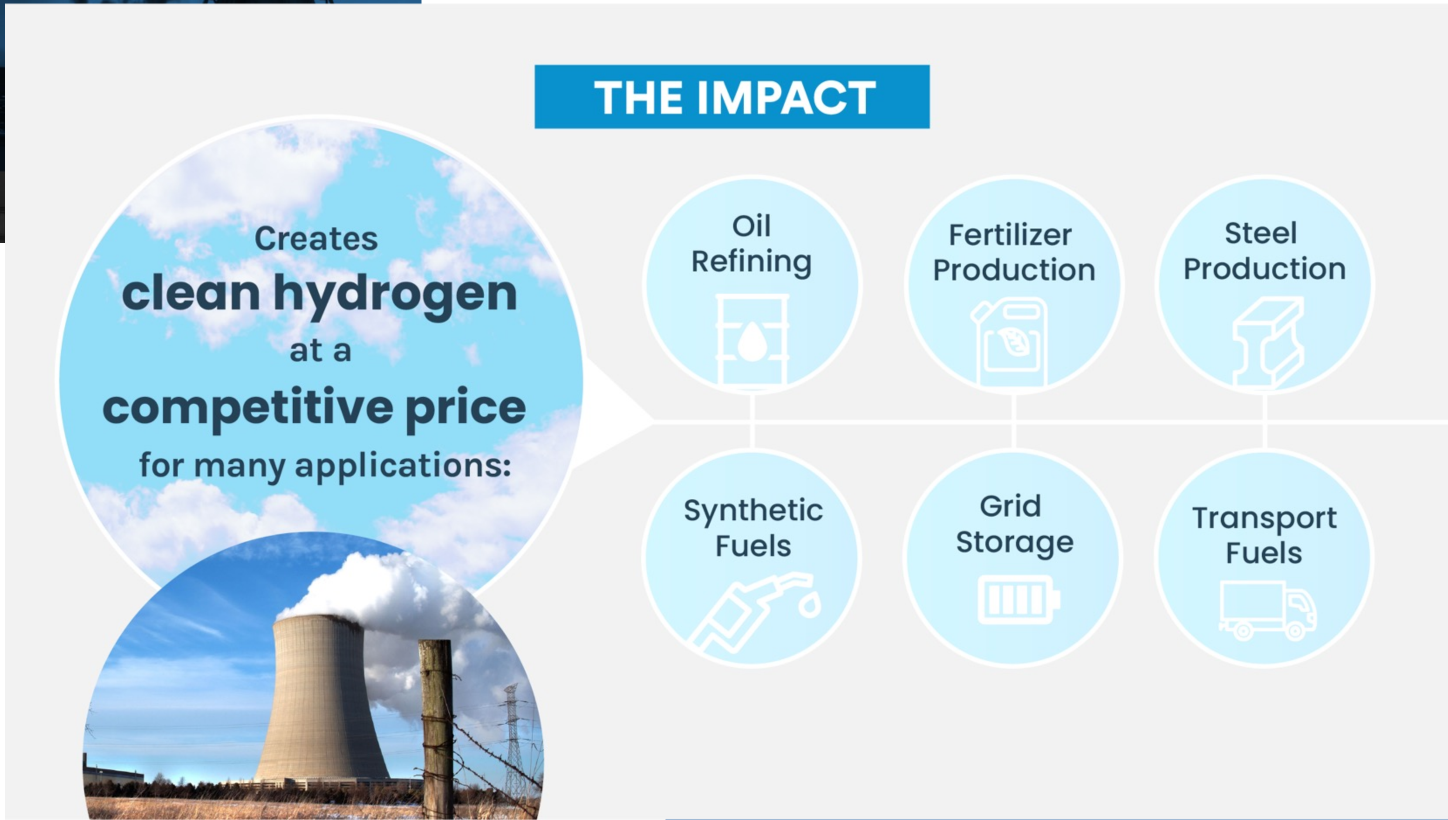
Reactor sizes align with the needs of each application; heat augmentation can be applied if needed to match process temperature demands.



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

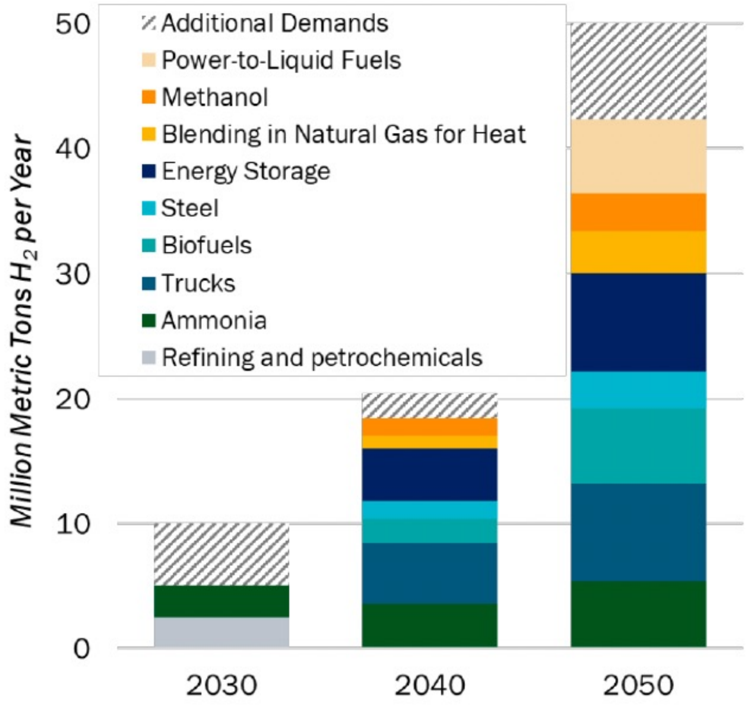


Why focus on hydrogen?



National clean H_2 strategy—The opportunity for clean H_2

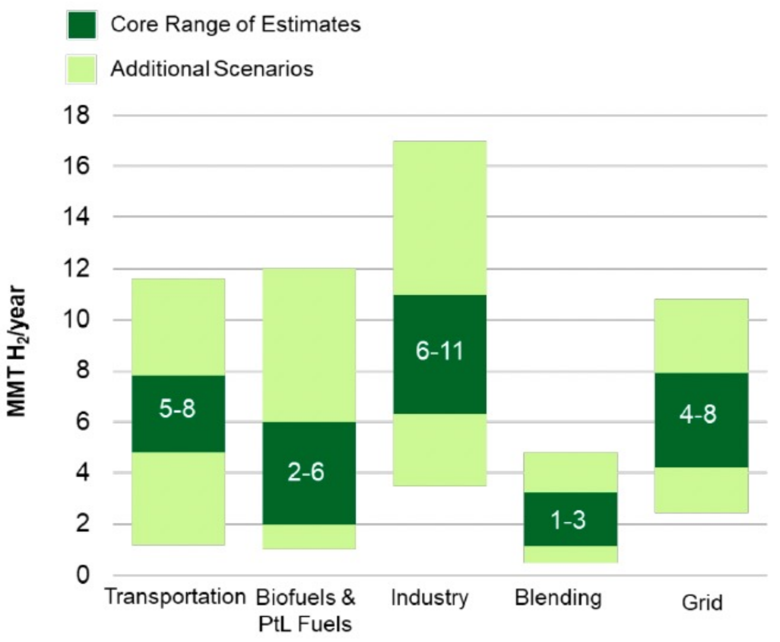
Opportunities for Clean Hydrogen Across Applications



Clean Hydrogen Use Scenarios

- Catalyze clean H_2 use in existing industries (ammonia, refineries), initiate new use (e.g., sustainable aviation fuels (SAFs), steel, potential exports)
- Scale up for heavy-duty transport, industry, and energy storage
- Market expansion across sectors for strategic, high-impact uses

Range of Potential Demand for Clean Hydrogen by 2050



- **Core range: ~ 18–36 MMT H_2**
- **Higher range: ~ 36–56 MMT H_2**

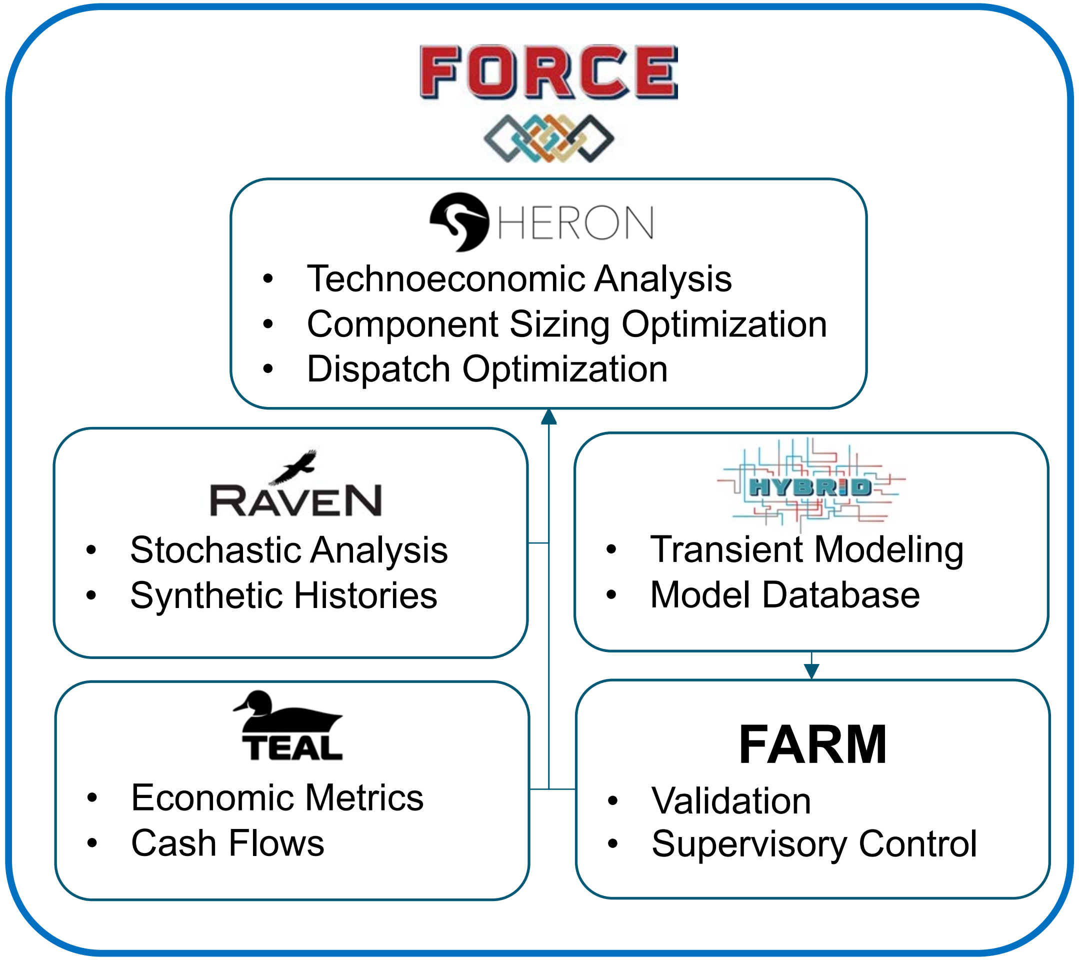
Refs: 1. NREL MDHD analysis using TEMPO model; 2. Analysis of biofuel pathways from NREL; 3. Synfuels analysis based off H2@Scale ; 4. Steel and ammonia demand estimates based off DOE Industrial Decarbonization Roadmap and H2@Scale. Methanol demands based off IRENA and IEA estimates; 5. Preliminary Analysis, NREL 100% Clean Grid Study; 6. DOE Solar Futures Study; 7. Princeton Net Zero America Study

U.S. Opportunity:
10MMT/yr by 2030, 20 MMT/yr by 2040, 50 MMT/yr by 2050

Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023

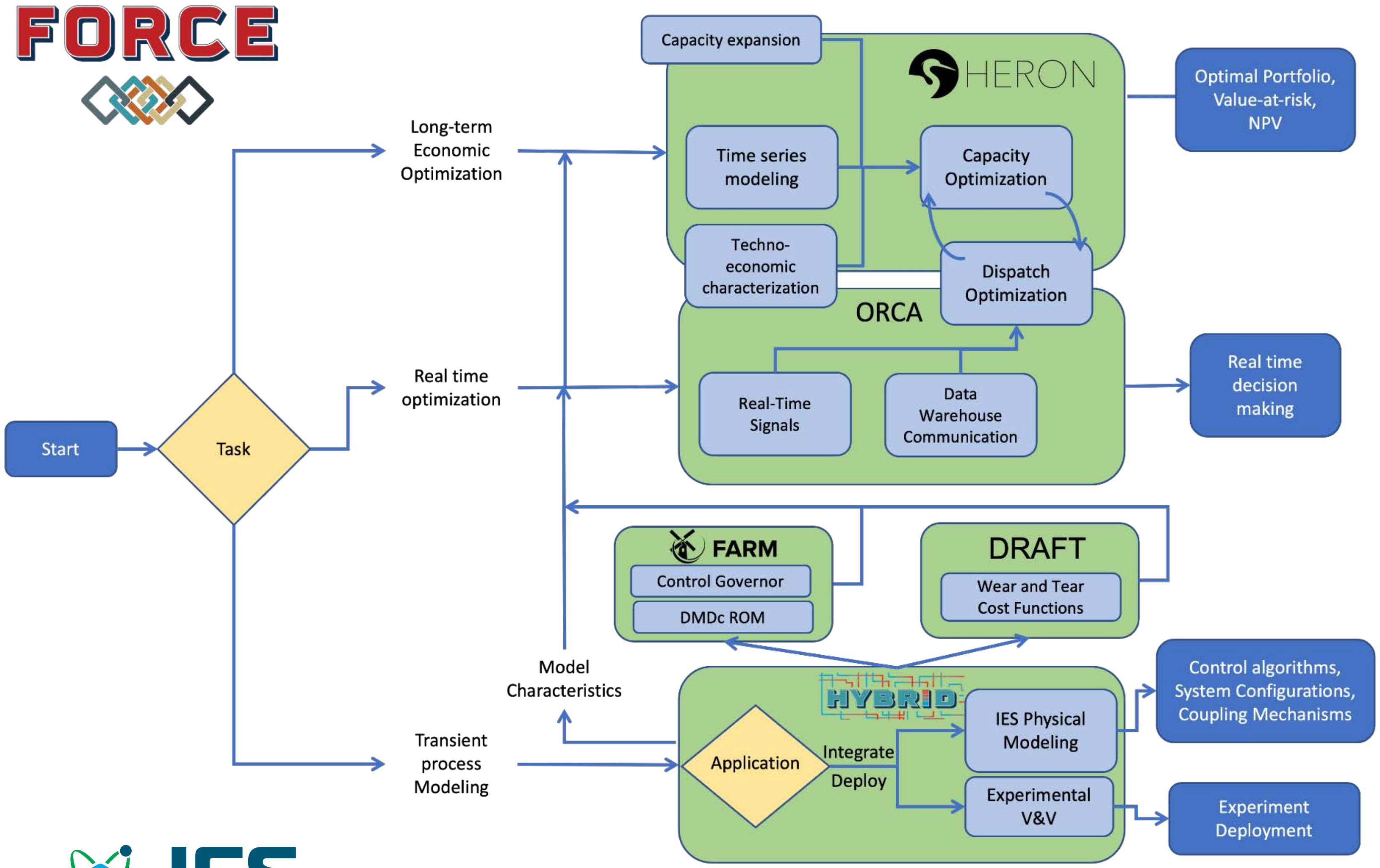
IES analysis and optimization tool suite

- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Physical process, integration modeling and safety analysis
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - Stochastic analysis, multiple commodities
  - Energy storage, various markets
  - Real-time optimization and control



For more information and to access opensource tools, see ***https://ies.inl.gov/SitePages/System_Simulation.aspx****.*
Recorded training modules can be viewed at https://ies.inl.gov/SitePages/FORCE_2022.aspx.

Software Map



How should each system be sized?

- Technical limitations
- Optimal economics
- Cross-market interaction

How will integrated systems be dispatched?

- What is optimal dispatch?

How are IES dispatched in real time?

- Can we respond to market activity?

What are heat and chemical balances for IES?

- How will IES handle transient operations?

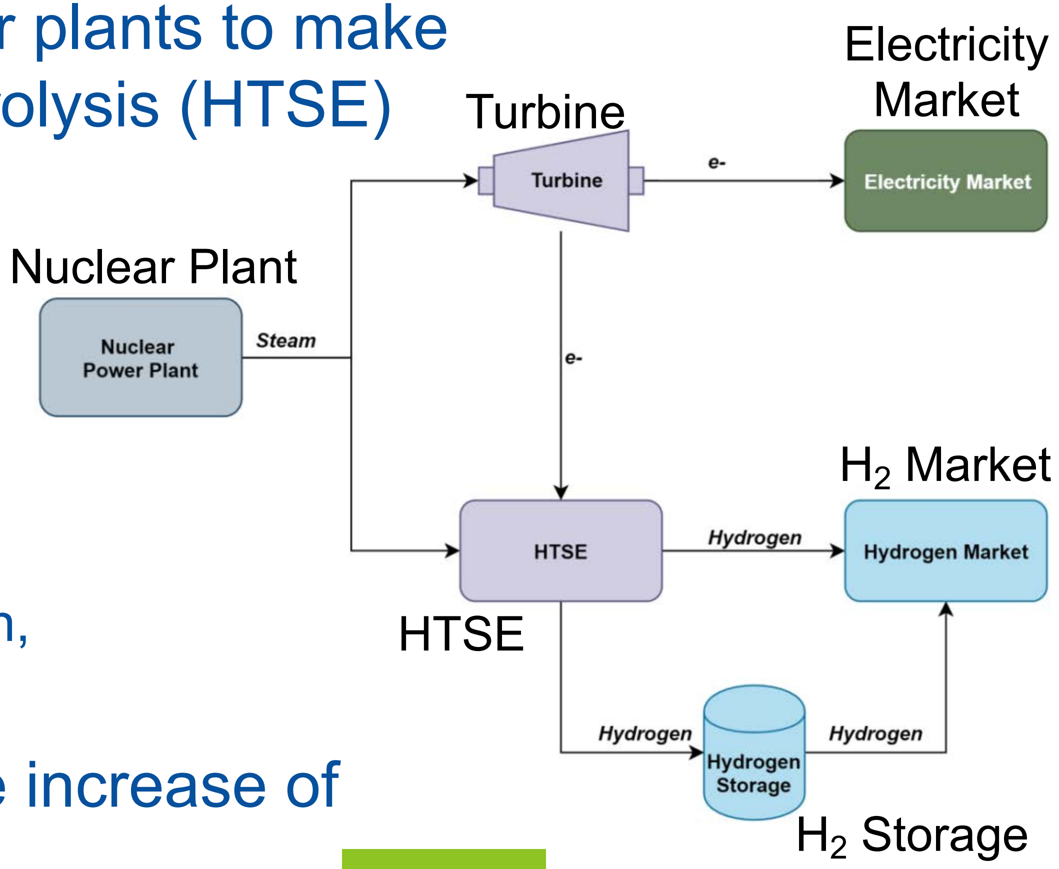
IES Integrated Energy Systems

A variety of detailed dynamic models are available for use

- Reactor technologies
  - 4-loop PWR
  - Small modular IPWR
  - Small modular natural circulation IPWR
  - High temperature gas-cooled reactor
  - Sodium fast reactor
  - Molten-salt cooled reactor (in development)
- Energy storage
  - Solid media thermal energy storage (TES)
  - 2-tank TES
  - Thermocline TES
  - Latent heat TES
  - Compressed air
  - Li-ion battery
- Energy use technologies
  - Reverse osmosis desalination
  - High T steam electrolysis (HTSE) for H_2 prod
  - HTSE "experimental"
  - Single-stage balance of plant
  - Two-stage balance of plant
  - Stage-by-stage balance of plant
  - Synthetic fuel production (F-T and methanol pathways in development)
  - Carbon conversion (in development)
- Other
  - Steam manifold
  - Switchyard
  - Electric grid
  - Natural gas turbine

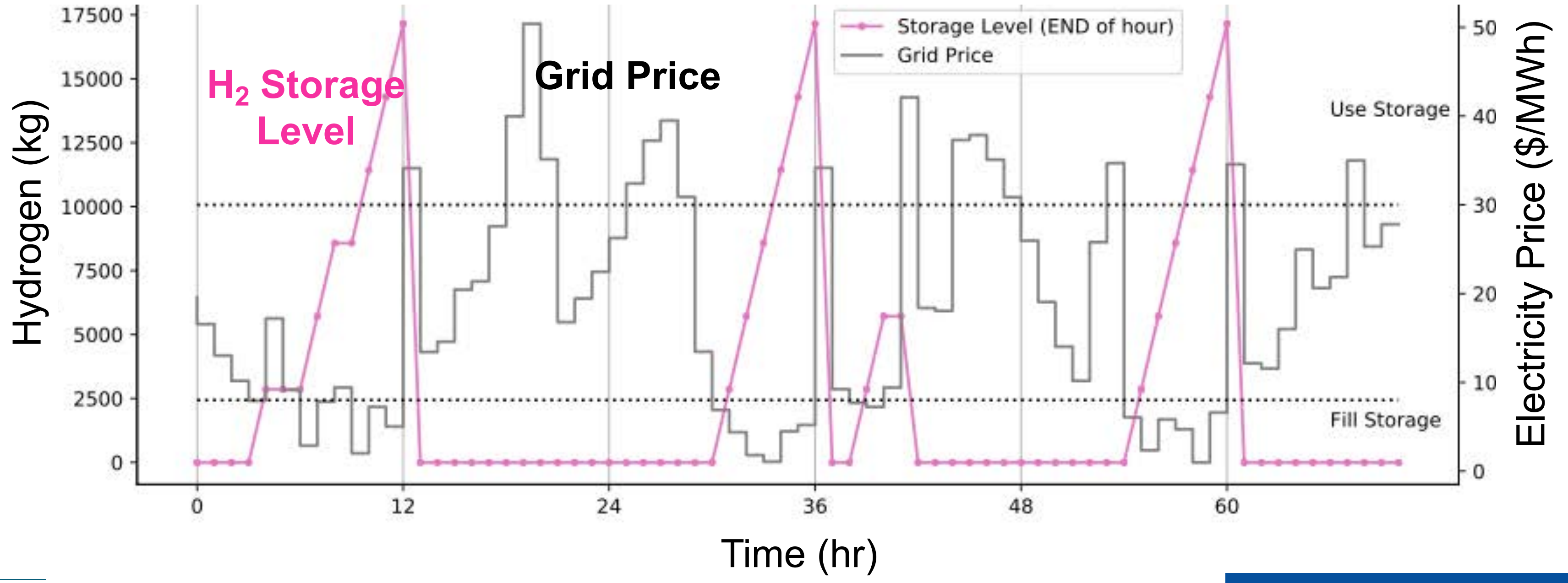
Example: Disruptive potential of nuclear produced hydrogen

- 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



Flexible hydrogen production

- 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)



IES Integrated Energy Systems

Nuclear synthetic fuels production

IES Integrated Energy Systems

- Synthetic fuels production linked to nuclear plant capacity
- Fischer-Tropsch TEA
  - LWRs
  - Different locations
  - Different CO_2 sources
- Incorporate advanced reactor designs (HTGR, SMR) in the production of synthetic fuel production using F-T process
- Next steps
  - Evaluate alternative processes for synfuel production
  - Develop models, use cases, and dynamically evaluate the Methanol-to-Diesel (MTD) process

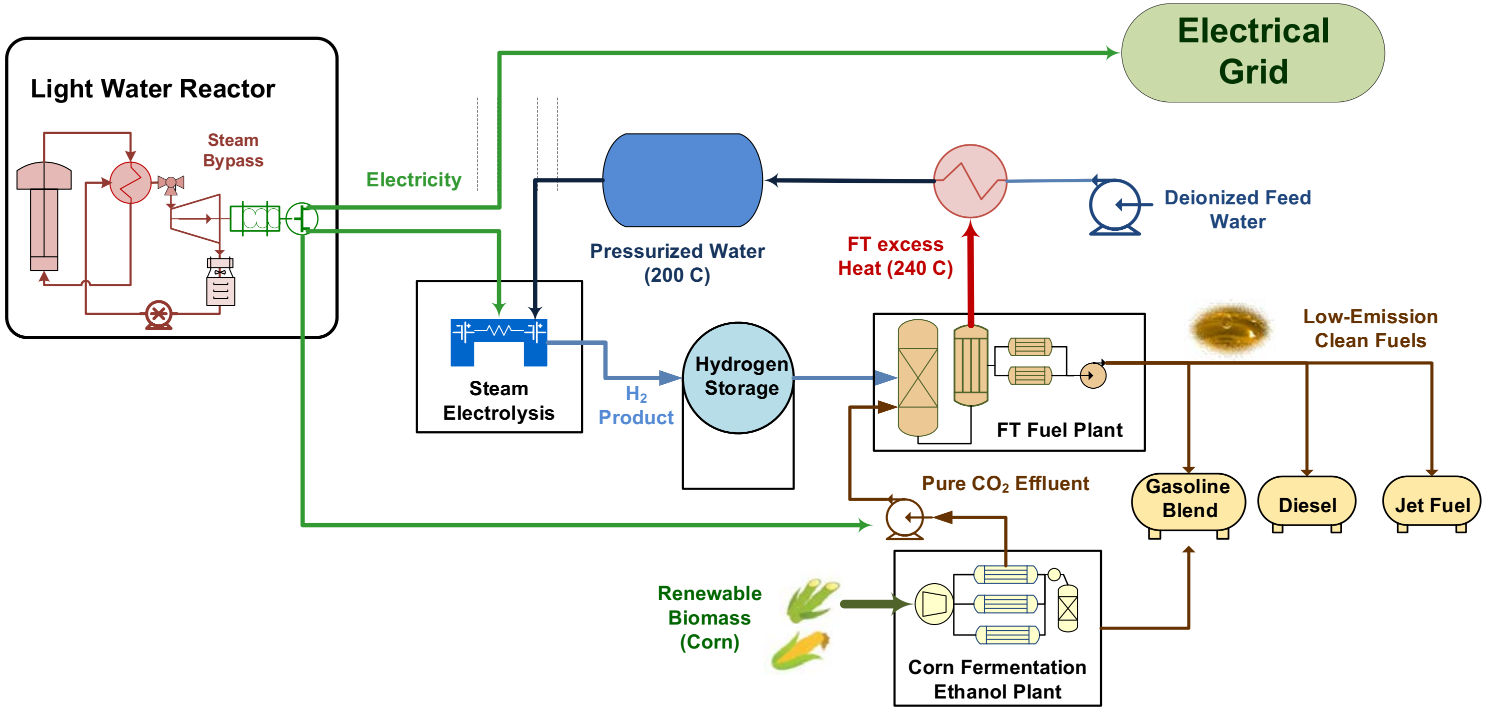
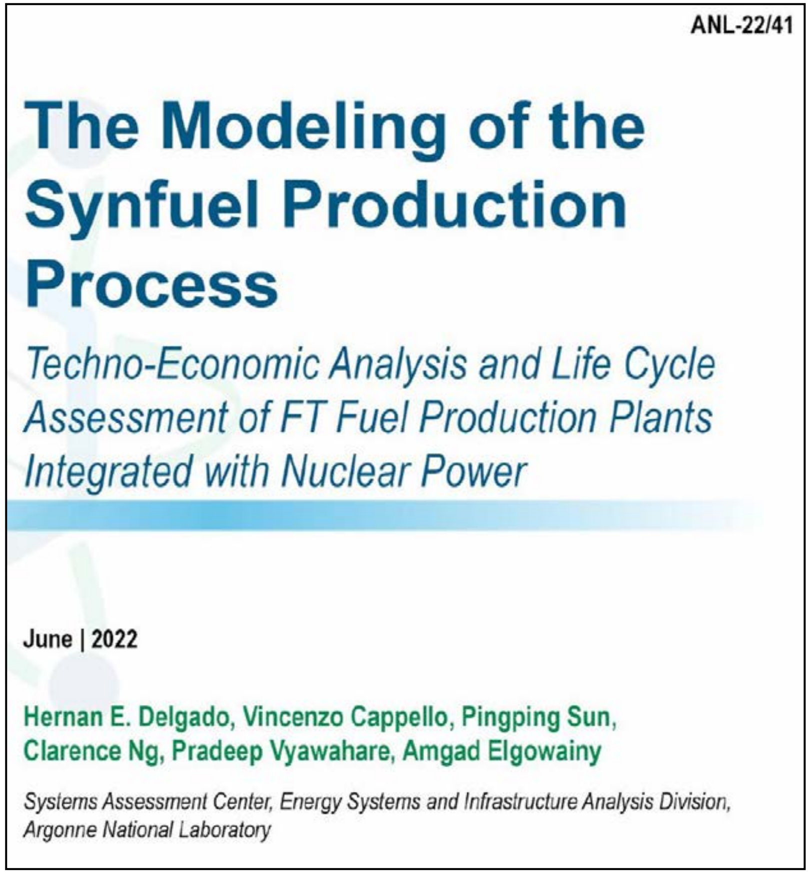


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

Grid-Integrated Production of Fischer-Tropsch Synfuels from Nuclear Power*, 2023, https://www.osti.gov/biblio/1984196*

1 GWe LWR, 10,000 bbl/day FT liquids


ANL-22/41

The Modeling of the Synfuel Production Process

Techno-Economic Analysis and Life Cycle Assessment of FT Fuel Production Plants Integrated with Nuclear Power

June | 2022

Hernan E. Delgado, Vincenzo Cappello, Pingping Sun, Clarence Ng, Pradeep Vyawahare, Amgad Elgowainy

Systems Assessment Center, Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory

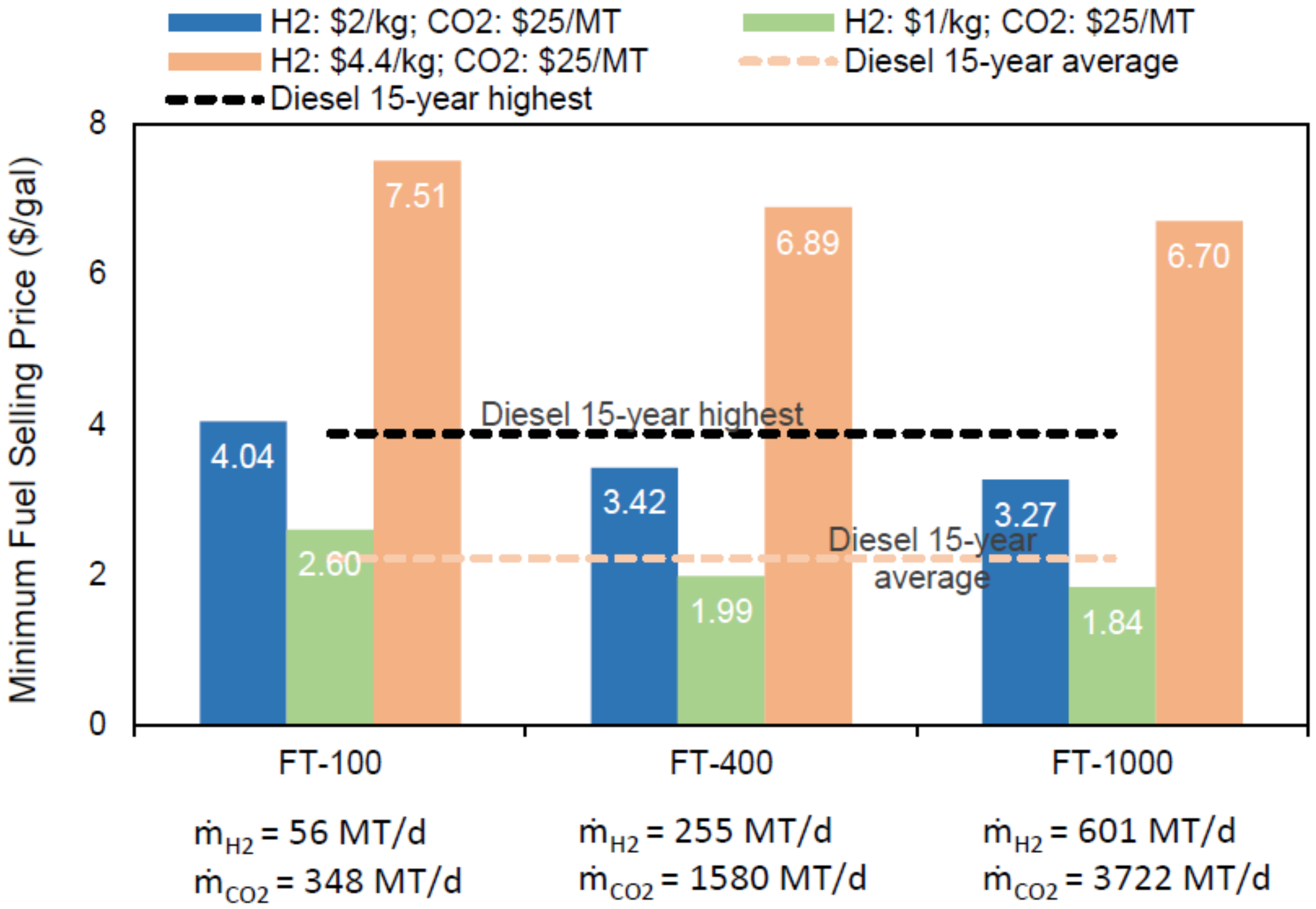
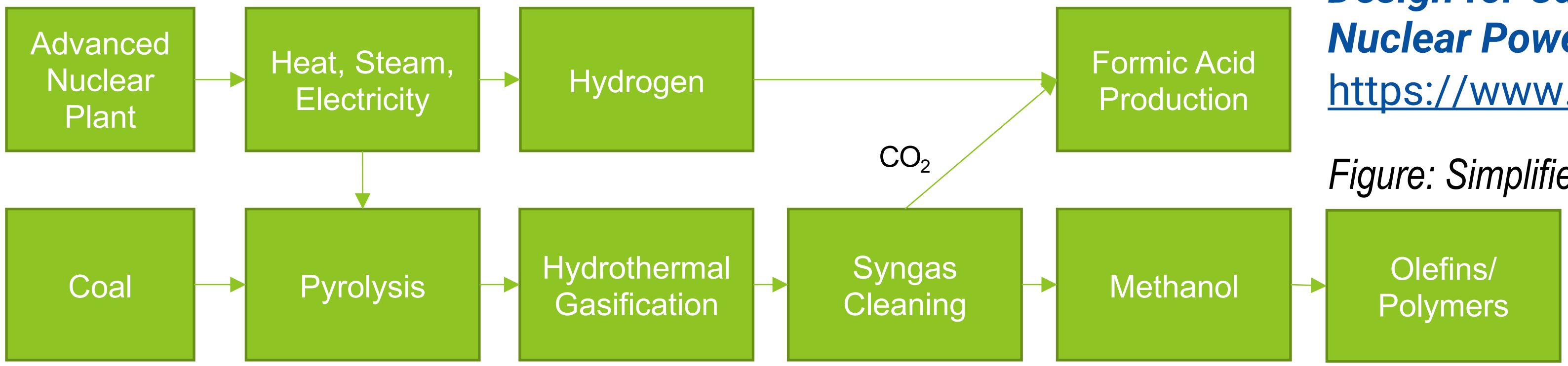


Figure I. Production cost of FT fuel at different plant scales and H_2 prices.

Carbon conversion pathways aim to preserve coal economies

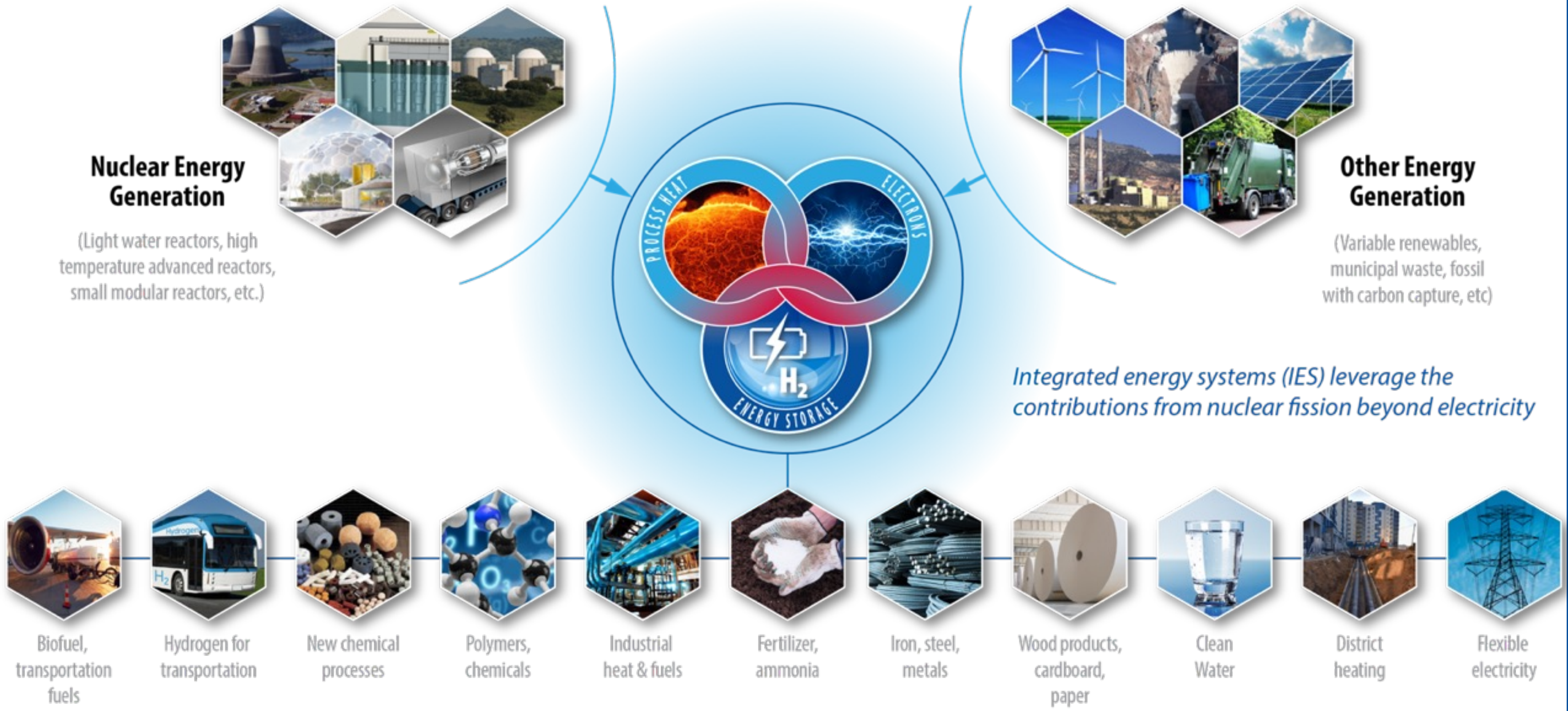
- "Carbon refinery" converts coal via pyrolysis and gasification to syngas for higher value product pathways w/carbon capture
- Focuses on synthesis of non-fuel products from coal utilizing an advanced reactor for heat and steam eliminates carbon output
- Design is optimized to maximize revenues from product streams
- Analyzed main product pathways:
  - **Methanol:** Main product pathway. Polymers chosen as the final product (e.g., polypropylene).
  - **Formic acid:** Ideal product for CO_2 utilization (livestock food preservative and potential hydrogen carrier); can be synthesized directly using hydrogen from electrolysis.
  - **Activated carbon**: Coal char from pyrolysis is converted to activated carbon (used for mercury removal from syngas).



Design for Carbon Conversion Product Pathways with Nuclear Power Plant Integration, 2022, https://www.osti.gov/biblio/1963875

Figure: Simplified flowsheet for the carbon refinery design.

Shifting the energy paradigm through research, development, & demonstration



The primary energy currencies for IES are:
Heat, Electricity, Hydrogen & Carbon

Heat

- Demonstrate high efficiency thermal energy use

Electricity

- Enable a sustainable, resilient, and reliable clean energy grid

Hydrogen & Carbon

- Develop novel chemical and industrial processes using low-emission energy

Integration

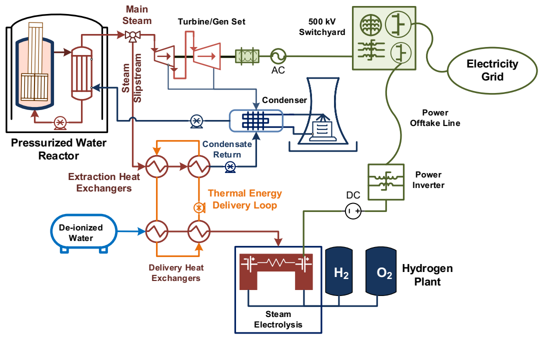
- Enhance tools and approaches to optimize IES operations

Hydrogen technology development and commercialization

Cell Fabrication and Stack Manufacturing

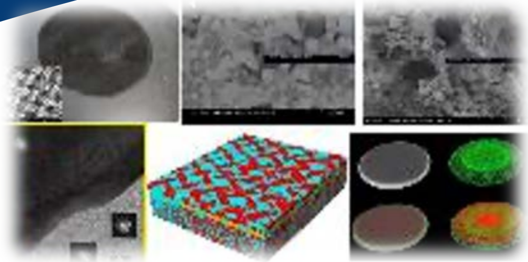
Modular Systems / Balance of Plant

Pilot Plant and Commercial Scale Demonstration



Commercial Demonstrations

High Throughput Materials Testing



Electrode Engineering & Diagnosis

Commercial Stack Testing

Materials Preparation

Materials Development and Testing

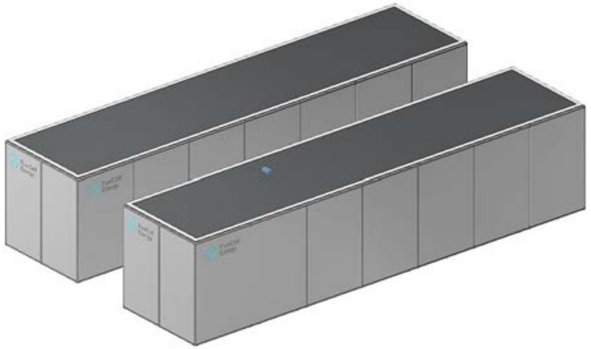
Accelerating hydrogen technology commercialization

- INL R&D enables commercial developers to operate and V&V fully integrated HTE electrolysis module performance
- Stack module testing
  - **Today:** Bloom Energy >100 kW_{eDC} SOEC stack module is in test under a CRADA supported project
    - > 5,000 hours of stable and transient testing
  - **Early 2024:** INL will commence performance testing of two factory-assembled modular 250 kW_{eDC} SOEC Systems
  - 50 kW rSOEC system and 50 kW "open" test architecture currently being installed
  - H_2 compression and fueling station to be installed, late 2023

INL HTE Support Facility:
- *CE+T America Power Converters*
- *Chromalox steam generator*

Bloom Energy 100 kWe HTE Stack Module

INL operators monitoring the Bloom Energy HTE stack module performance



FuelCell Energy 250 kW_{eDC} HTE module Installation and operation early 2024

25 kW_{eDC} commercial stack testing module

Pilot plant hydrogen production demonstration projects

Constellation: Nine-Mile Point Plant

- H_2 production beginning in 2023
- 1 MW_{eDC} nel hydrogen proton electrolyte membrane electrolysis module

Energy Harbor: Davis-Besse Plant

- H_2 production beginning in 2024
- 2 MW_{eDC} Cummins proton electrolyte membrane electrolysis module

Xcel Energy: Prairie Island Plant

- H_2 production beginning in 2024
- Bloom Energy high temperature solid-oxide electrolysis module

LWRS LIGHT WATER REACTOR SUSTAINABILITY | H2@Scale U.S. Department of Energy | NREL NATIONAL RENEWABLE ENERGY LABORATORY

Nuclear-based hydrogen production has commenced!

Press release:
https://www.constellationenergy.com/newsroom/2023/Constellation-Starts-Production-at-Nations-First-One-Megawatt-Demonstration-Scale-Nuclear-Powered-Clean-Hydrogen-Facility.html

Constellation Starts Production at Nation's First One Megawatt Demonstration Scale Nuclear-Powered Clean Hydrogen Facility

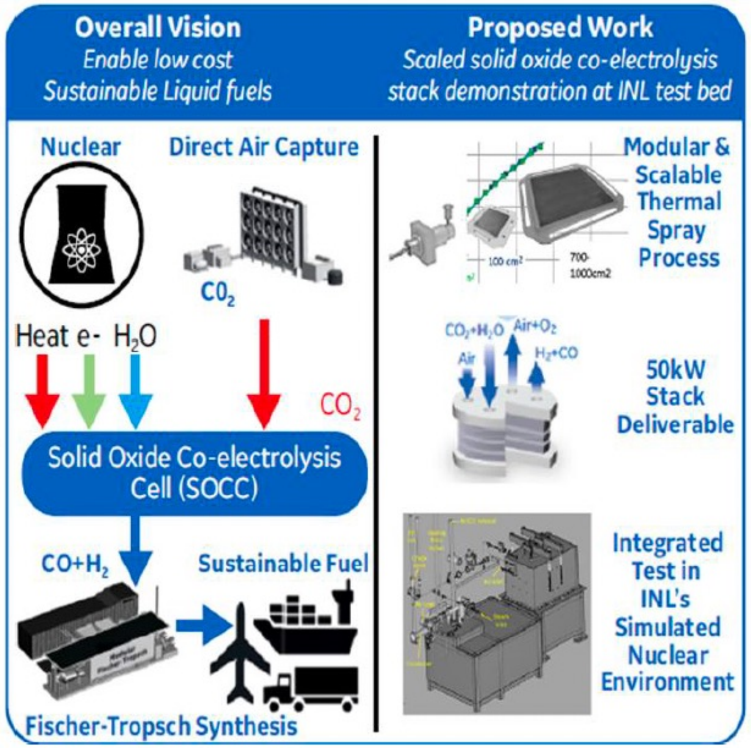
State-of-the-art facility will demonstrate the value of producing hydrogen with carbon-free nuclear energy to help address the climate crisis

OSWEGO, NY (Mar. 7, 2023) — Hydrogen production has commenced at the nation's first 1 MW demonstration scale, nuclear-powered clean hydrogen production facility at Constellation's Nine Mile Point Nuclear Plant in Oswego, New York, an advancement that will help demonstrate the potential for hydrogen to power a clean economy.

Photos courtesy Constellation, https://www.ans.org/news/article-4810/constellation-starts-hydrogen-production-at-nine-mile-point/

New nuclear-H_2 integration projects (cross-DOE collaboration)

GE Research – Scaled Solid Oxide Co-Electrolysis for Low-Cost Syngas Synthesis from Nuclear Energy



Goals:

Complete engineering design/testing for **production of synthetic jet fuel using nuclear energy from existing light water reactors & Solid Oxide Co-Electrolysis**

- Complete TEA
- Manufacture of scaled solid oxide cells
- Integration & testing of 50kW stack at INL

<u>Potential Impact:</u> Nuclear to H_2 + CO to Synthetic Aviation Fuel

Westinghouse – FEEDs for Integrating Commercial Electrolysis H_2 Production with Selected LWRs

Goals:

Complete Front-End Engineering Designs (FEEDs) development for **nuclear-coupled SOEC H_2 production** at specific U.S. LWR plants

- Designs will be developed for **both pressurized water reactor (PWR) & boiling water reactor (BWR)**
- Licensing impact assessments will be completed
- TEA & LCA for markets under consideration

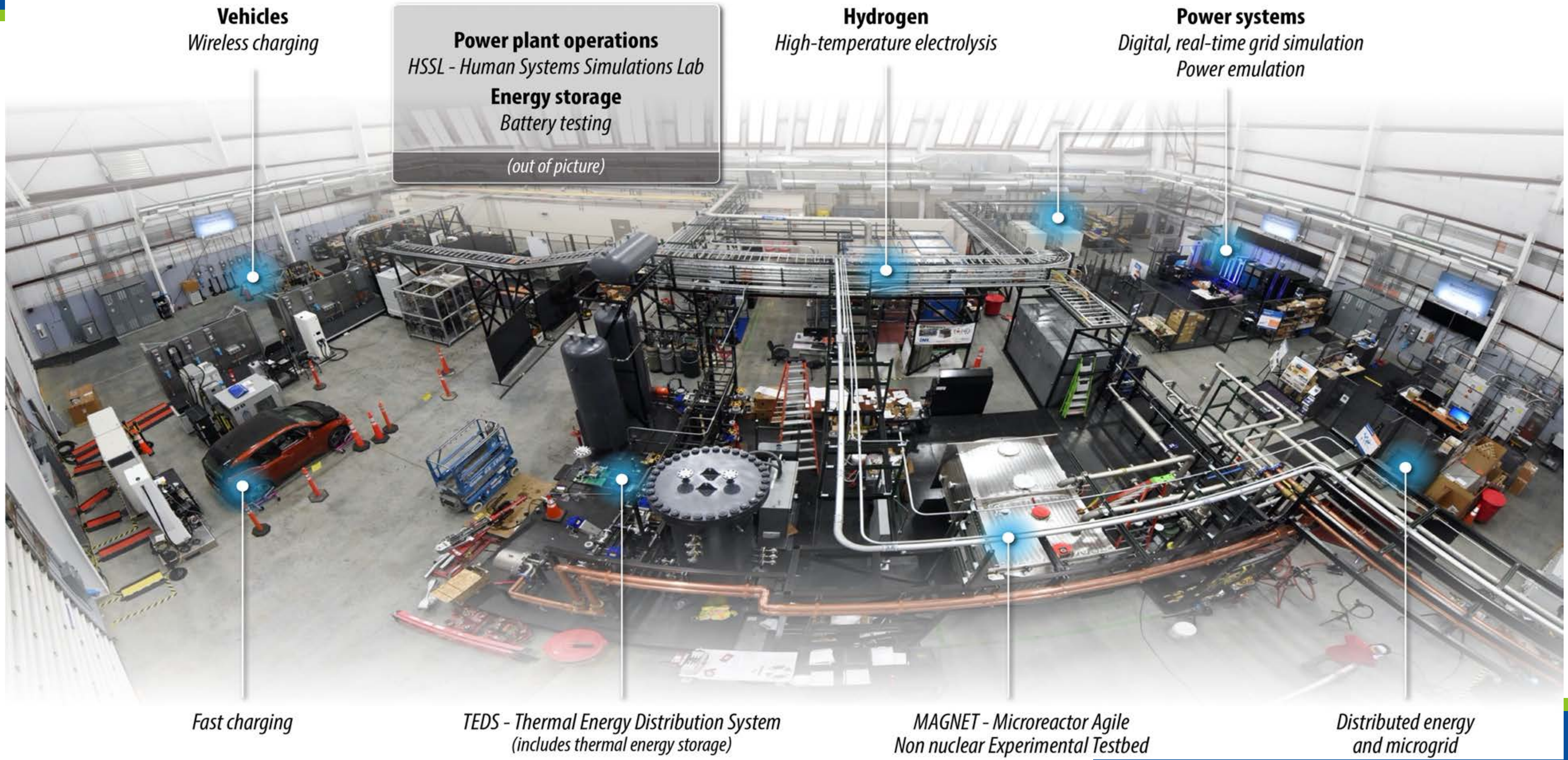
Westinghouse

Sub-Recipient/FFRDC	INL Idaho National Laboratory
Utility Support	aps (1), energy harbor (1), Xcel Energy (1)
Industry Support	Bloomenergy (1), FAUSKE & Associates, LLC (2)
Academia Support	The University of Toledo (3)

<u>Potential Impact:</u> Higher system efficiencies / lower cost through thermal integration of SOEC with nuclear plant

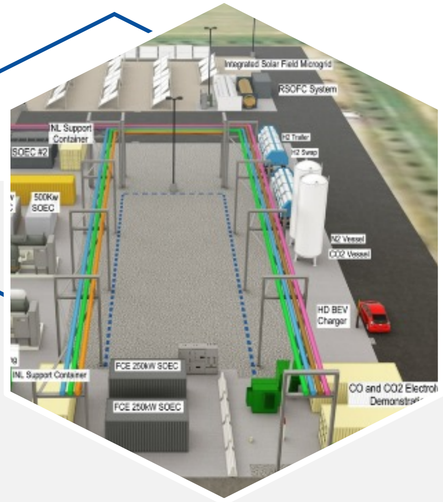
Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023

Dynamic Energy Transport and Integration Laboratory (DETAIL)



At-scale demonstrations, > 1 MW systems, fill the gap

Example, Hydrogen production via HTSE



“ The GAP”

25 kWe High Temperature Electrolysis Stacks V&V

100-500kWe Modular High Temperature Electrolysis Pilot Plant Demonstration

2-10 MWe Modular HTE Units

- Integrated proof of operation system
- Hydrogen supply for user technology demonstrations
- Accelerates high temp H2 production pathway to commercialization

Wide Commercial Deployment:

- Hydrogen production at nuclear power plants
- Industry-embedded hydrogen production and use

Proposed INL Energy Technology Proving Ground (ETPG)—Multi-scale research program areas

- High Temperature Hydrogen Production
- Thermal Energy Management
- High Temperature Electrochemistry
- Biomass & Waste Carbon Feedstocks
- Transportation & Electric Storage
- Distributed Clean Energy Systems — Microgrid
- Microreactor Testing & Operations
- Digital Engineering & Cyber Security
- Real-Time Power & Energy Analysis

~2500 acres of land identified for growth, leveraging existing infrastructure and recent substation and transmission upgrades to provide 15 MWe

INL's Roadmap to Net-Zero:

Develop Clean Energy Technologies I Reduce Emissions
Increase Efficiencies I Capture Carbon

Implementation Plan

Purchased Electricity

Secure carbon-free electricity from power providers, including nuclear, when available.

Mobile Combustion

Convert to non-carbon emitting vehicles and develop fueling alternatives.

Stationary Combustion

Increase building efficiencies, electrify equipment, and identify carbon-free alternatives.

Wastewater

Monitor and mitigate emissions from wastewater facilities.

Other Fugitive Emissions

Monitor and mitigate emissions from fugitive sources.

Landfill

Monitor and mitigate landfill emissions.

Public Engagement: Communication, Outreach and Education

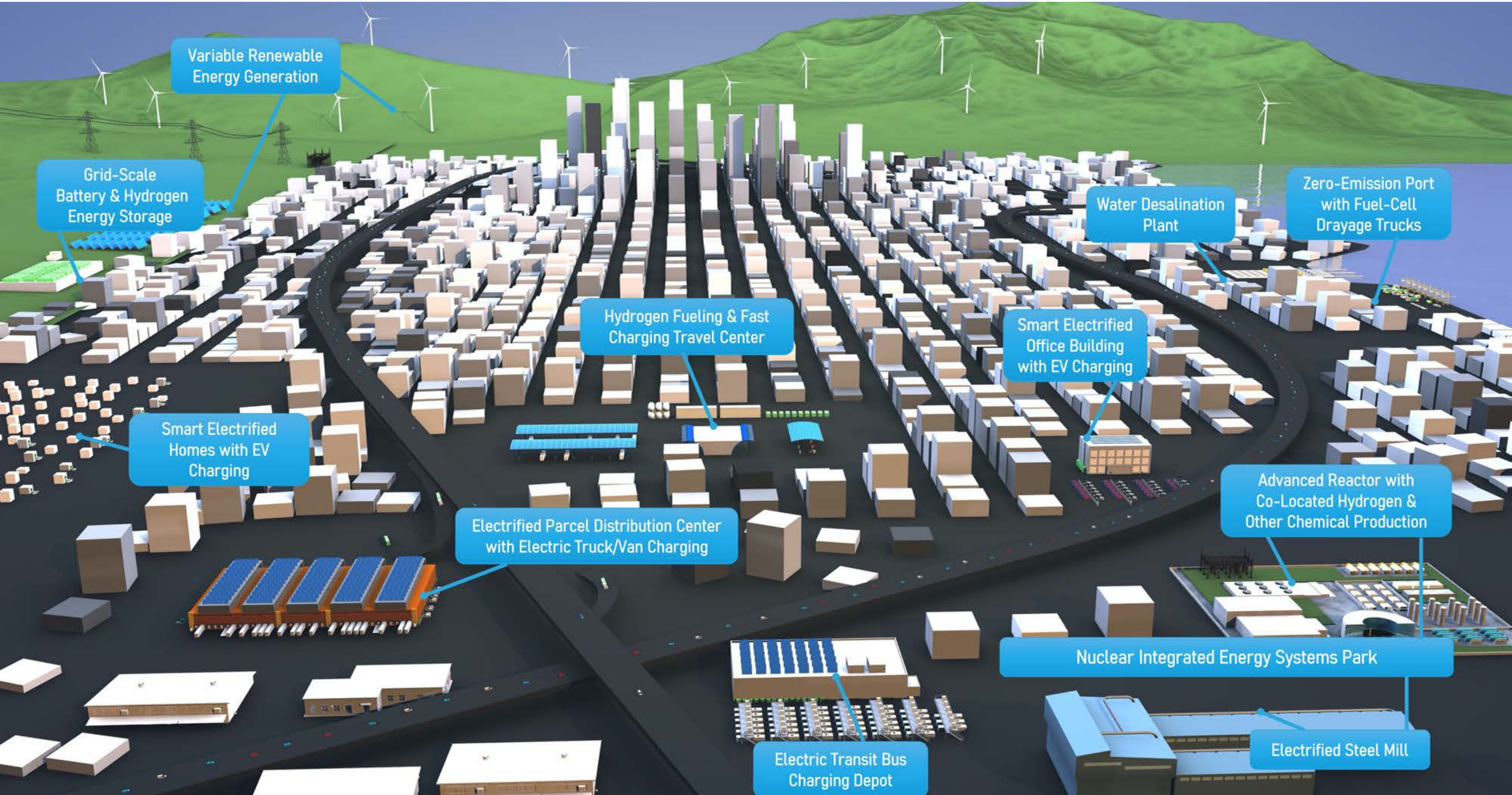
Nuclear Microgrid

Establish microgrid to demonstrate secure, clean integrated energy systems with the potential to support discrete site operations.

23-50457_R5

https://NuclearNowFilm.com

A vision for a net-zero future



Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Additional references

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