INL/MIS-24-76549-Revision-0

Achieving a Net-Zero Future: The Role of Nuclear Energy

February 2024

Changing the World's Energy Future

Shannon M Bragg-Sitton

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February 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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

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Achieving a Net-Zero Future: The Role of Nuclear Energy

February 7, 2024
Texas A&M University Energy Institute

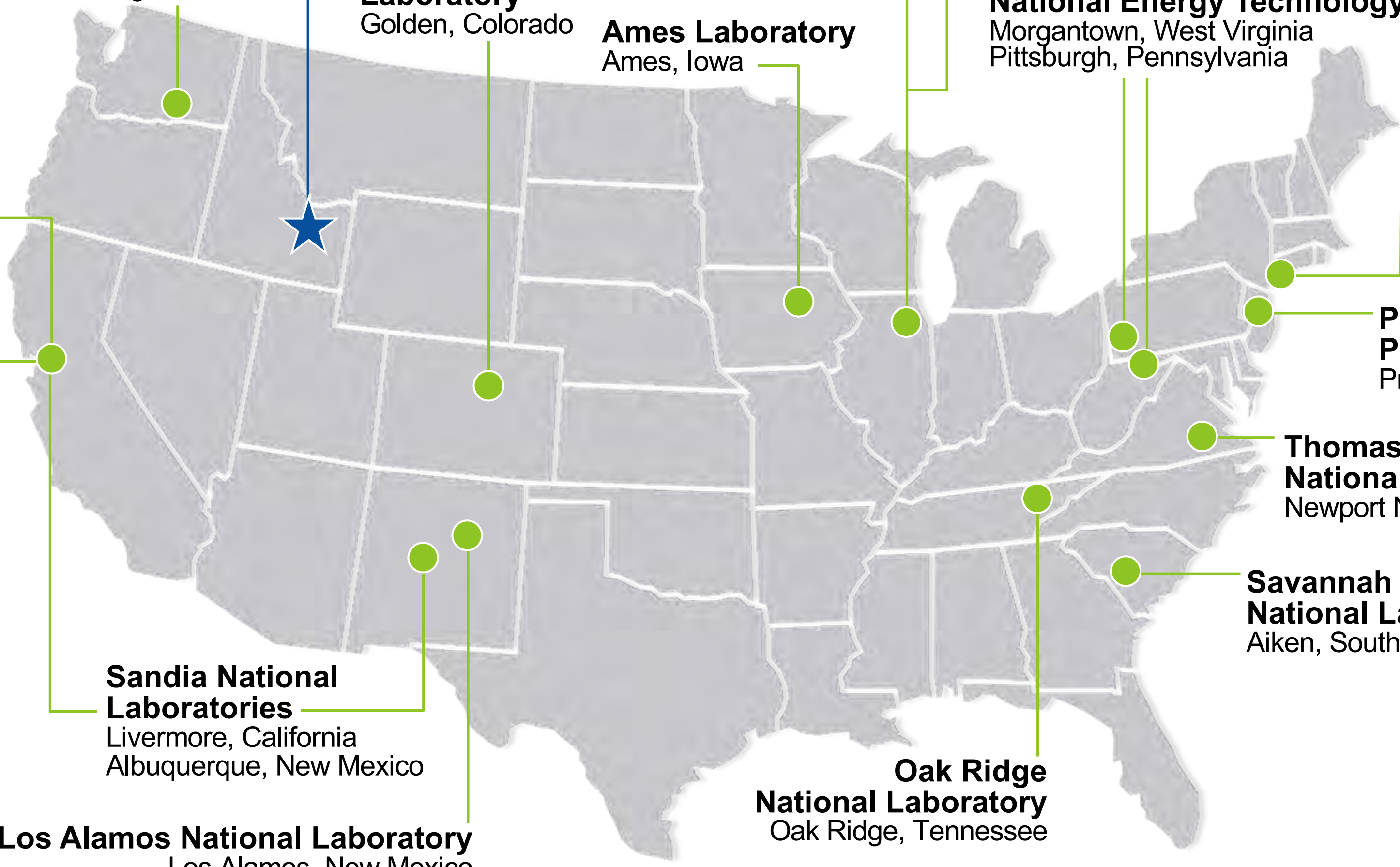
Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

Presentation Overview

- Brief introduction to Idaho National Laboratory
- Current state of energy in the U.S.
- Nuclear energy options
- Novel deployment opportunities: Moving beyond the grid
- Demonstration and deployment timelines

DOE National Laboratories



Idaho National Laboratory
Idaho Falls, Idaho

Pacific Northwest National Laboratory
Richland, Washington

National Renewable Energy Laboratory
Golden, Colorado

Argonne National Laboratory
Argonne, Illinois

Ames Laboratory
Ames, Iowa

Fermi National Accelerator Laboratory
Batavia, Illinois

National Energy Technology Laboratory
Morgantown, West Virginia
Pittsburgh, Pennsylvania

Brookhaven National Laboratory
Upton, New York

SLAC National Accelerator Laboratory
Menlo Park, California

Lawrence Berkeley National Laboratory
Berkeley, California

Lawrence Livermore National Laboratory
Livermore, California

Princeton Plasma Physics Laboratory
Princeton, New Jersey

Thomas Jefferson National Accelerator Facility
Newport News, Virginia

Savannah River National Laboratory
Aiken, South Carolina

Sandia National Laboratories
Livermore, California
Albuquerque, New Mexico

Los Alamos National Laboratory
Los Alamos, New Mexico

Oak Ridge National Laboratory
Oak Ridge, Tennessee

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

Multipurpose Science Labs

- Brookhaven National Laboratory
- SLAC NATIONAL ACCELERATOR LABORATORY
- BERKELEY LAB
- Argonne NATIONAL LABORATORY
- Pacific Northwest NATIONAL LABORATORY
- OAK RIDGE National Laboratory

Multipurpose Security Labs

- Los Alamos NATIONAL LABORATORY
- Sandia National Laboratories
- Lawrence Livermore National Laboratory

Multipurpose Environmental Labs

- SRNL SAVANNAH RIVER NATIONAL LABORATORY OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

SCIENCE TECHNOLOGY

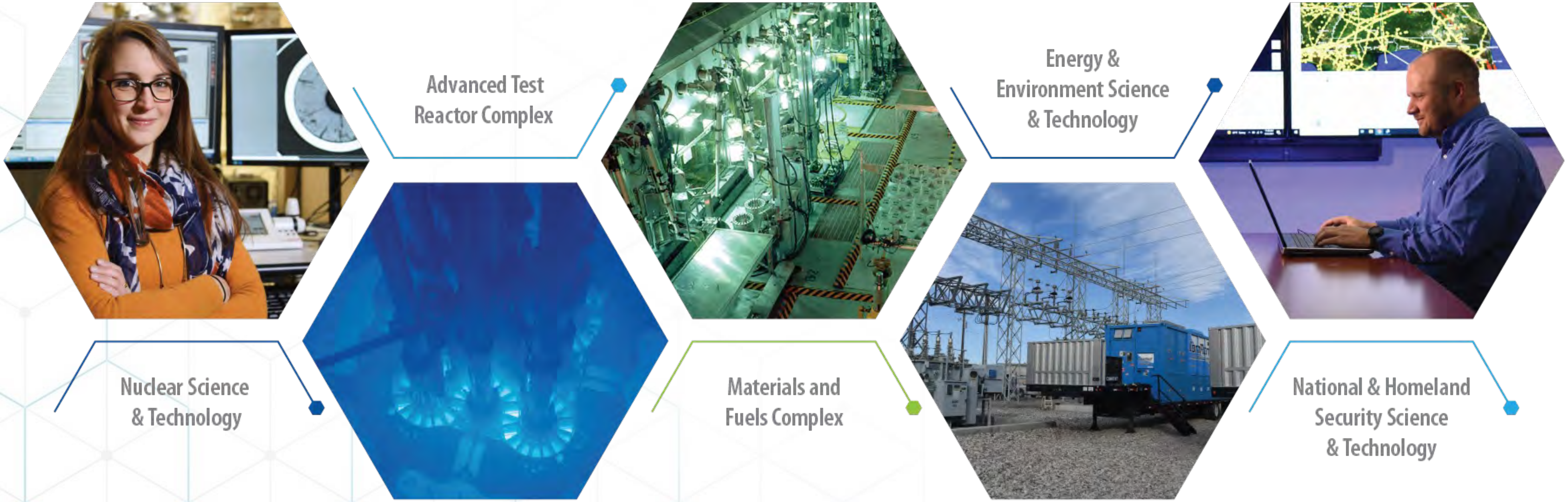
Single Program Science Labs

- Jefferson Lab Thomas Jefferson National Accelerator Facility
- PPPL PRINCETON PLASMA PHYSICS LABORATORY
- Fermilab

Energy Technologies Labs

- AMES LABORATORY U.S. DEPARTMENT OF ENERGY
- NREL NATIONAL RENEWABLE ENERGY LABORATORY
- INL Idaho National Laboratory
- NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

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



Nuclear Science
& Technology

Advanced Test
Reactor Complex

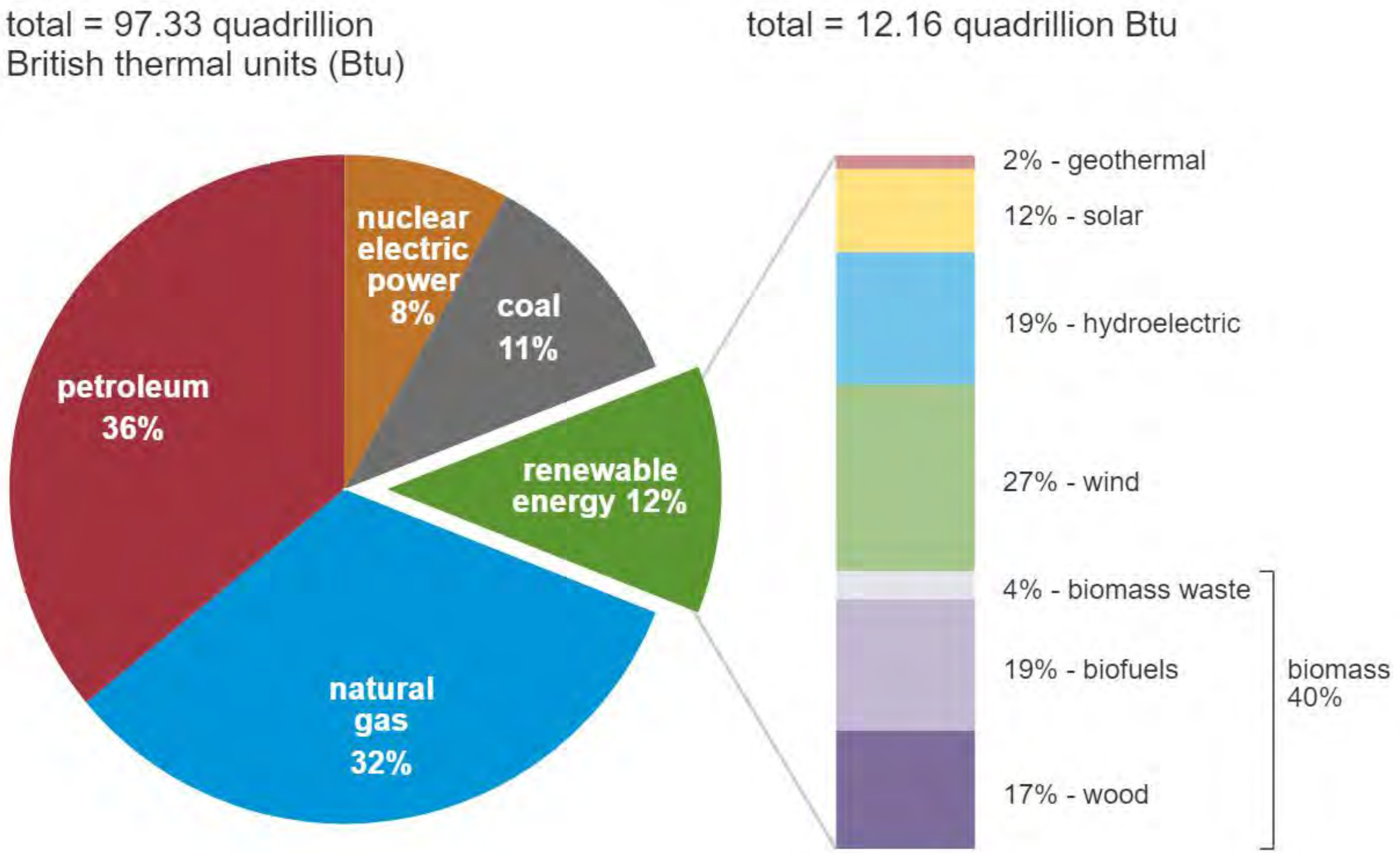
Materials and
Fuels Complex

Energy &
Environment Science
& Technology

National & Homeland
Security Science
& Technology

Addressing the global challenge: Climate change

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



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2022, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

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

- *Energy Earthshots^{TM} 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

Long Duration Storage Shot

Carbon Negative Shot

Enhanced Geothermal Shot

Floating Offshore Wind Shot

Industrial Heat Shot

Clean Fuels & Products Shot

Affordable Home Energy Shot

ENERGY earthshots U.S. DEPARTMENT OF ENERGY

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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

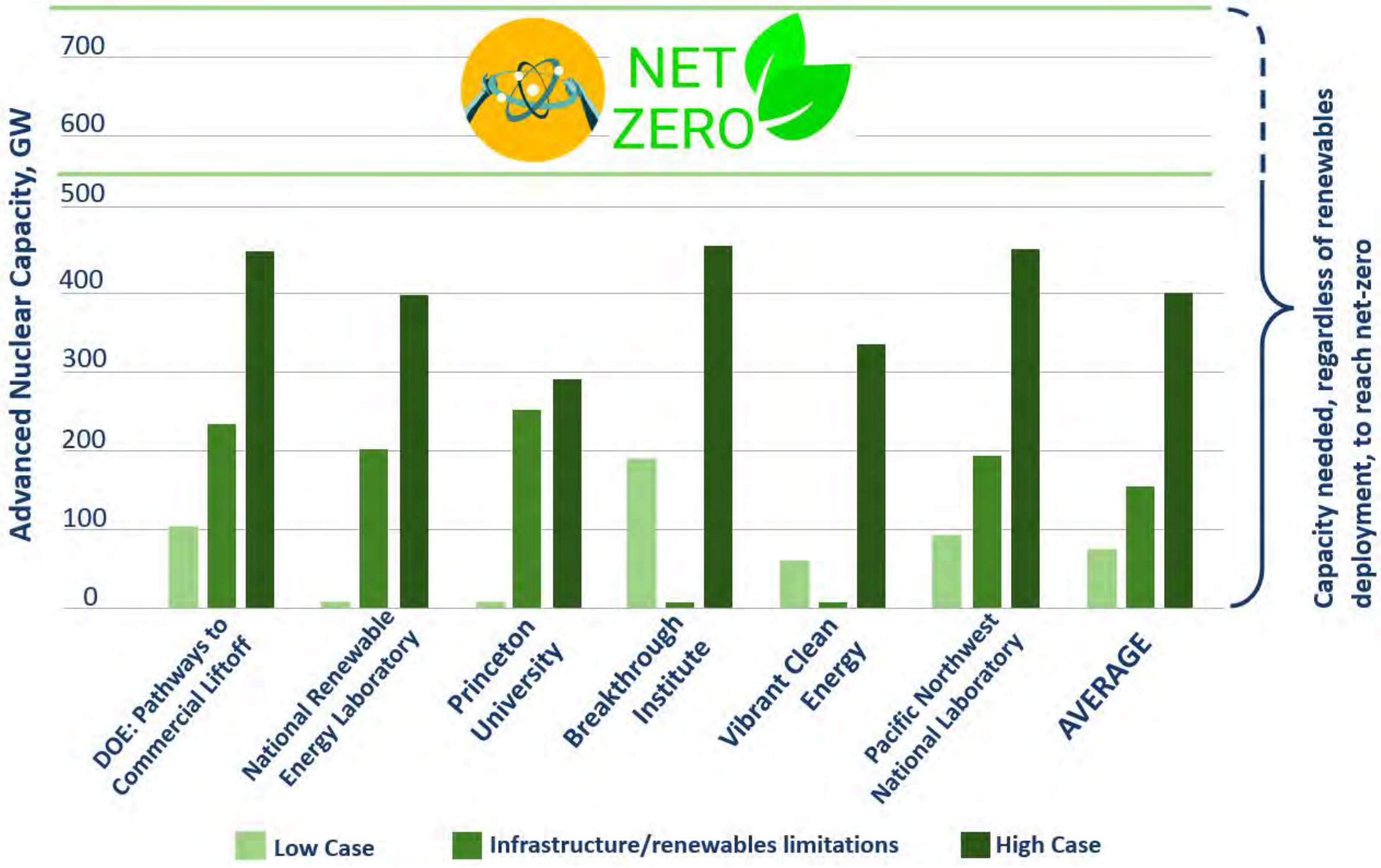
Floating Offshore Wind Shot

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

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

Affordable Home Energy Shot

The magnitude of clean energy needed is overwhelming



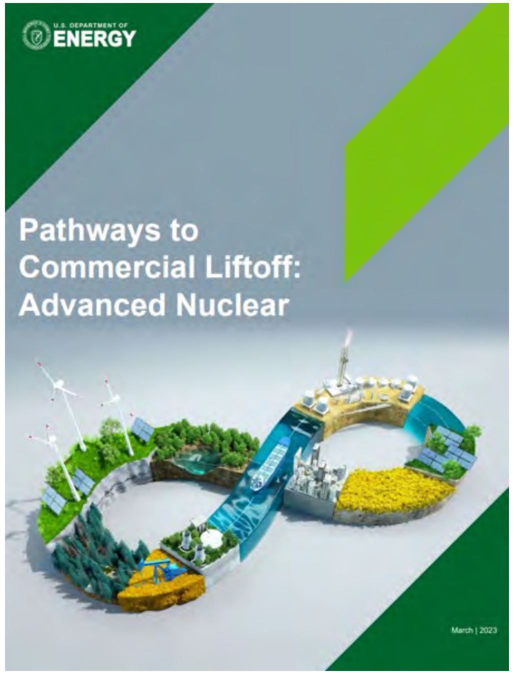
The U.S. needs ~550-750 GW of clean firm power to reach net-zero GHG emissions

- Firm zero-C electricity to meet demands in all seasons
- Flexible energy sources that can quickly ramp to support variable supply (e.g., VRE) and demand
- Decarbonization of current non-electric energy sources

→ Advanced nuclear energy could provide ~75-425 GW of this capacity addition while complementing other clean energy options

Nuclear Innovation Alliance, Factsheet, *Advanced Nuclear Energy is a Key Climate Solution*, Factsheet, May 2023, https://www.nuclearinnovationalliance.org/resources

Regional economic benefits from nuclear power plant deployment



U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Advanced Nuclear

March | 2023

~$90-100B

Added to the economy by 2030

~140k

Direct job-years[1] by 2030

~60k

Indirect job-years created from construction and operation activities

~$114k

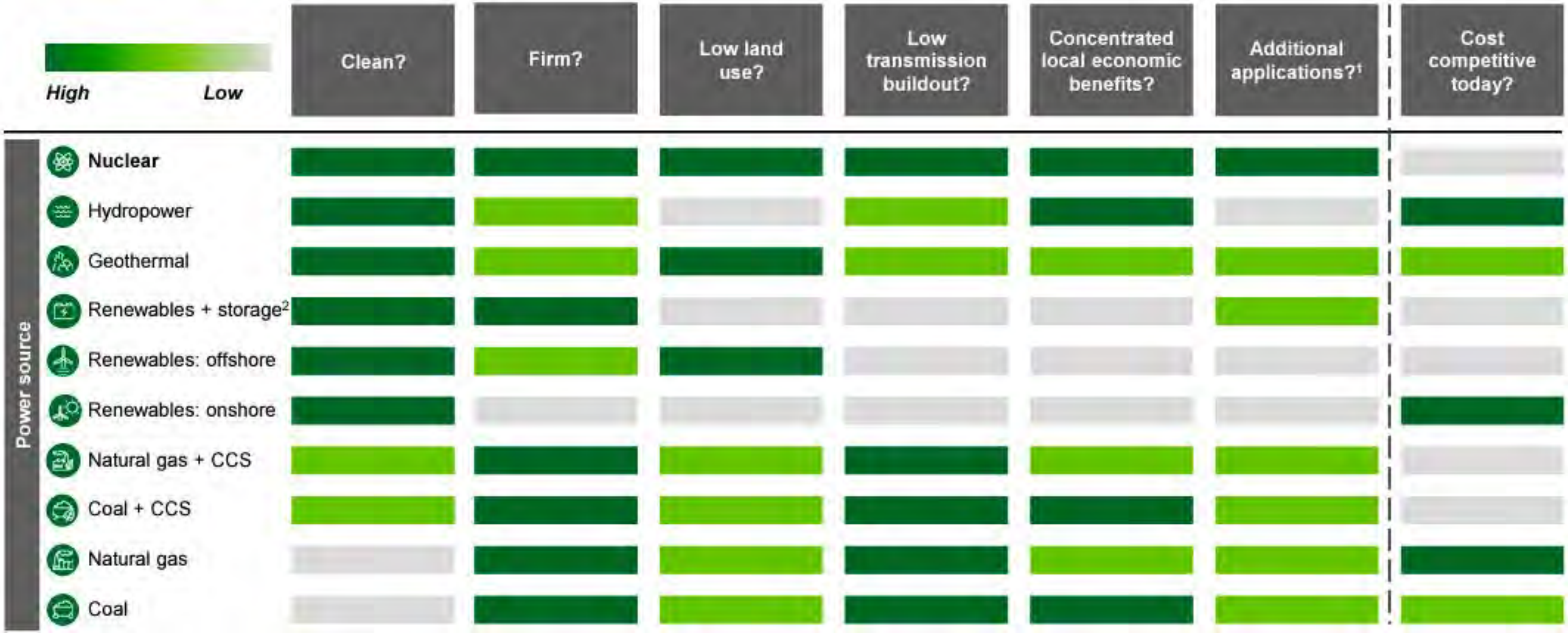
Average[2] income of job-years created

1. A job-year is one year of work for one person; a new construction job that lasts five years is five job-years. 2.Weighted average

Figure 10: Estimated job creation from new nuclear power plant construction by 2030[xvi]

DOE Liftoff Reports:
https://liftoff.energy.gov/

Value proposition for multiple energy options



High ● ◐ ○ *Low*

Power source	Clean?	Firm?	Low land use?	Low transmission buildout?	Concentrated local economic benefits?	Additional applications?[1]	Cost competitive today?
Nuclear	●	●	●	●	●	●	○
Hydropower	●	◐	○	◐	●	○	●
Geothermal	●	◐	●	◐	◐	◐	◐
Renewables + storage[2]	●	●	○	○	○	◐	○
Renewables: offshore	●	◐	●	○	○	○	○
Renewables: onshore	●	○	○	○	○	○	●
Natural gas + CCS	◐	●	◐	●	◐	◐	○
Coal + CCS	◐	●	◐	●	●	◐	○
Natural gas	○	●	◐	●	◐	◐	●
Coal	○	●	◐	●	●	◐	◐

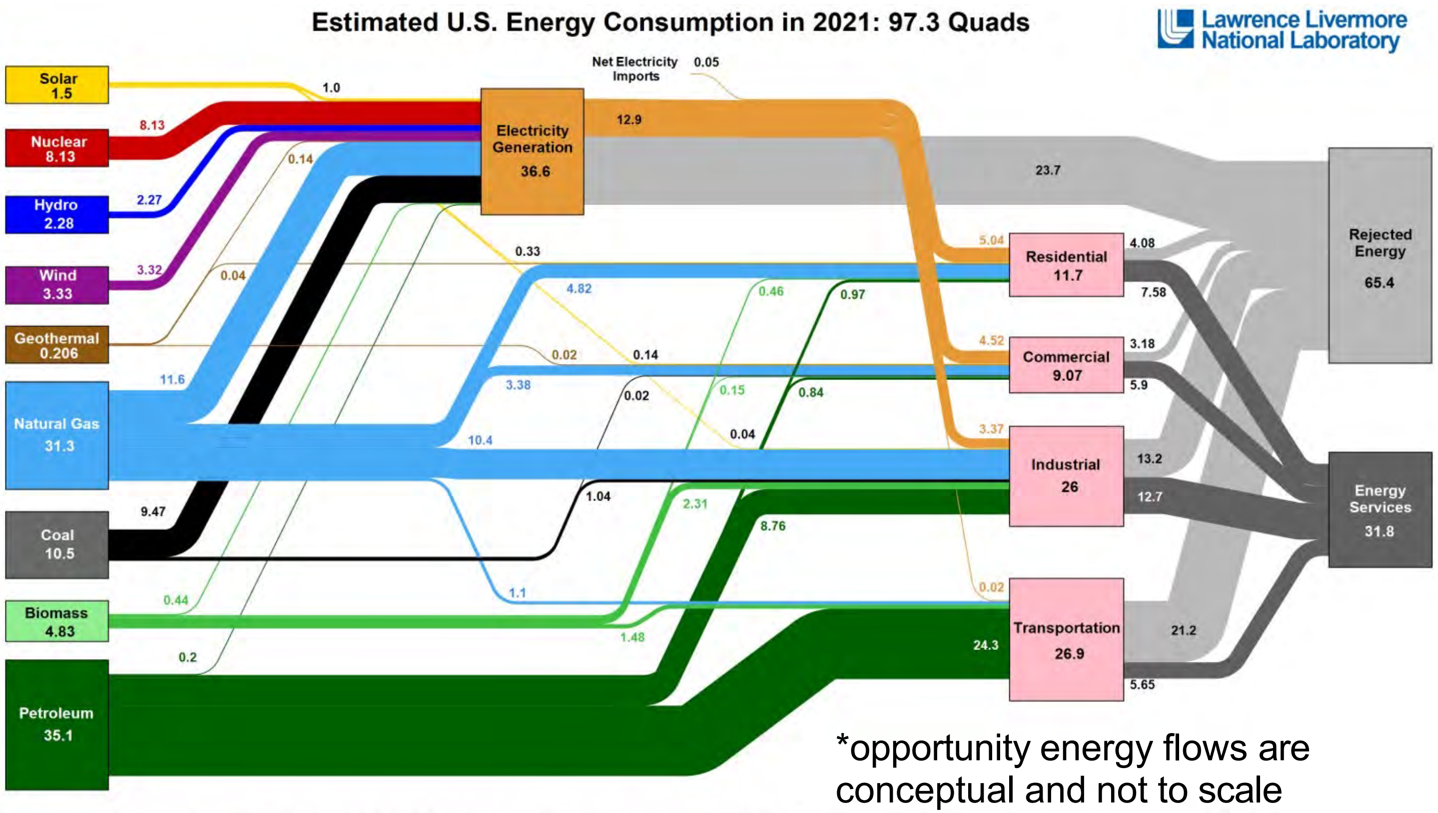
Source: DOE Pathways to Commercial Liftoff, 2023

A broad technology portfolio that includes renewables, flexible energy sources, AND nuclear energy can provide the most cost effective carbon-free energy systems.

Significant opportunities for nuclear energy expansion

Chemical, electrical and thermal energy to Transportation, Industrial, Commercial and Residential Sectors

Future Opportunities for Nuclear Energy in U.S.



*opportunity energy flows are conceptual and not to scale

Source: LLNL March, 2022. Data is based on DOE/EIA MER (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

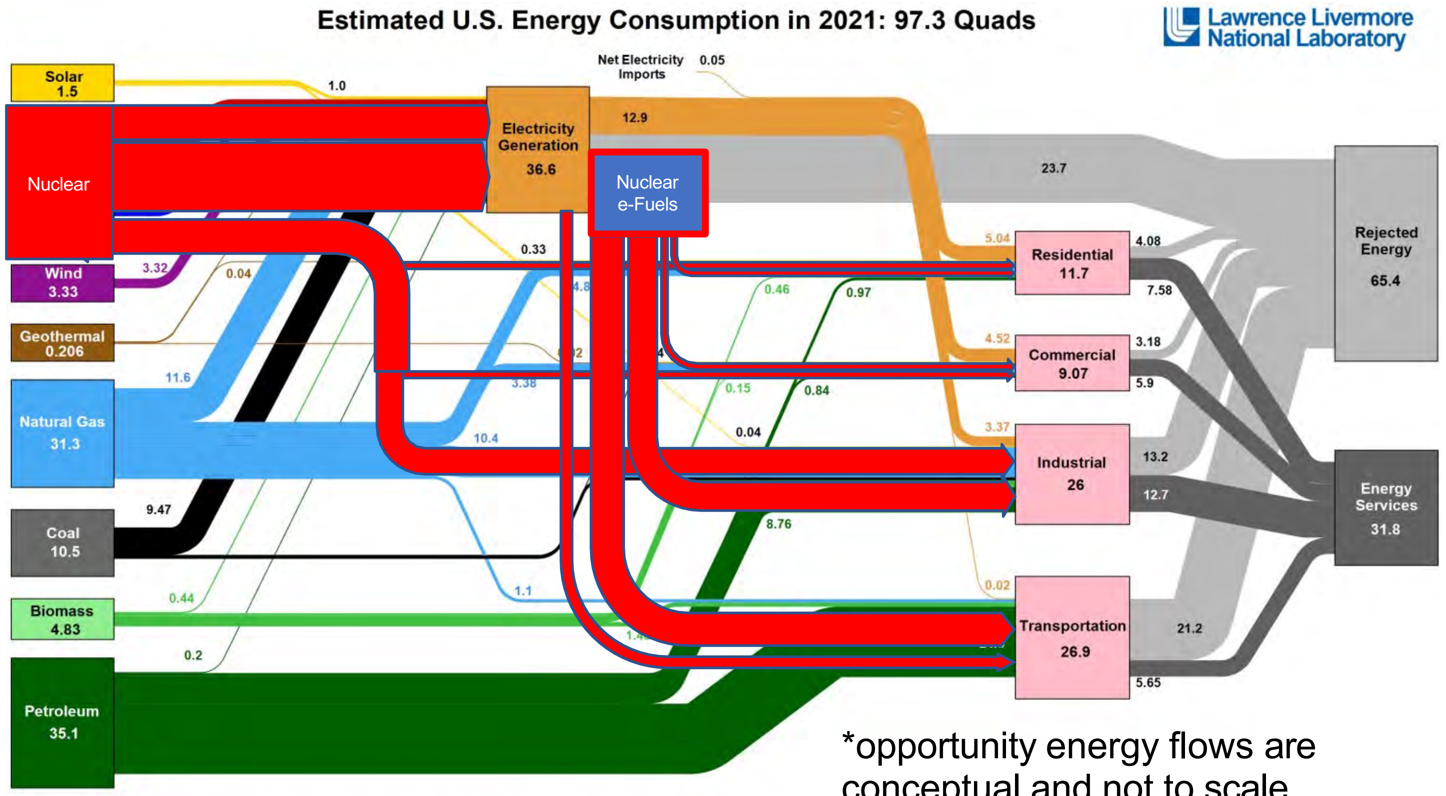
Significant opportunities for nuclear energy expansion

Chemical, electrical and thermal energy to Transportation, Industrial, Commercial and Residential Sectors

Future Opportunities for Nuclear Energy in U.S.

- ✓ Heat for residential, commercial, industry use
- ✓ Flexible electricity
- ✓ Electricity for transportation
- ✓ Fuels for industry
- ✓ Fuels for transportation
- ✓ Fuels for commercial
- ✓ Fuels for residential

Hydrogen has a role in these future opportunities…



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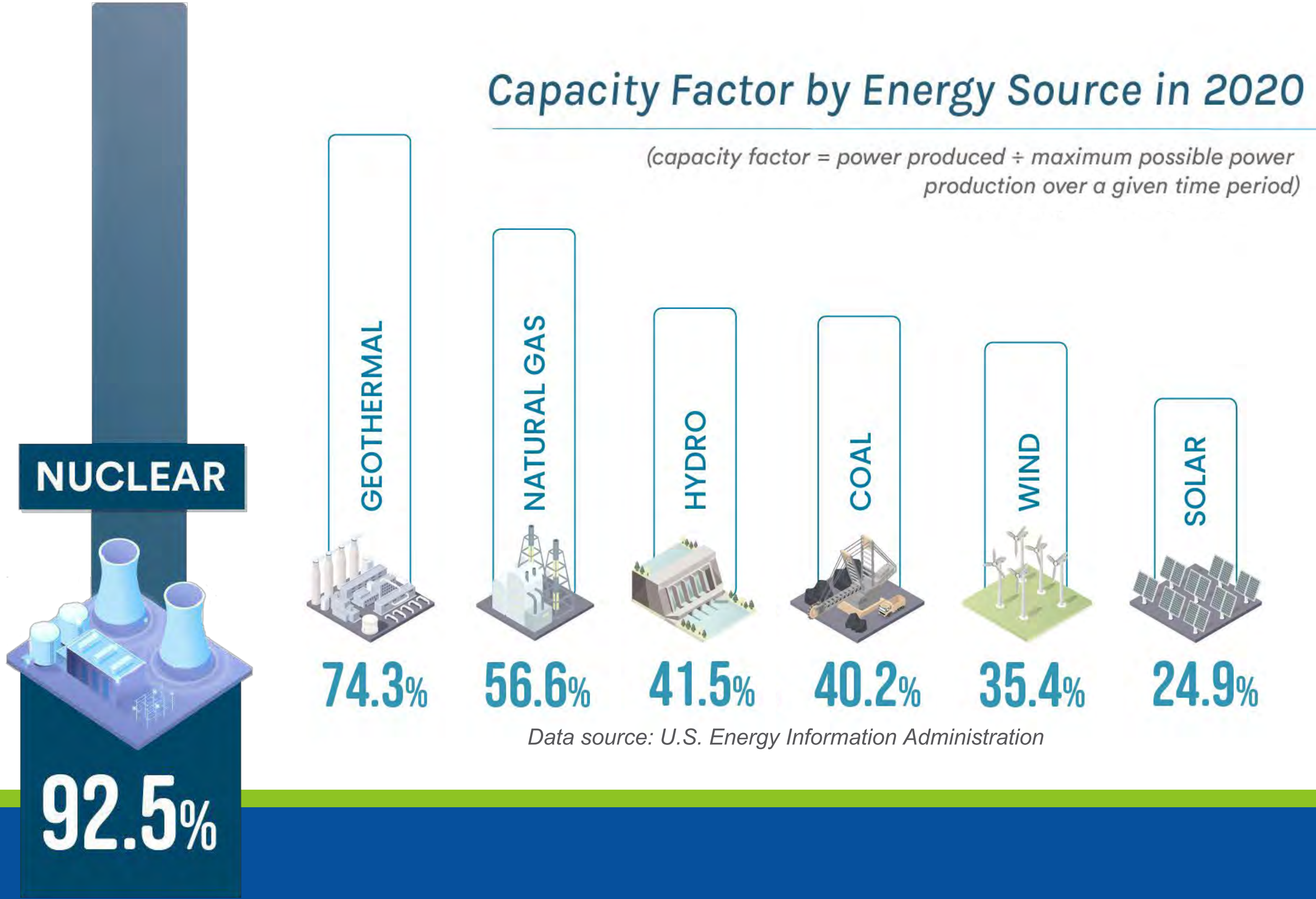
What is the status of nuclear energy?

Nuclear provides reliable, high-density energy with comparatively low land use

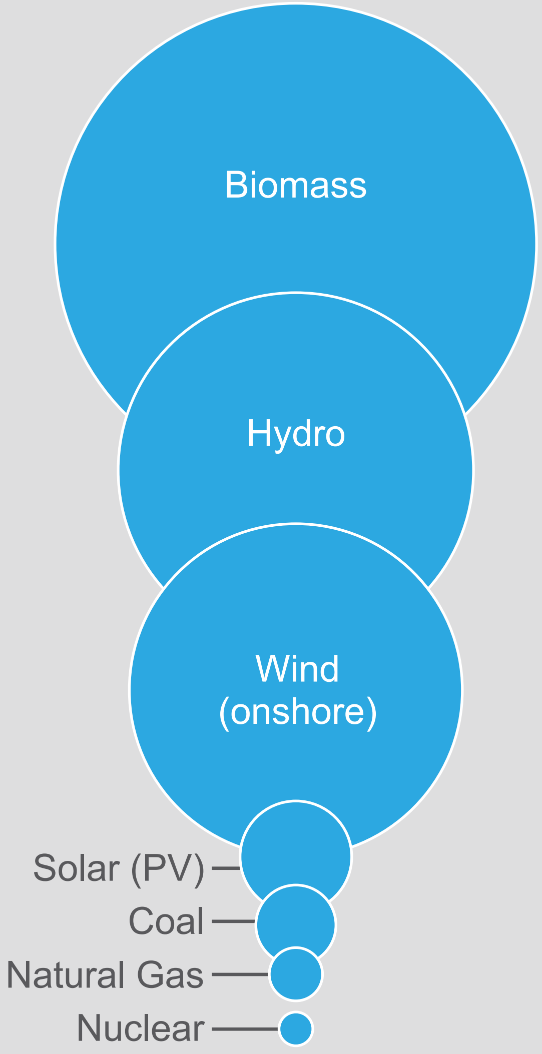


Capacity Factor by Energy Source in 2020

(capacity factor = power produced ÷ maximum possible power production over a given time period)

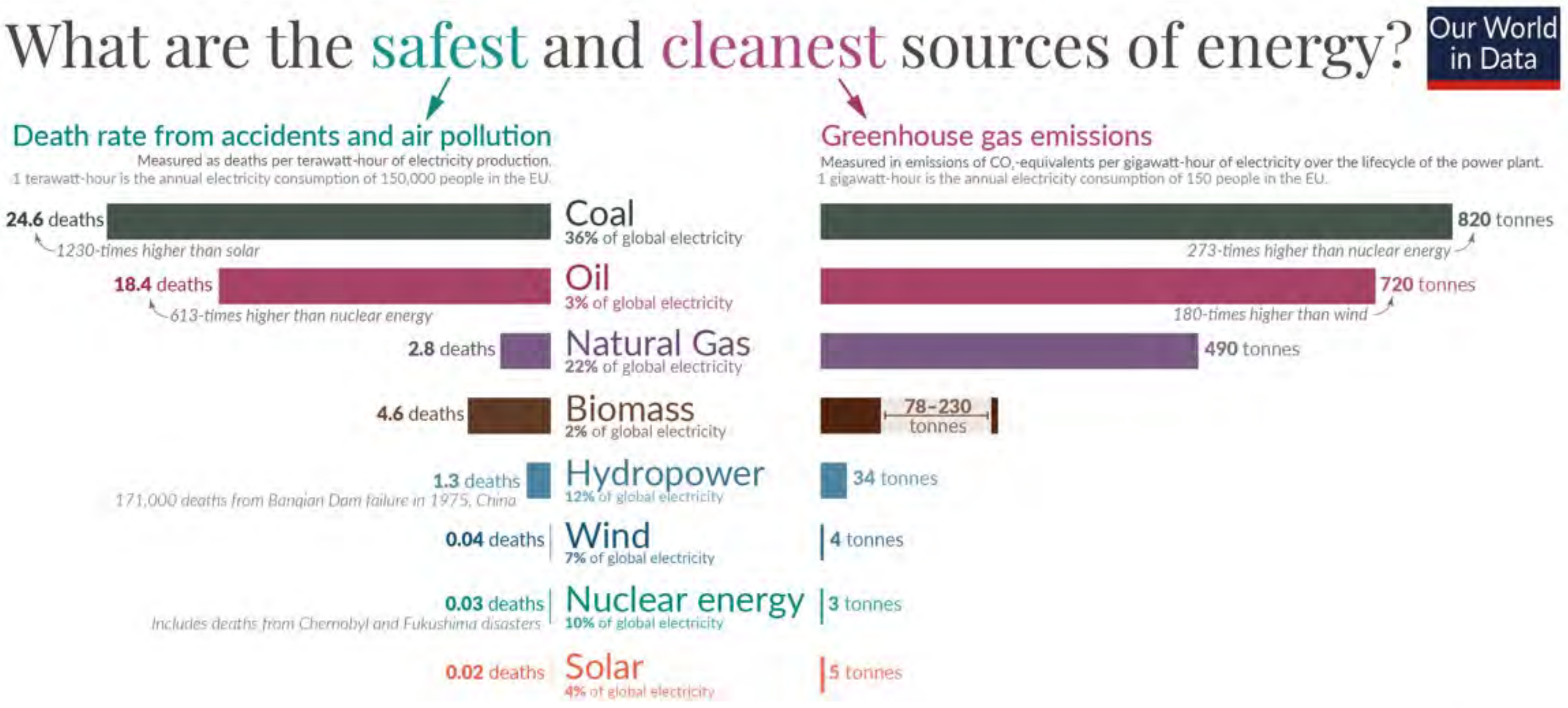
Data source: U.S. Energy Information Administration

RELATIVE LAND FOOTPRINTS



Source: World Nuclear Association

Nuclear is safe and clean



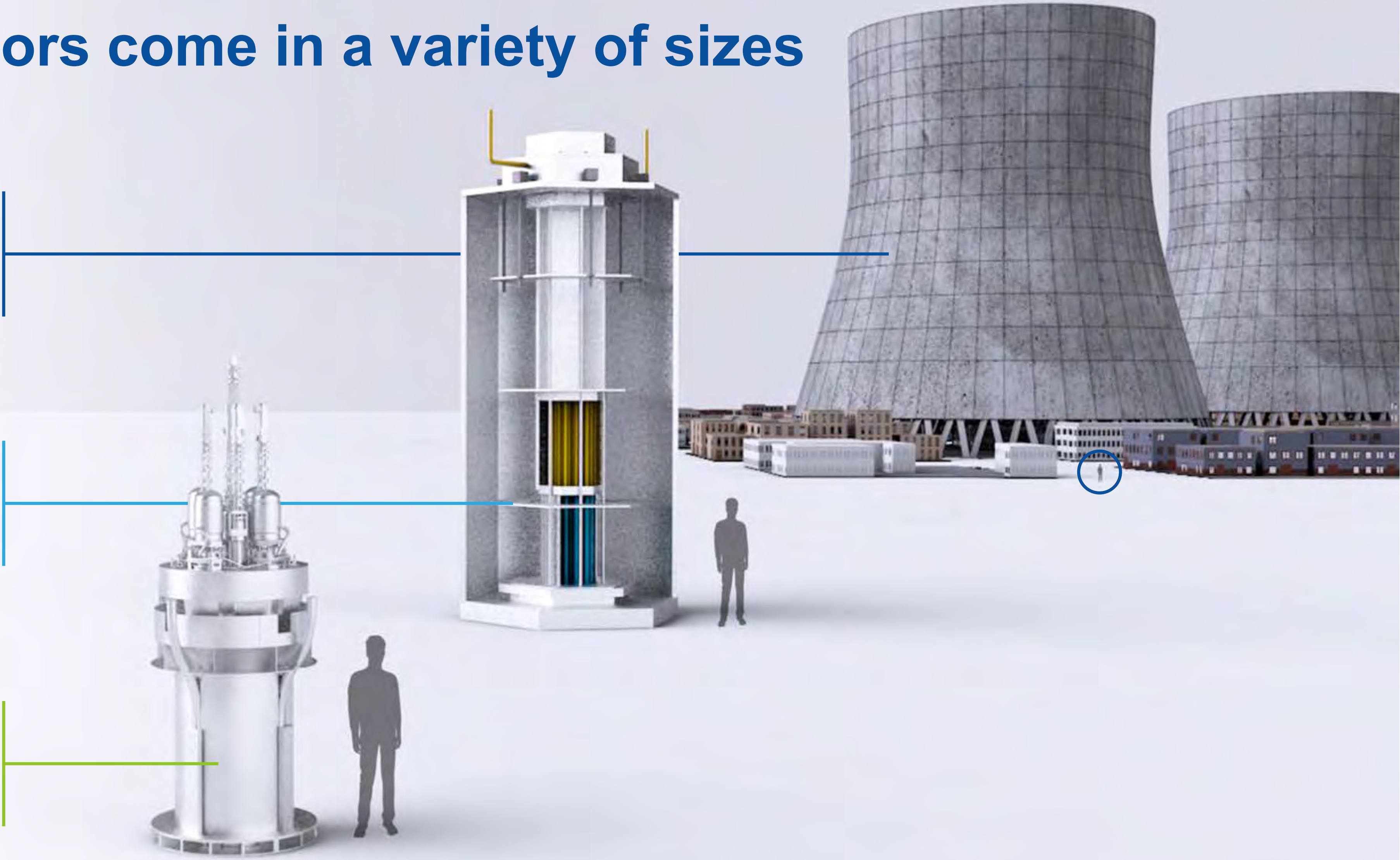
What are the safest and cleanest sources of energy?

Death rates from fossil fuels and biomass are based on state-of-the art plants with pollution controls in Europe, and are based on older models of the impacts of air pollution on health.
This means these death rates are likely to be very conservative. For further discussion, see our article: OurWorldinData.org/safest-sources-of-energy. Electricity shares are given for 2021.
Data sources: Markandya & Wilkinson (2007); UNSCEAR (2008; 2018); Sovacool et al. (2016); IPCC AR5 (2014); Pehl et al. (2017); Ember Energy (2021).
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

In the United States clean, 24/7 nuclear power has produced **83,000 metric tons** of spent fuel since the 1950s—and all of it could fit on a single football field at a depth of less than 10 yards.

While about **110 million metric tons** of coal ash are produced by the coal industry annually—more every single day than all the spent fuel since the beginning of the commercial nuclear industry.

Advanced reactors come in a variety of sizes



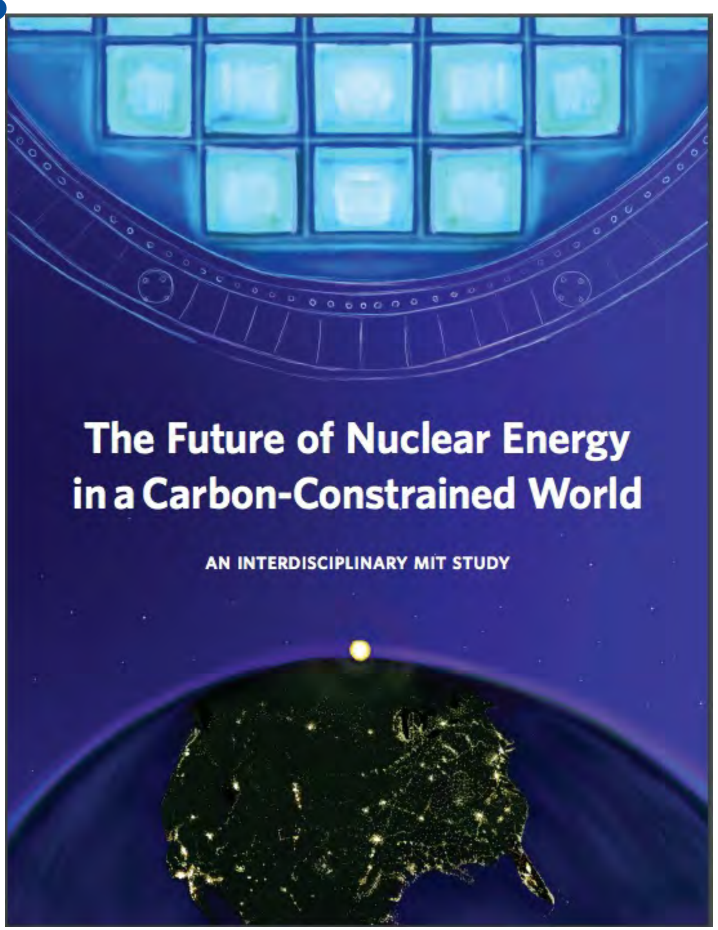
Large-Scale Reactor
300 MW – 1,000+ MW
1,500 ACRES

Small Modular Reactor
20 MW – 300 MW
50 ACRES

Microreactor
1 MW – 20 MW
LESS THAN AN ACRE

MIT 2018 Future of Nuclear Study – Findings

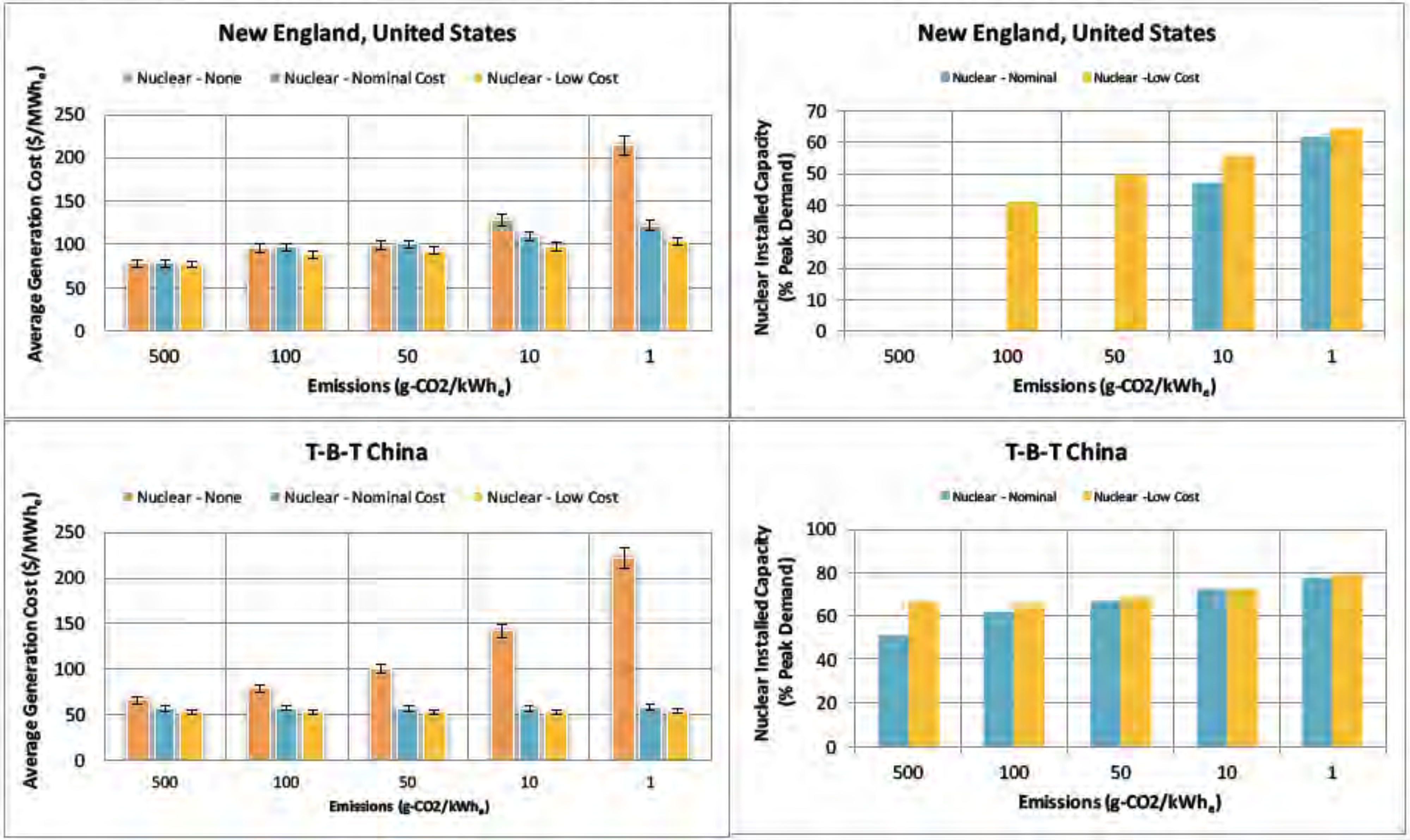
- The world faces the new challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity to billions of people
- A variety of low- or zero-carbon technologies can be employed in various combinations to meet the growing energy demand, but…
  - Without contribution from nuclear, the cost of achieving deep decarbonization targets increases significantly
  - The least-cost portfolios include an important share for nuclear, the magnitude of which significantly grows as the cost of nuclear drops
- So why isn't nuclear thriving?
  - *The fundamental problem is cost*
  - Public concern
  - Energy policy


The Future of Nuclear Energy in a Carbon-Constrained World

AN INTERDISCIPLINARY MIT STUDY

MIT, 2018
https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf

Figure E.1: (left) Average system cost of electricity (in $/MWh_e$) and (right) nuclear installed capacity (% of peak demand) in the New England region of the United States and the Tianjin-Beijing-Tangshan (T-B-T) region of China for different carbon constraints (gCO_2/kWh_e) and three scenarios of various available technologies in 2050: (a) no nuclear allowed, (b) nuclear is allowed at nominal overnight capital cost ($5,500 per kW_e for New England and $2,800 per kW_e for T-B-T), and (c) nuclear is allowed with improved overnight capital cost ($4,100 per kW_e for New England and $2,100 per kW_e for T-B-T)

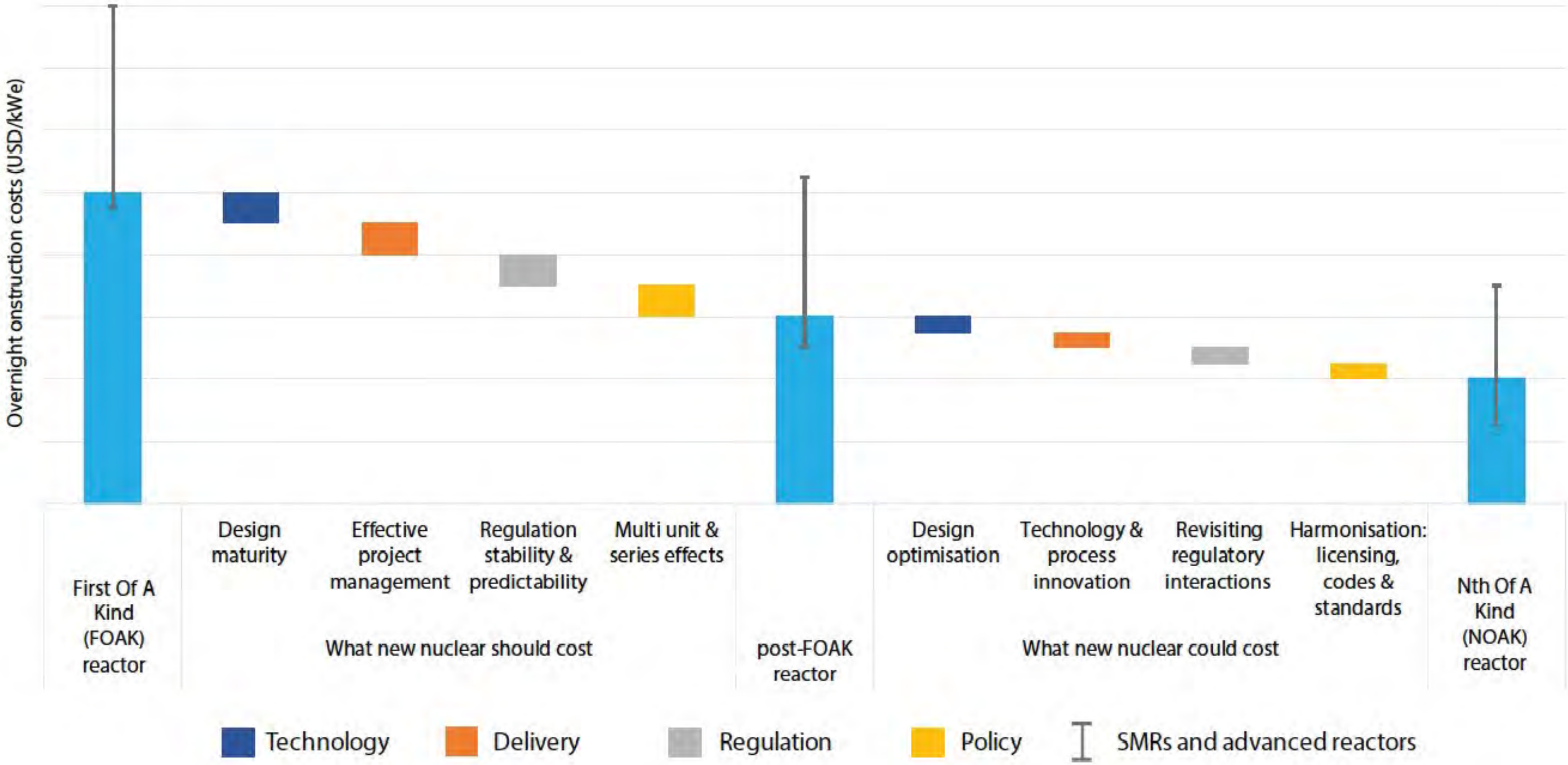


Addressing challenges to nuclear energy growth

- Cost
  - Increase focus on proven project/construction management practices will increase probability of success
  - A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants
- Public concerns on consequences of severe accidents
  - A shift toward reactor designs that incorporate inherent and passive safety features – such design evolution has already occurred in some Generation-III LWRs and is exhibited in new plants built in China, Russia, and the United States
  - Certain modifications to the current regulatory framework could improve the efficiency and efficacy of licensing reviews
- Policy
  - Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits
  - Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing
  - Governments should establish funding programs around prototype testing and commercial deployment of advanced reactor designs

MIT, 2018

Advanced nuclear economics

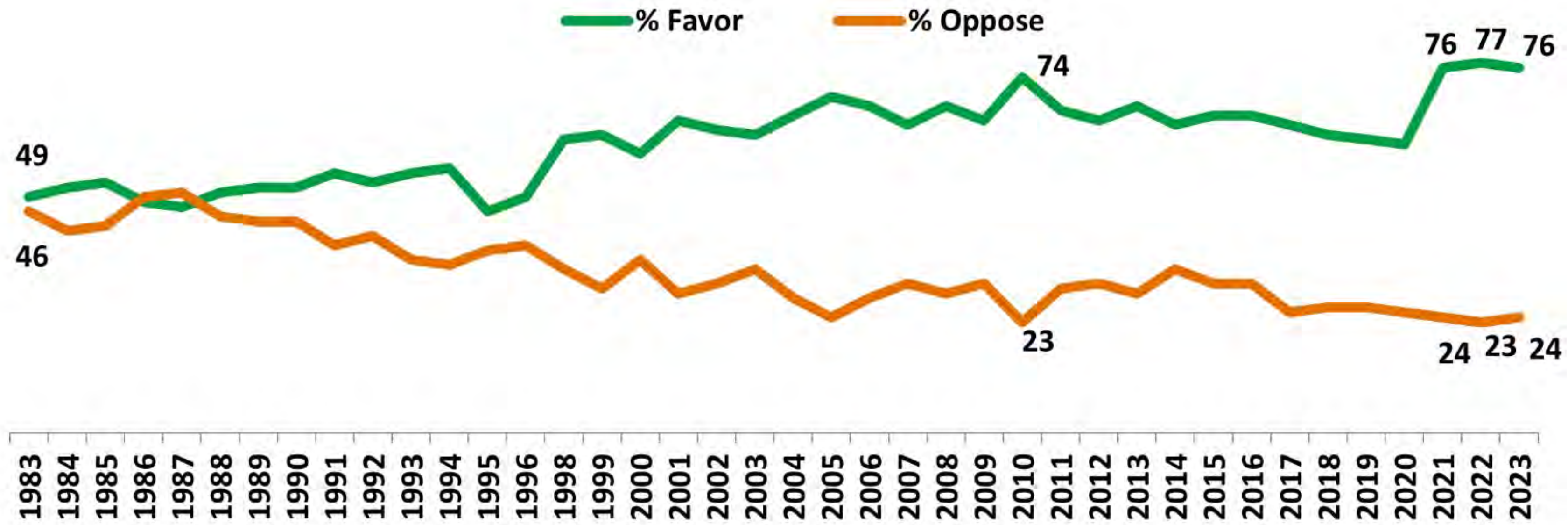


Nuclear Innovation Alliance, 2023

Record high favorability to nuclear energy

Favorability to Nuclear Energy 1983-2023

Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States? (%)



Bisconti Research, Inc., 2023 National Nuclear Energy Public Opinion Survey: Public Support for Nuclear Energy Stays at Record Level For Third Year in a Row, April-May 2023, https://www.bisconti.com/blog/public-opinion-2023

Most Americans hold favorable opinions about nuclear energy and its role:

- 86%, nuclear energy will be important in meeting nation’s electricity needs
- 89%, should renew the license of nuclear power plants that continue to meet federal safety standards
- 87%, our nation should prepare now so that advanced nuclear power plants will be available
- 71%, we should definitely build more nuclear power plants in the future.

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

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

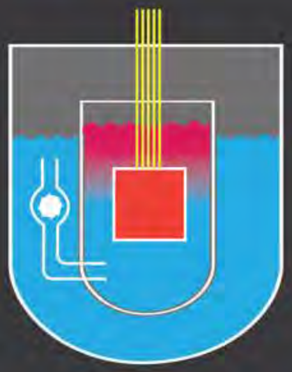
300 MW to 1,000 + MW

Full-size Reactors

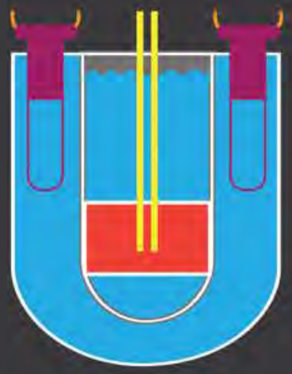
Can provide reliable, emissions-free baseload power

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.



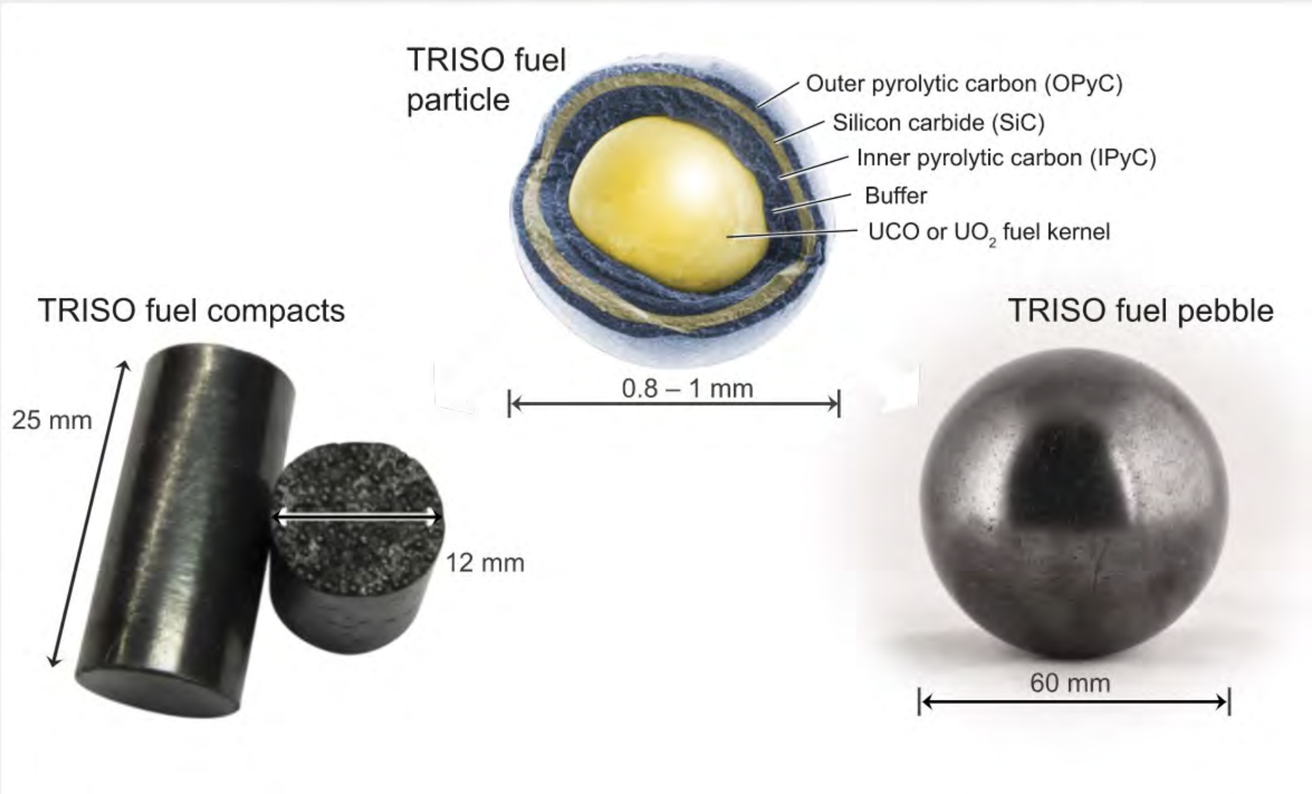
LIQUID METAL FAST REACTORS - Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.

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

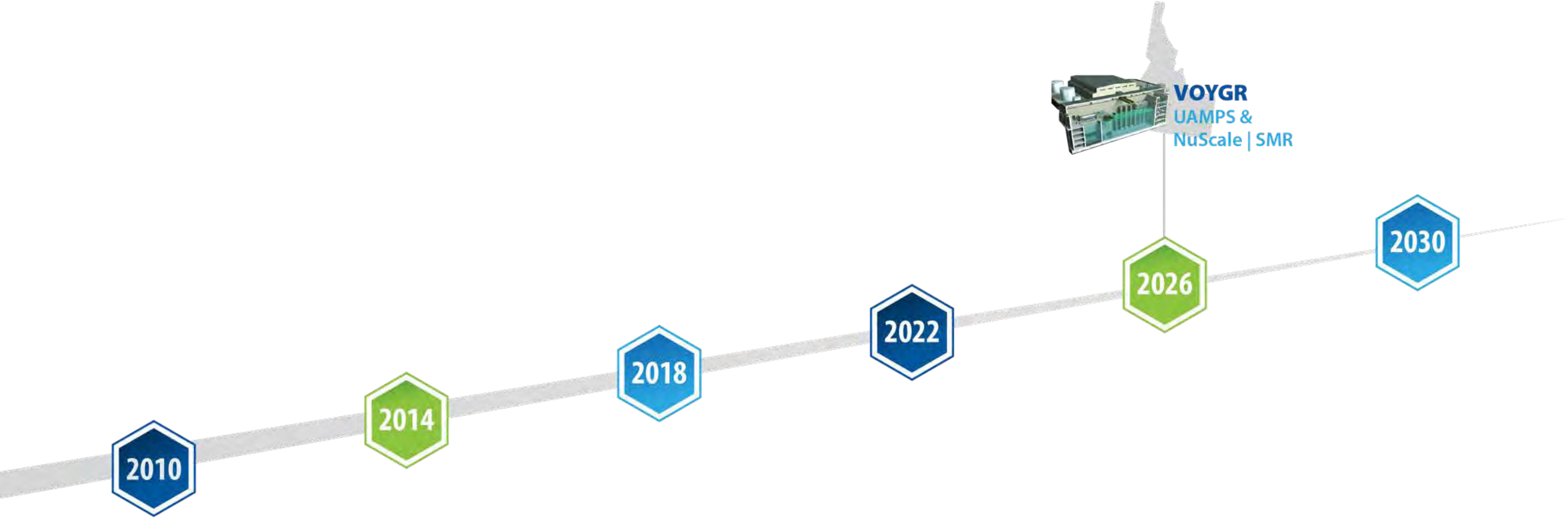
Advanced Safety Approaches

- “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

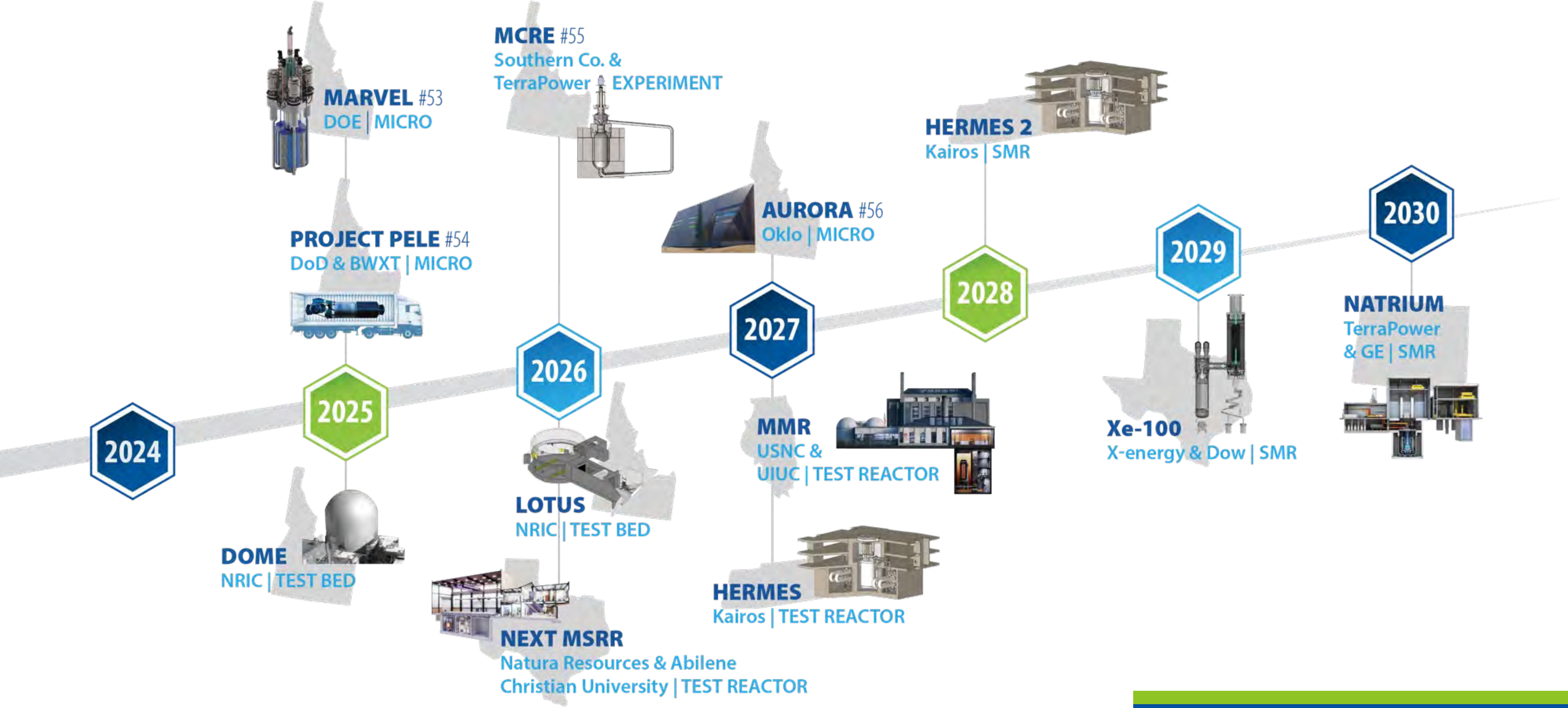
- Limit impacts to site boundary through novel fuel designs
  - TRISO fuel – contains fission products around each fuel element
  - Keep fuel cool without power supply using passive safety approaches
  - Molten salt fuel – contains fission products in liquid or removes and stores continuously; online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



10 years ago the advanced reactor ecosystem was bleak



Accelerating advanced reactor demonstration & deployment



2024

2025

DOME
NRIC | TEST BED

PROJECT PELE #54
DoD & BWXT | MICRO

MARVEL #53
DOE | MICRO

2026

LOTUS
NRIC | TEST BED

NEXT MSRR
Natura Resources & Abilene Christian University | TEST REACTOR

MCRE #55
Southern Co. & TerraPower | EXPERIMENT

2027

AURORA #56
Oklo | MICRO

MMR
USNC & UIUC | TEST REACTOR

HERMES
Kairos | TEST REACTOR

2028

HERMES 2
Kairos | SMR

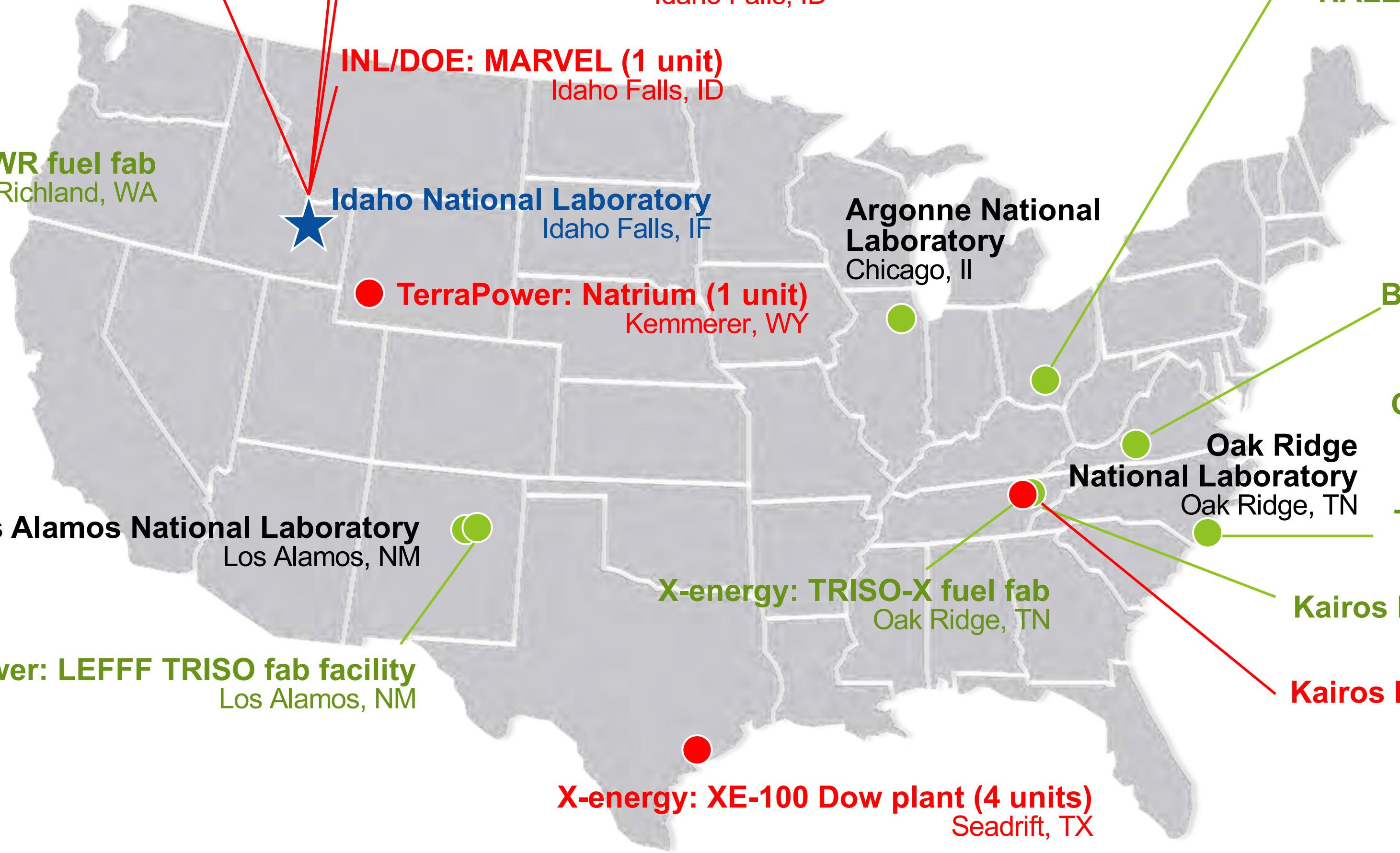
2029

Xe-100
X-energy & Dow | SMR

2030

NATRIUM
TerraPower & GE | SMR

Advanced reactor projects and fuel fabrication facilities



UAMPS/NuScale: VOYGR (6 units)
Idaho Falls, ID

OKLO: AURORA (1 unit)
Idaho Falls, ID

BWXT/DOD: PELE (1 mobile unit)
Idaho Falls, ID

INL/DOE: MARVEL (1 unit)
Idaho Falls, ID

American Centrifuge Operating (Centrus Energy) HALEU production
Piketon, OH

Framatome: LWR fuel fab
Richland, WA

Idaho National Laboratory
Idaho Falls, IF

Argonne National Laboratory
Chicago, Il

TerraPower: Natrium (1 unit)
Kemmerer, WY

BWXT: Pele & BANR fuel fab
Lynchburg, VA

GEH, Westinghouse: LWR fuel fab
Wilmington NC, Columbia, SC

Oak Ridge National Laboratory
Oak Ridge, TN

TerraPower: Natrium fuel fab
Wilmington, NC

Los Alamos National Laboratory
Los Alamos, NM

X-energy: TRISO-X fuel fab
Oak Ridge, TN

Kairos Power: Atlas fuel fab
Oak Ridge, TN

Kairos Power: LEFFF TRISO fab facility
Los Alamos, NM

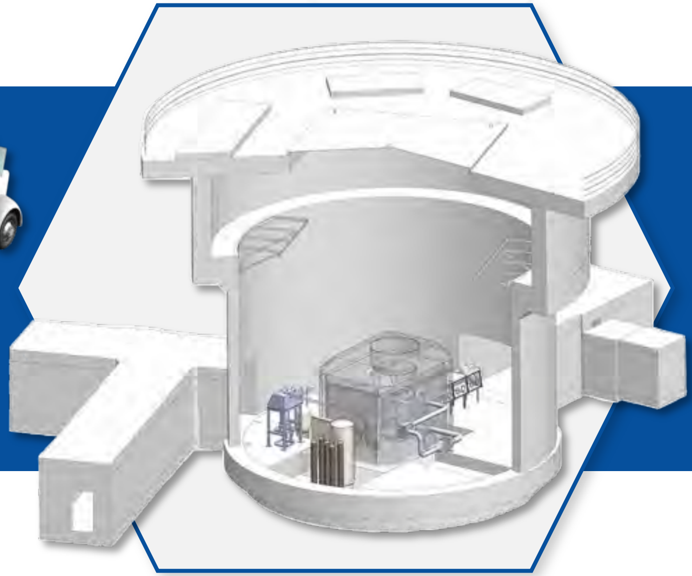
Kairos Power: HERMES (1 unit)
Oak Ridge, TN

X-energy: XE-100 Dow plant (4 units)
Seadrift, TX

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

Shifting the energy paradigm

TODAY

Electricity-only focus

Nuclear Energy Generation

(Light water reactors, high temperature advanced reactors, small modular reactors, etc.)

Other Energy Generation

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

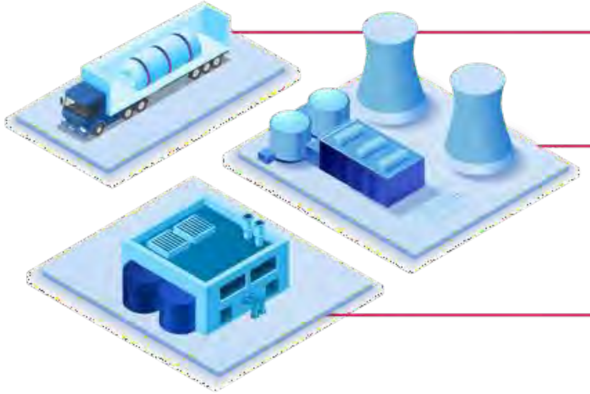
Integrated energy systems (IES) leverage the contributions from nuclear energy beyond electricity

- Biofuel, transportation fuels
- Hydrogen for transportation
- Chemicals, polymers
- Fertilizer, ammonia
- Iron, steel, metals
- Wood products, cardboard, paper
- Other industrial processes
- Clean Water
- District heating
- Flexible electricity

*Energy storage includes electrical batteries, chemicals and thermal storage.

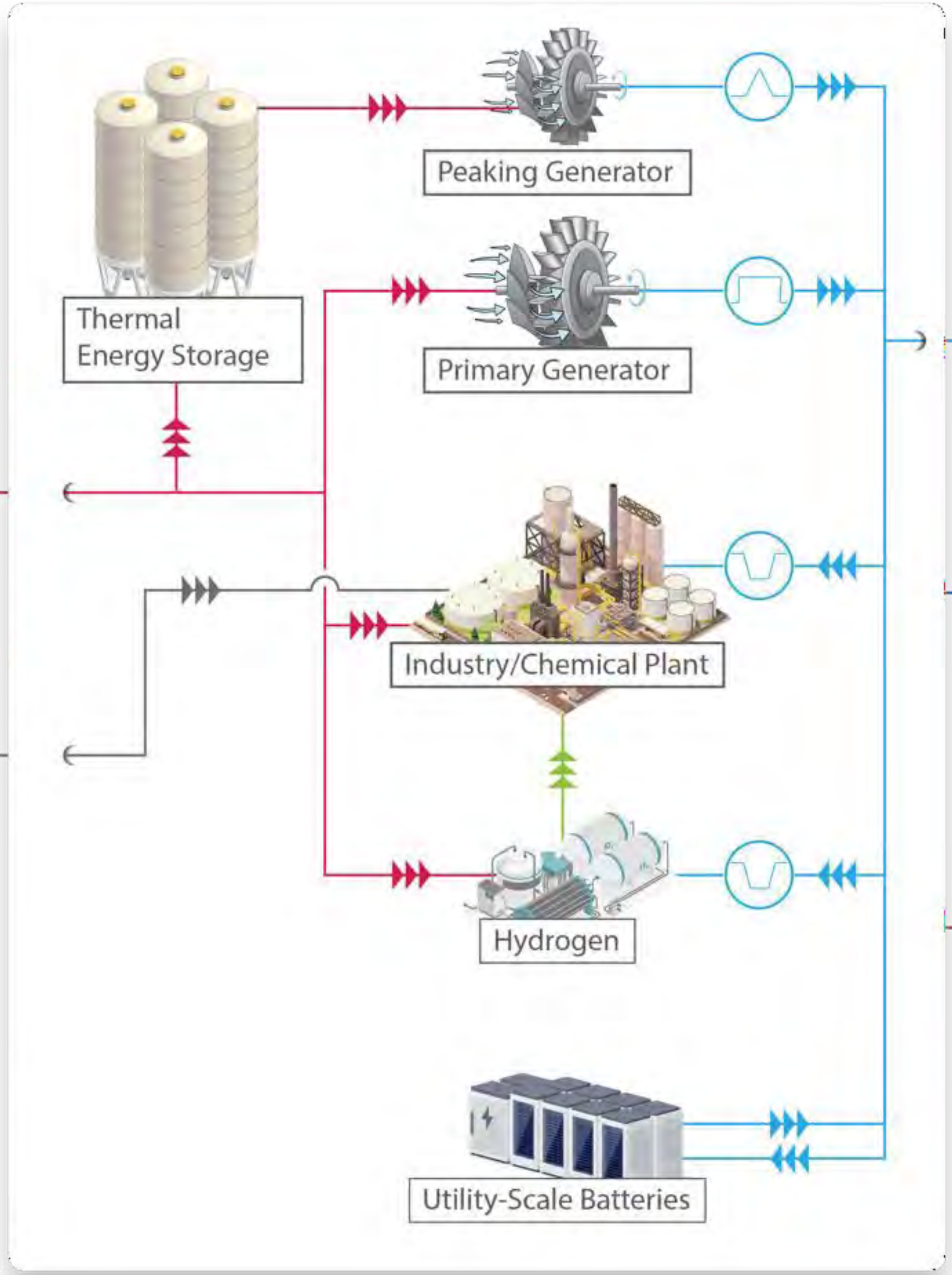
Flexible Reactor Siting

Data Centers
Manufacturing Plants
Biofuel Plants / Processing
Desalination
Industrial Parks / Plants
Fueling Stations



CO2 / Carbon Sources

Ethanol Plants
Direct Air Capture
Power Generators
Cement Plants
Biomass
Polymer / Chemical Waste



Thermal Energy Storage

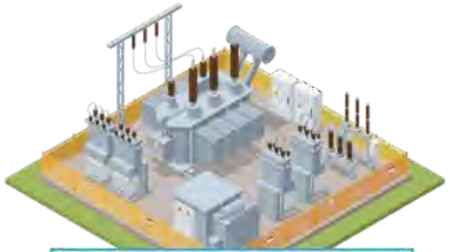
Peaking Generator

Primary Generator

Industry/Chemical Plant

Hydrogen

Utility-Scale Batteries



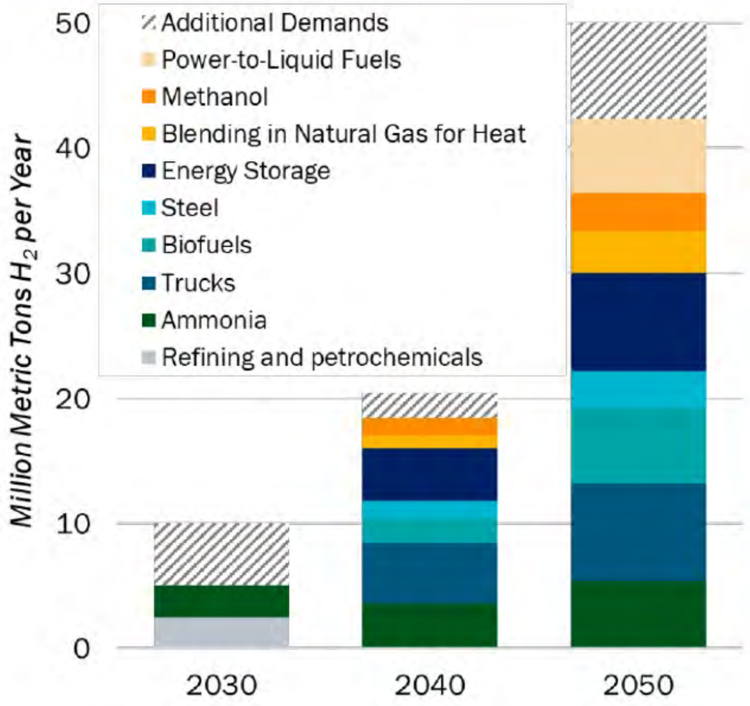
Grid Capacity
Firm, Flexible, Zero Carbon

Transportation Fuels
Steel Production
Fertilizer / Ammonia
Polymers / Chemicals
Hydrogen

Refineries / Oil Production
Minerals
Wood / Paper Plants
District Heating

National clean H_2 strategy—The opportunity for clean H_2

Opportunities for Clean Hydrogen Across Applications

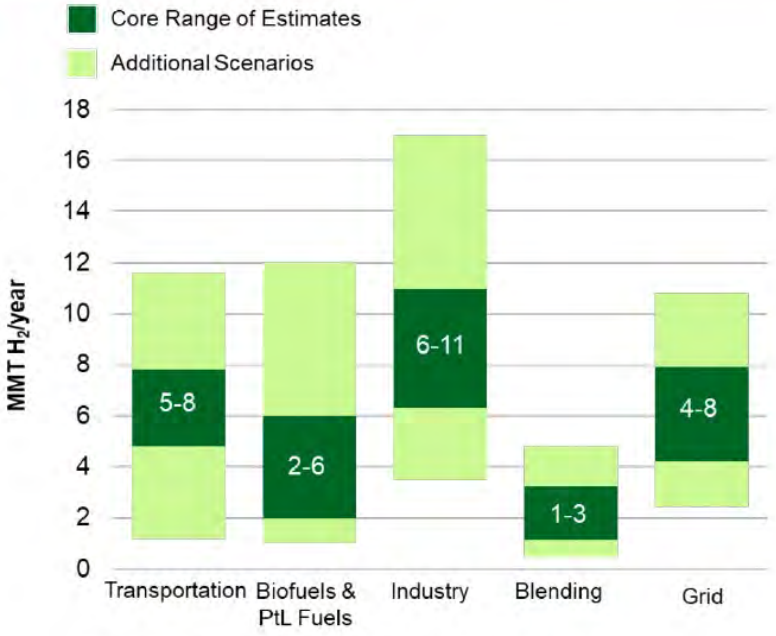


U.S. Opportunity:
10MMT/yr by 2030, 20 MMT/yr by 2040, 50 MMT/yr by 2050

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



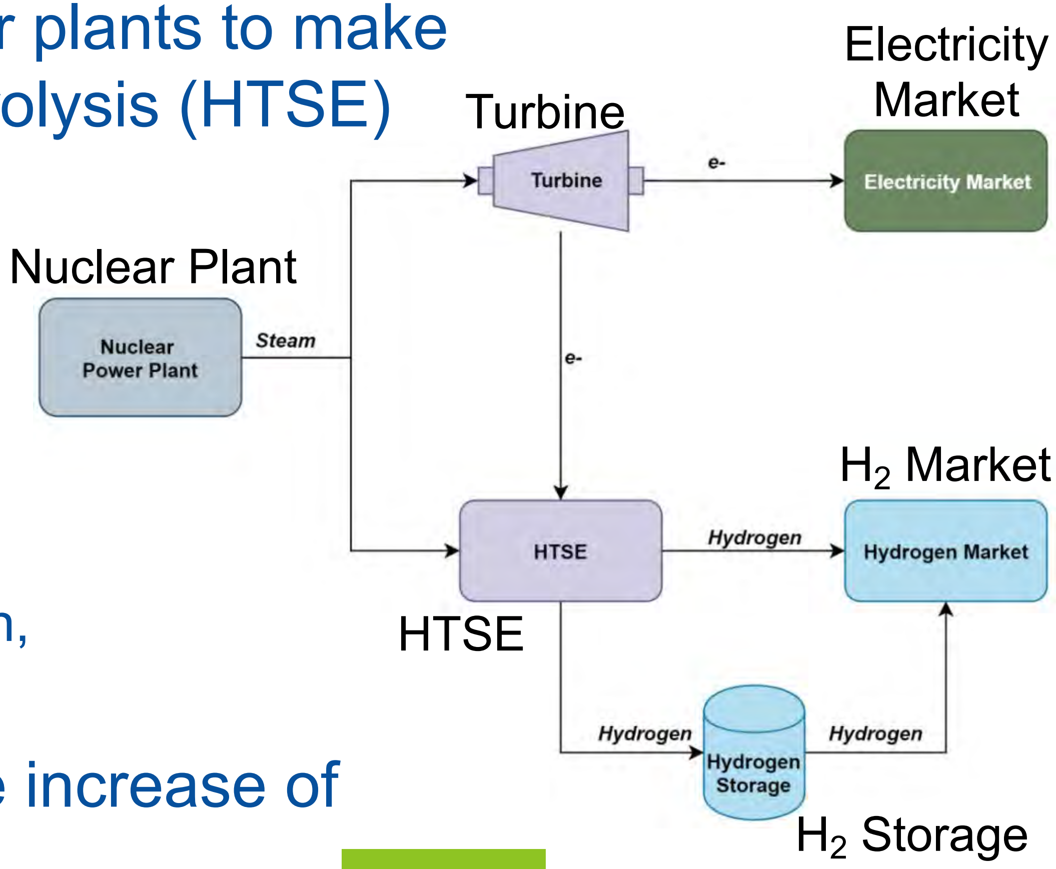
- **Core range: ~ 18–36 MMT H_2**
- **Higher range: ~ 36–56 MMT H_2**

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

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

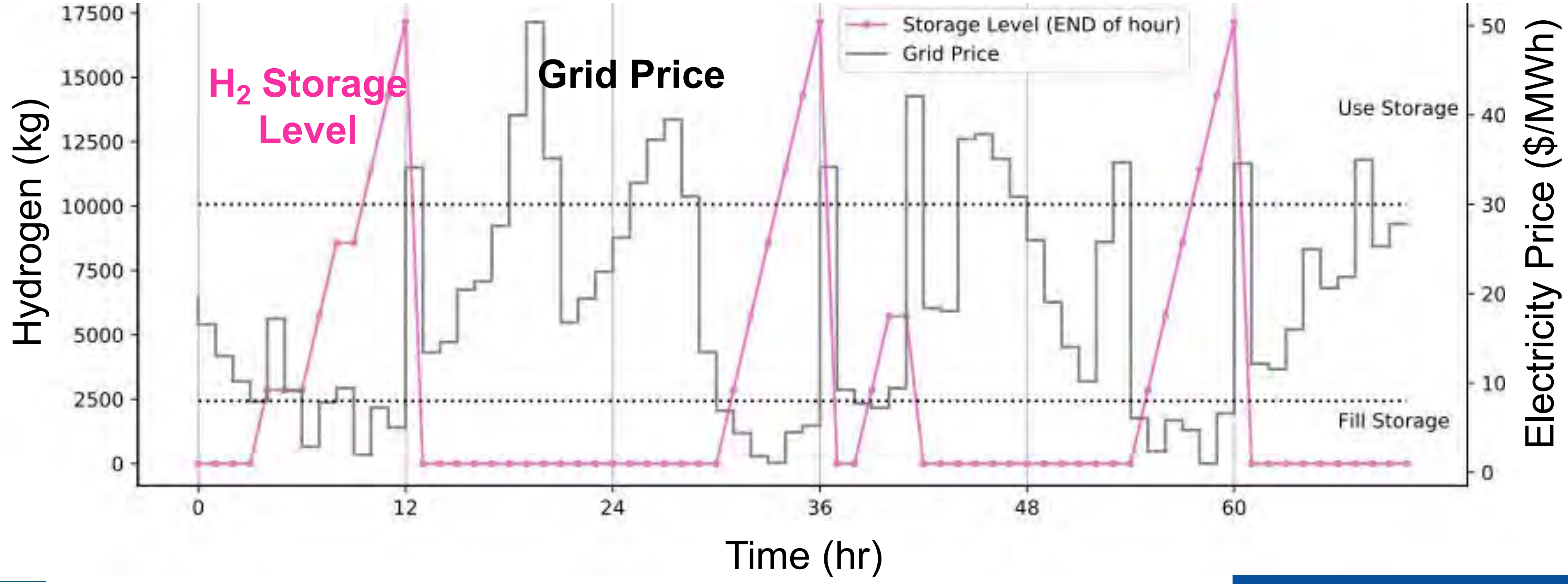
Example: Disruptive potential of nuclear produced hydrogen

- 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)



Integrated Energy Systems

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/

Example: Nuclear synthetic fuels production

- 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

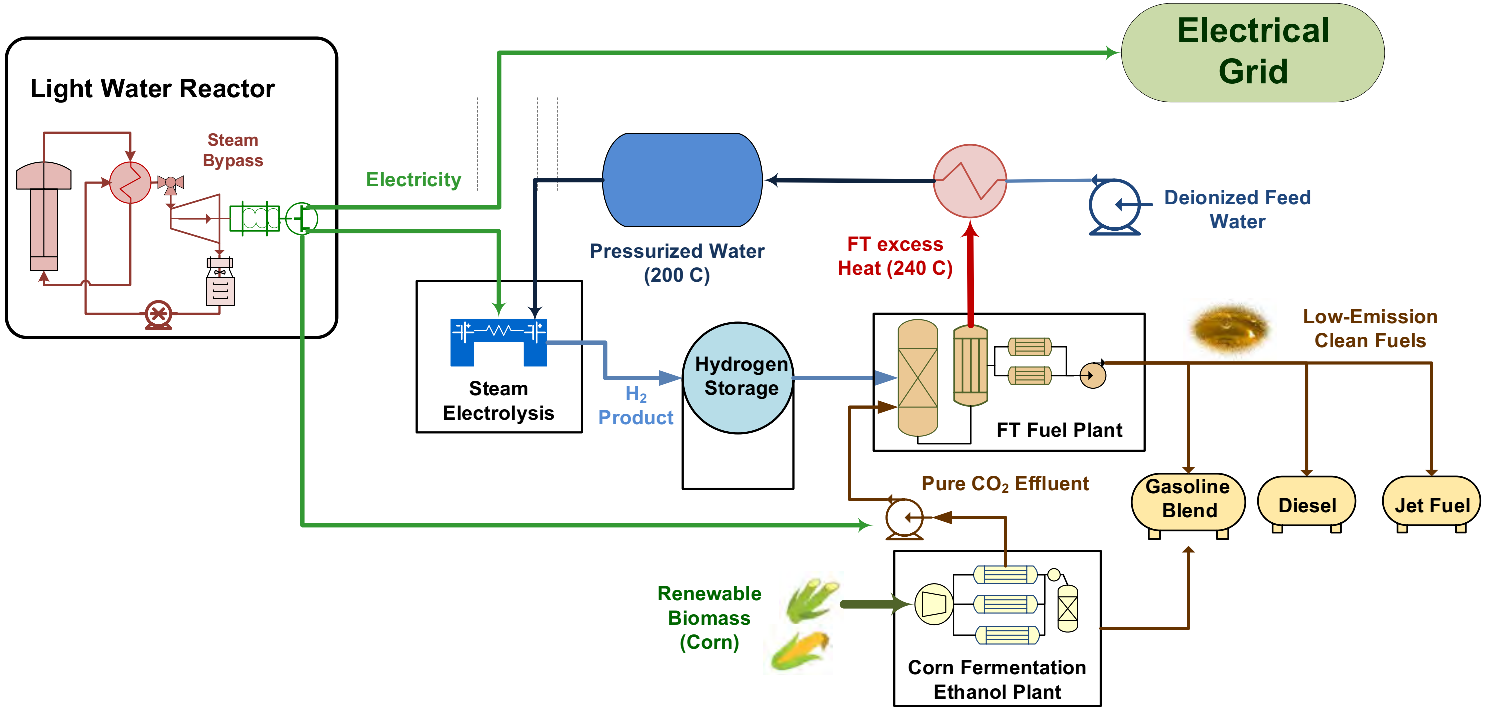
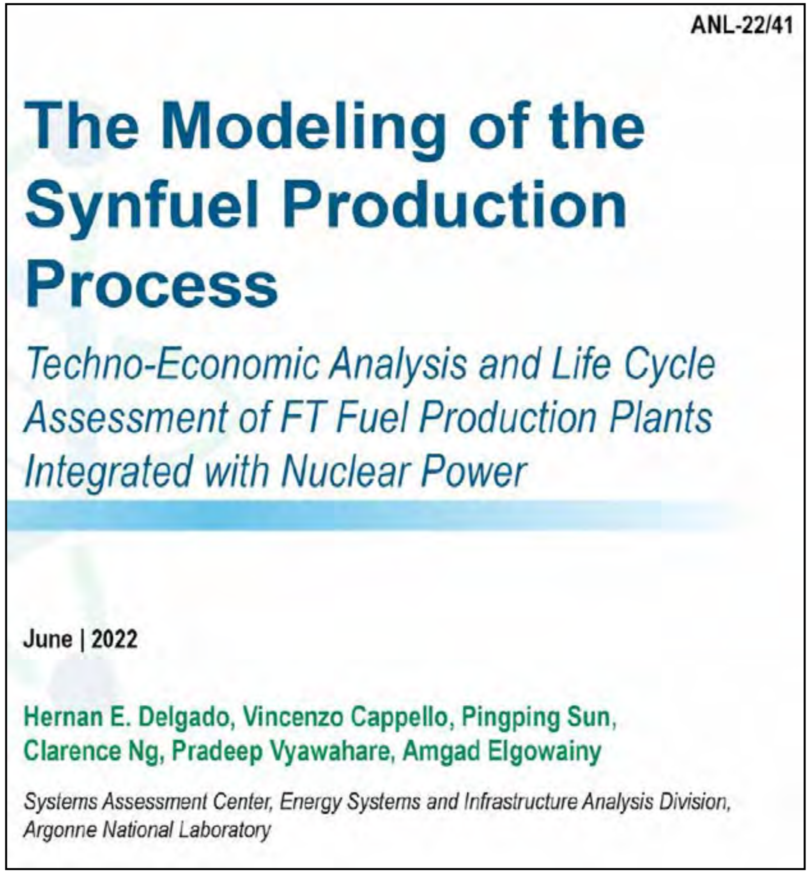


Figure: Representation of a Nuclear Coupled Synthetic Fuels Process

***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

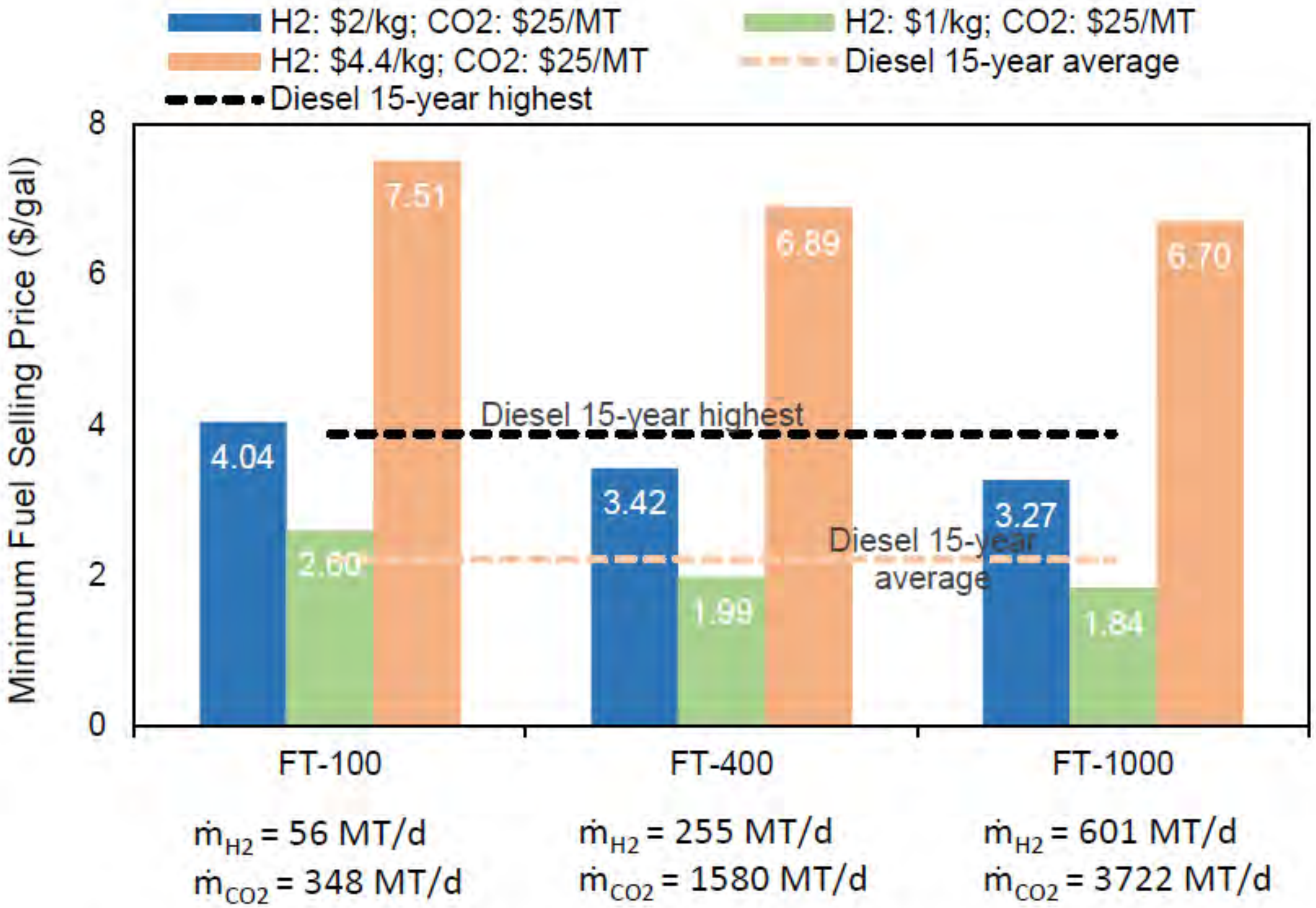
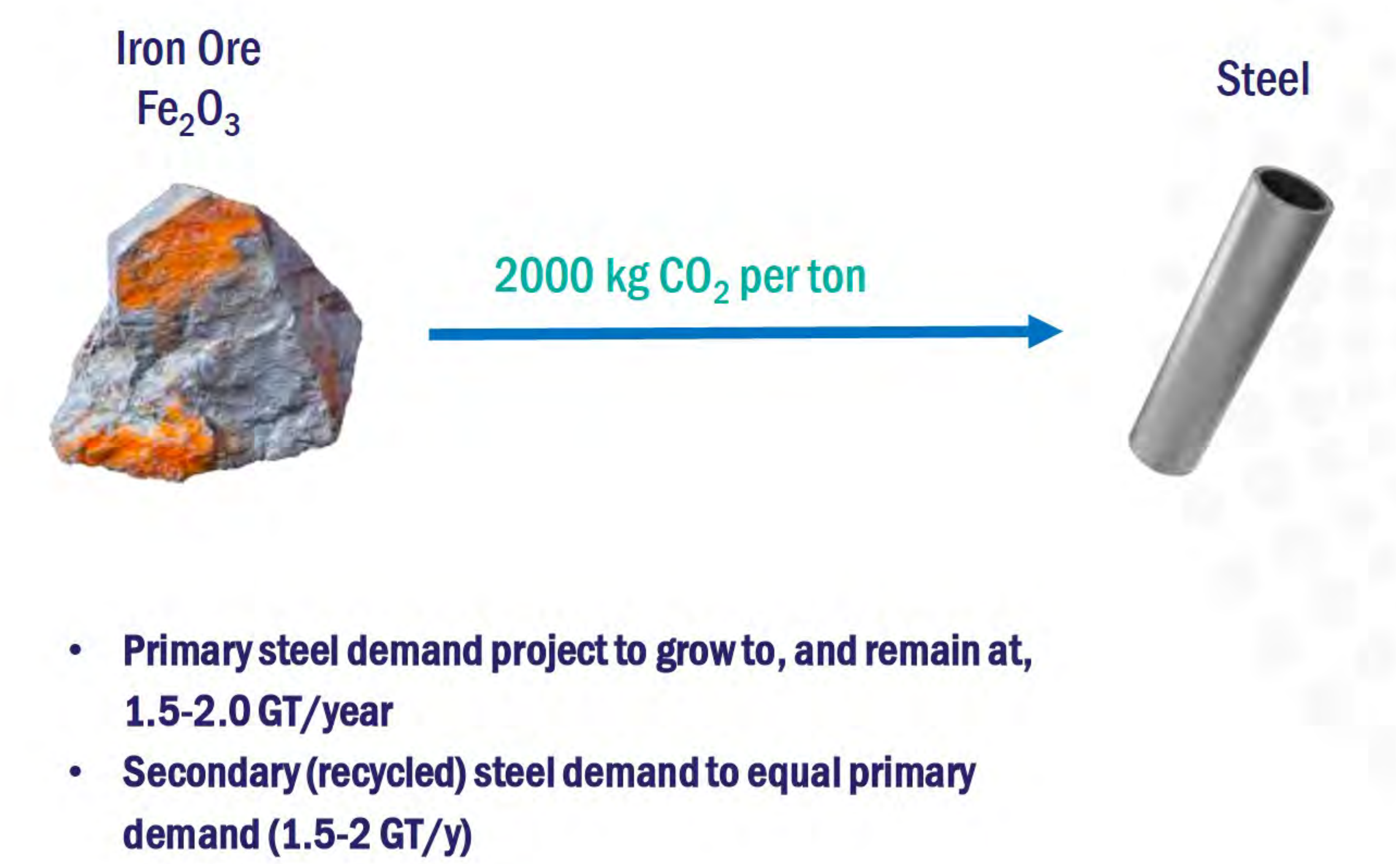


Figure I. Production cost of FT fuel at different plant scales and H_2 prices.

Example: Decarbonizing steel production

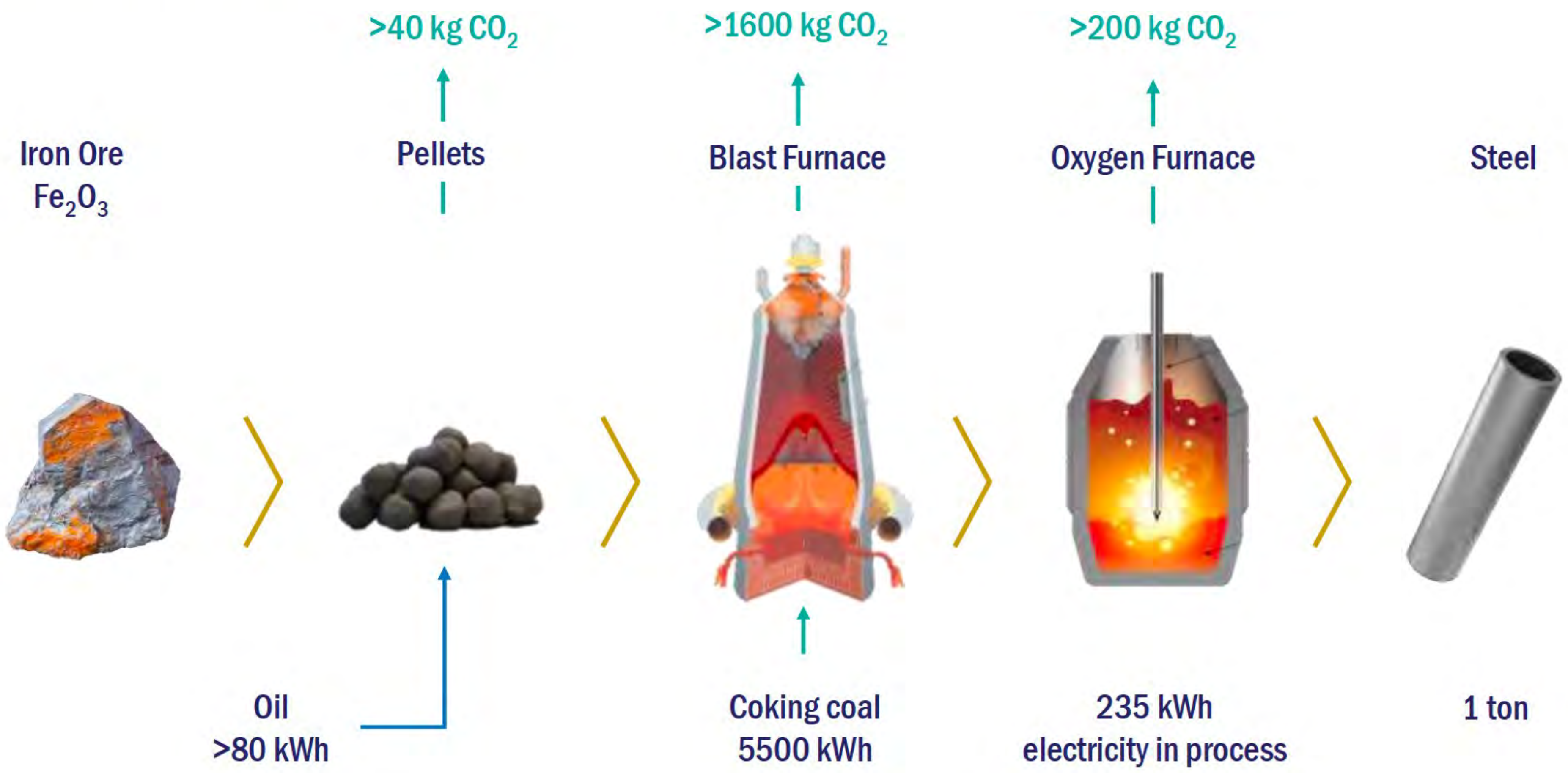


- Primary steel demand project to grow to, and remain at, 1.5-2.0 GT/year
- Secondary (recycled) steel demand to equal primary demand (1.5-2 GT/y)

Iron & Steel contribute 8.5% of global CO_2 emissions today, more than air, ship, rail, and cement combined

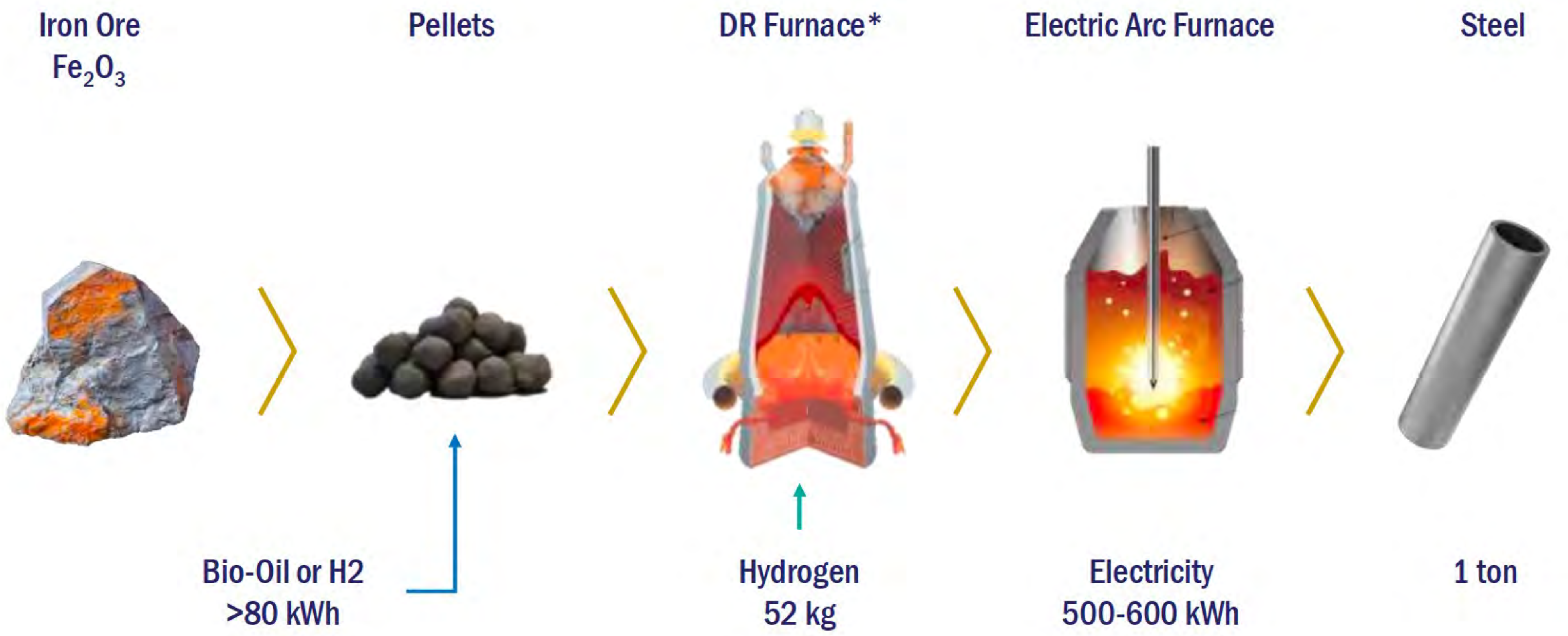
Reference: S. Qvist and D. Victor, The Staggering Need for Clean Electrons and Molecules, Net Zero Nuclear Summit, December 2023.

Standard process, iron→steel



Reference: S. Qvist and D. Victor, The Staggering Need for Clean Electrons and Molecules, Net Zero Nuclear Summit, December 2023.

Green process, iron→steel



Reference: S. Qvist and D. Victor, The Staggering Need for Clean Electrons and Molecules, Net Zero Nuclear Summit, December 2023.

Overall energy demand for green steel

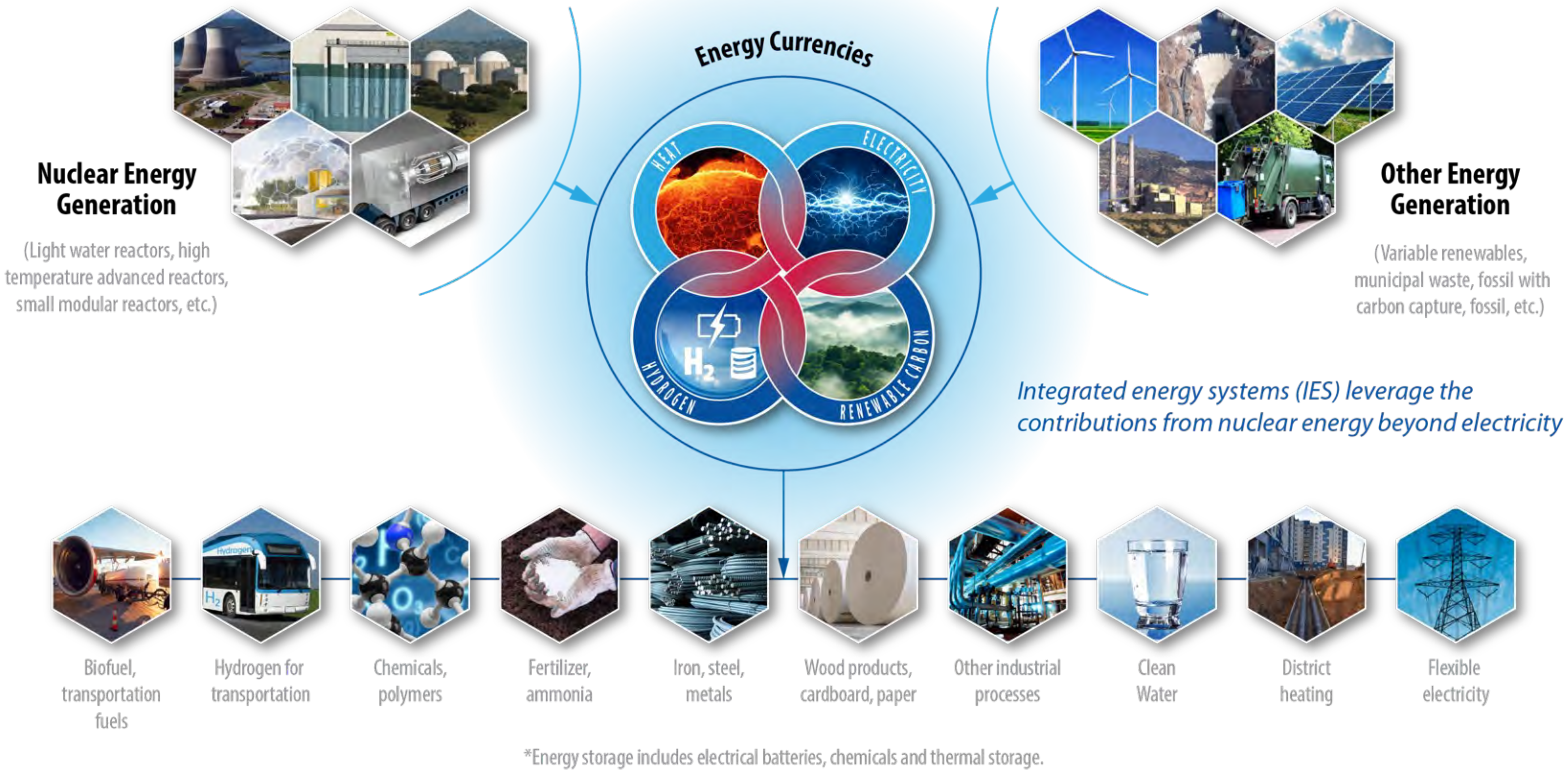
- Energy requirement for production of 1 ton of green steel is equivalent to the annual global per capita energy consumption in 2022 (3.6 MWh)
  - Primary: 3.6 MWh/ton steel
  - Secondary: 0.6 MWh/ton steel

- Switching to FULLY green steel would require
  - 680 large scale reactors for primary steel (from ore)
  - 110 large scale reactors for secondary steel (from scrap)

- **This industry ALONE would demand 3x nuclear power relative to today**

Moving the Needle—Demonstrating Component and System Performance

Integrated Energy Systems: *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

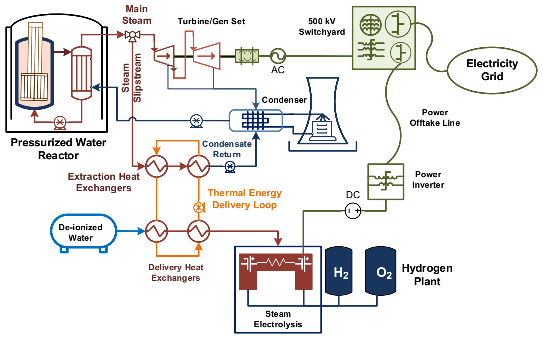
- Enhance tools and approaches to optimize IES operations

Hydrogen technology development and commercialization

Cell Fabrication and Stack Manufacturing

Modular Systems / Balance of Plant

Pilot Plant and Commercial Scale Demonstration



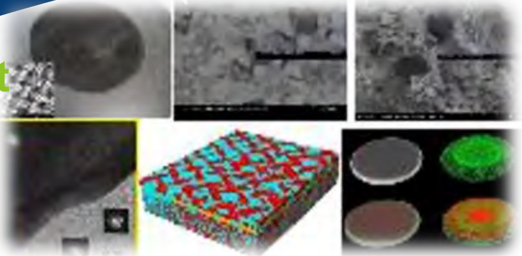
Commercial Demonstrations

High Throughput Materials Testing

5-20 kWe stack assembly and performance testing

3-10 cell short stack testing

Materials Preparation



Electrode Engineering & Diagnosis

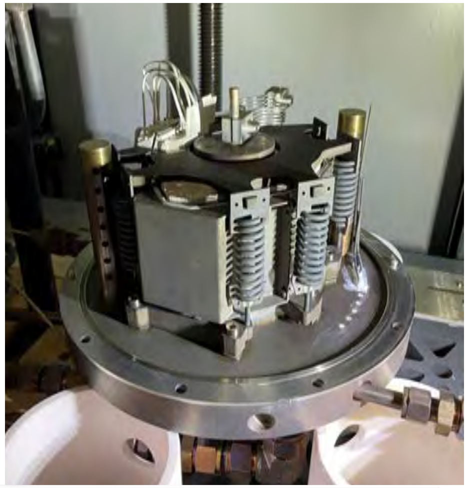
Commercial Stack Testing

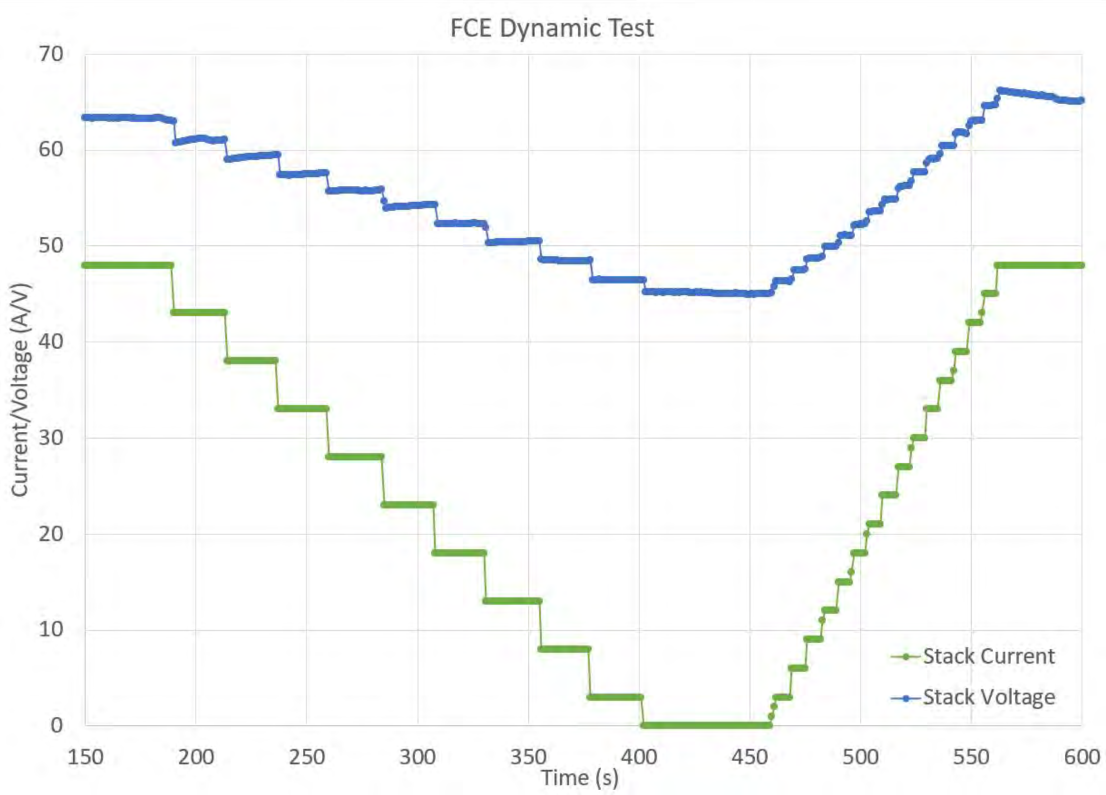
Materials Development and Testing

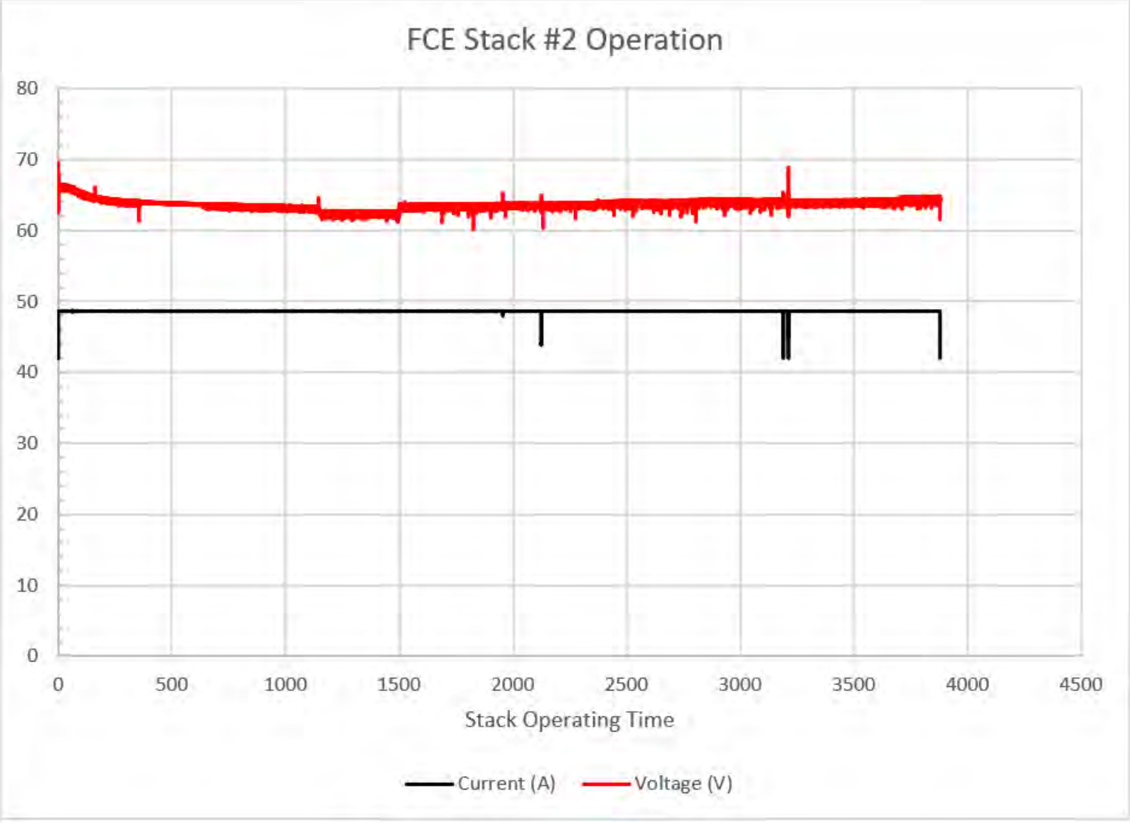
Targeting high performance, durability, and cost efficiency

Commercial Stack Testing (25kW)

- Total Hours >2000 hr
- Dynamic Loading 0-100% <10 Mins
- DC Electric Efficiency ~34 kWh/kg
- No discernable degradation



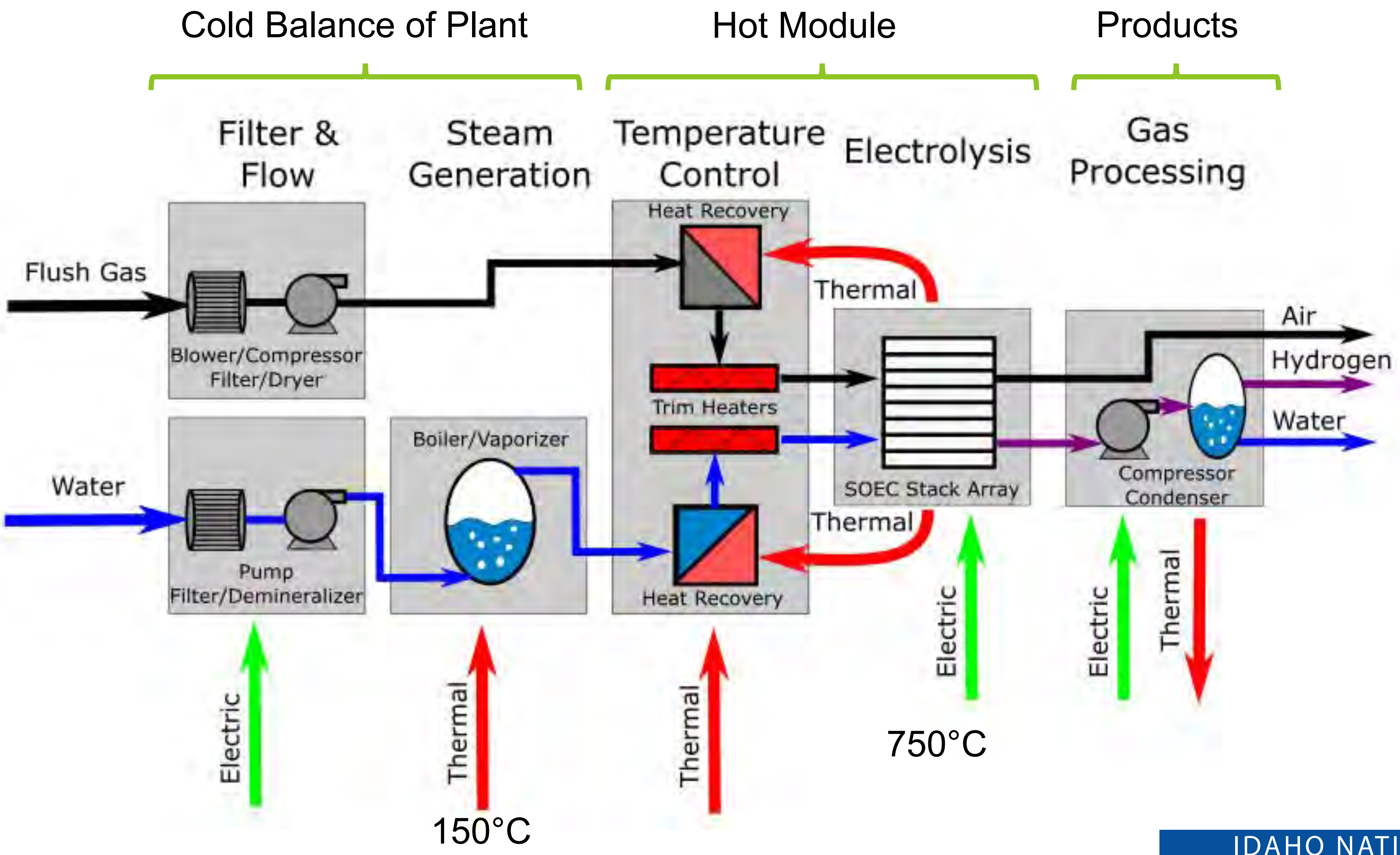




50 kW SOEC Test Systems

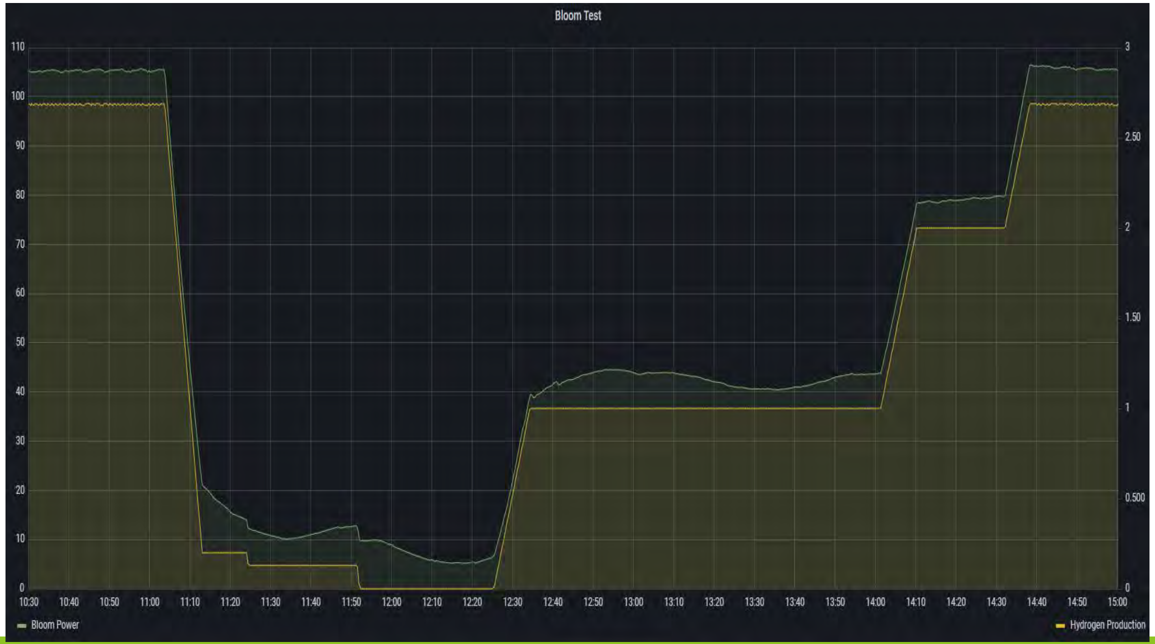
- System Architecture
  - Outdoor installation in Conex
  - Shared Steam Source
  - Independent Reactant/Power
  - Flexible operation
- 1st 50kW SOEC System Complete
  - Steam Commissioning, September 2023
  - OxEon Stack Array Install, October 2023
- 2nd 50kW SOEC System – In Process
  - Build Ongoing, ~50% complete
  - Stack Install TBD

Hight temperature electrolysis system block diagram

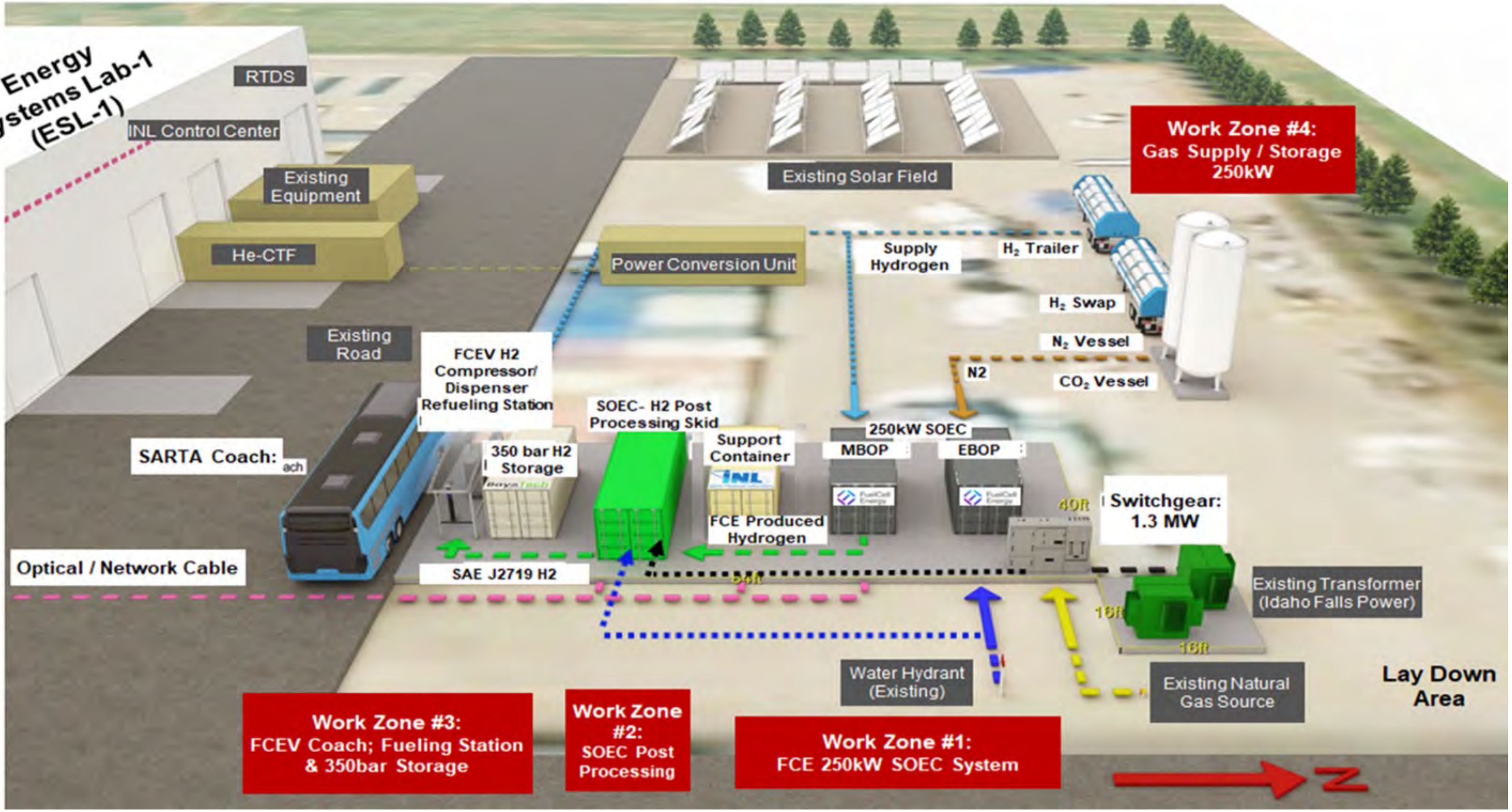


Commercial System Test

- Operating Test
  - Total Hours >5000 hr
  - Dynamic Loading 0-100% <10 Mins
  - Steam input @ 150°C
  - DC Electric System Efficiency ~37.5 kWh/kg
  - No Discernable Degradation



Post Processing and Refueling Station



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

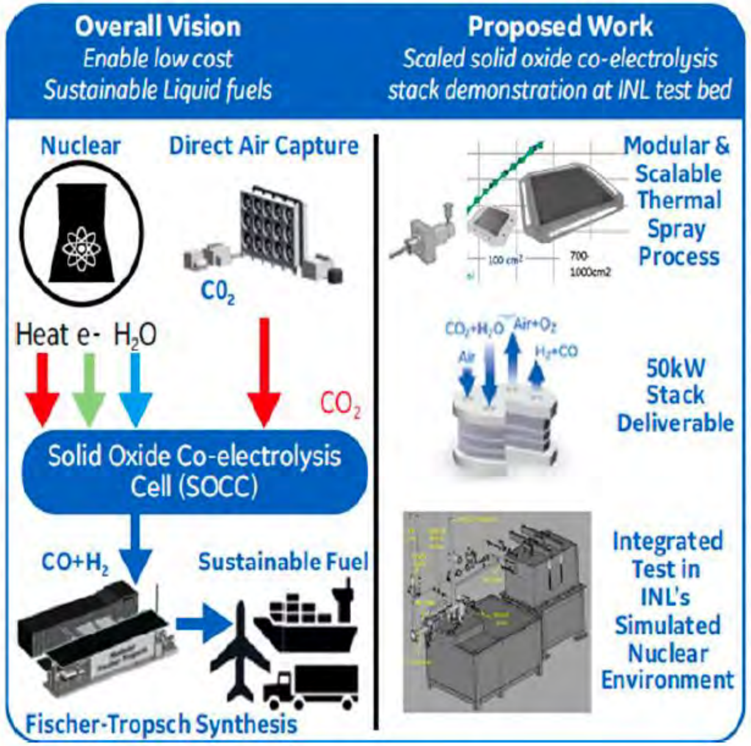
Xcel Energy: Prairie Island Plant

- 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

Additional 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

Potential Impact: 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

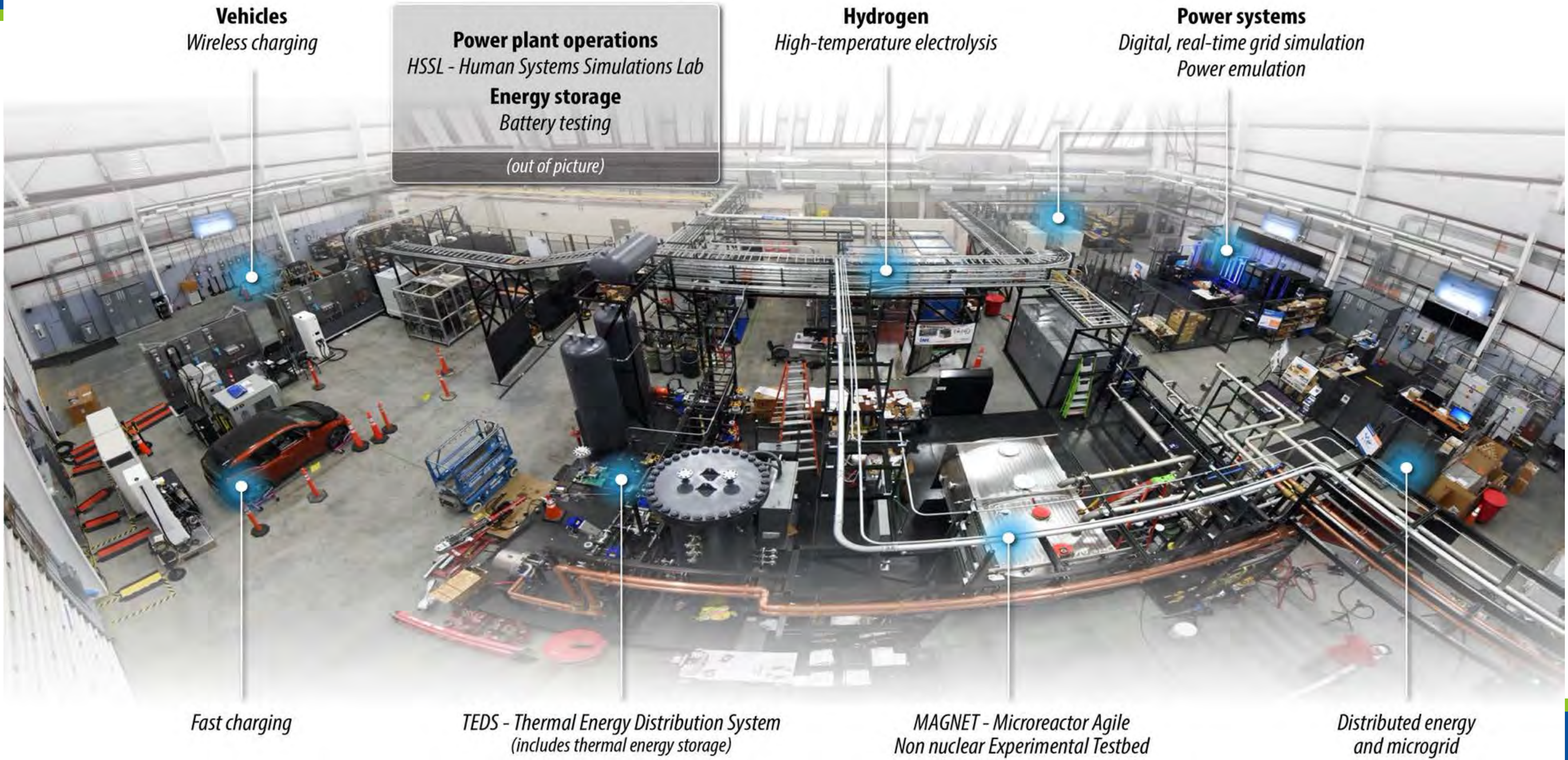
Westinghouse

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)

Potential Impact: 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)



Vehicles
Wireless charging

Power plant operations
HSSL - Human Systems Simulations Lab
Energy storage
Battery testing
(out of picture)

Hydrogen
High-temperature electrolysis

Power systems
Digital, real-time grid simulation
Power emulation

Fast charging

TEDS - Thermal Energy Distribution System
(includes thermal energy storage)

MAGNET - Microreactor Agile
Non nuclear Experimental Testbed

Distributed energy
and microgrid

Energy Technology Proving Ground (ETPG)

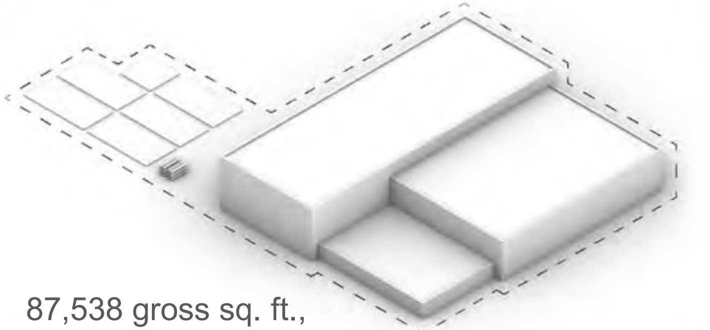
**Artist rendition of the ETPG.*

A demonstration and testbed complex that:

- *Validates industrial technologies*
- *Designs and controls integrated energy systems*
- *Leverages contributions from nuclear energy beyond electricity*
- *Integrates and leverages testbeds across the DOE laboratory complex, e.g. NREL-ARIES*

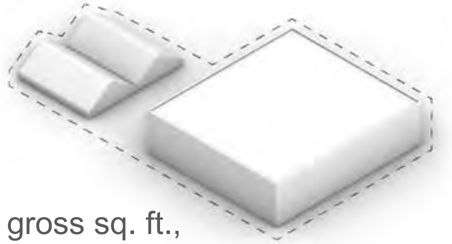
Conceptual Energy Technology Proving Ground R&D Facilities

High Temperature Test Facility



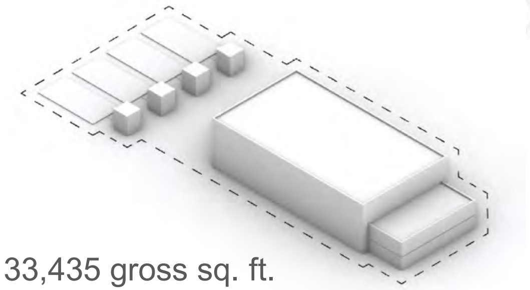
87,538 gross sq. ft.,
0.4 acres of test pads

Biomass & Waste Carbon Preprocessing



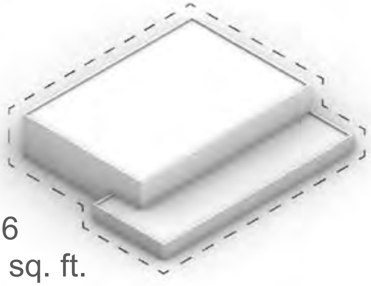
56,926 gross sq. ft.,
1.0 acre of paved space

Microreactor Testing & Operations Facility



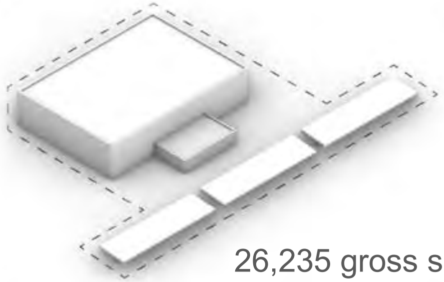
33,435 gross sq. ft.
2.5 acres of test pad space

Thermal Energy & Carbon Management Facility



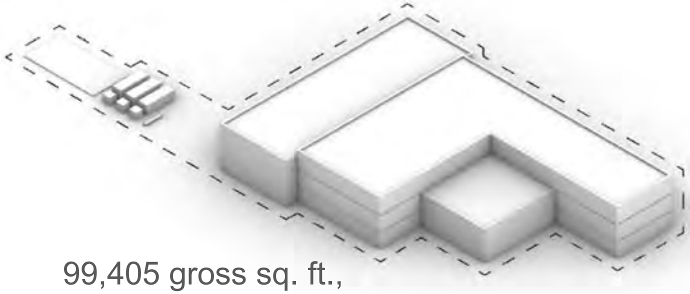
45,336
gross sq. ft.

Travel Center of the Future Facility



26,235 gross sq. ft.,
34 acres of paved space

Integrated Energy Systems Testing Facility



99,405 gross sq. ft.,
1.1 acres of test pad space

The Energy Technology Proving Ground contributes to six DOE Energy Earth Shots

Industrial Heat

85% lower emissions by 2035

Enhanced Geothermal

$45/MWh by 2035

Long Duration Storage

90% lower cost
10+hrs of storage
1 decade

Hydrogen

$1 per kg in 1 decade

Carbon Negative

< $100 per ton in 1 decade

Clean Fuels & Products

85% lower GHG emissions by 2035

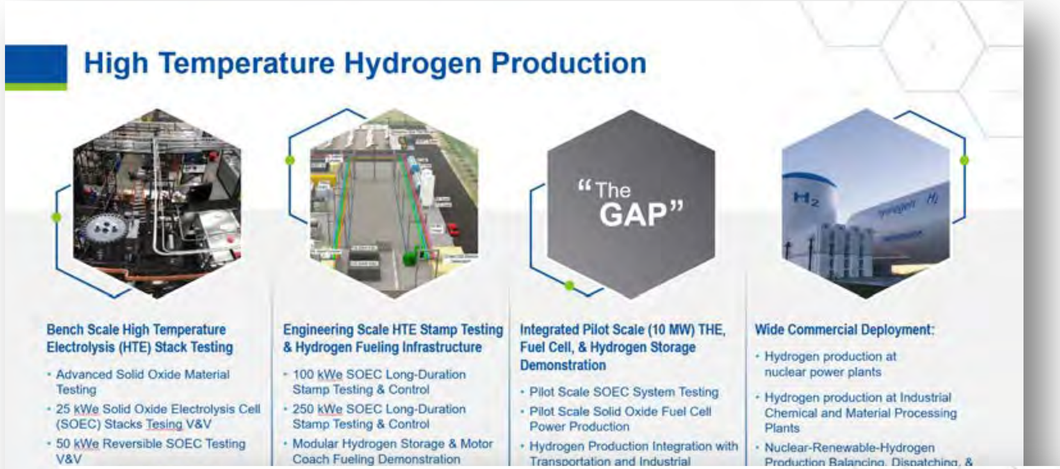
Offshore Wind

$45/MWh by 2035

Affordable Home

Lower Energy Costs by 20% by 2034

The Energy Technology Proving Ground Fills R&D Gaps for At-Scale Demonstrations



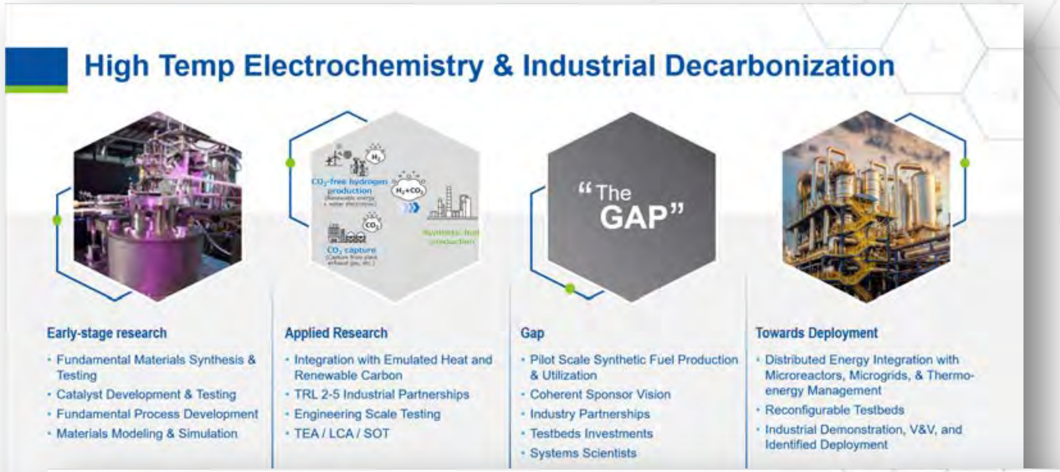
High Temperature Hydrogen Production

Bench Scale High Temperature Electrolysis (HTE) Stack Testing
- Advanced Solid Oxide Material Testing
- 25 kWe Solid Oxide Electrolysis Cell (SOEC) Stacks Tesing V&V
- 50 kWe Reversible SOEC Testing V&V

Engineering Scale HTE Stamp Testing & Hydrogen Fueling Infrastructure
- 100 kWe SOEC Long-Duration Stamp Testing & Control
- 250 kWe SOEC Long-Duration Stamp Testing & Control
- Modular Hydrogen Storage & Motor Coach Fueling Demonstration

Integrated Pilot Scale (10 MW) THE, Fuel Cell, & Hydrogen Storage Demonstration
- Pilot Scale SOEC System Testing
- Pilot Scale Solid Oxide Fuel Cell Power Production
- Hydrogen Production Integration with Transportation and Industrial

Wide Commercial Deployment:
- Hydrogen production at nuclear power plants
- Hydrogen production at Industrial Chemical and Material Processing Plants
- Nuclear-Renewable-Hydrogen Production Balancing, Dispatching, &



High Temp Electrochemistry & Industrial Decarbonization

Early-stage research
- Fundamental Materials Synthesis & Testing
- Catalyst Development & Testing
- Fundamental Process Development
- Materials Modeling & Simulation

Applied Research
- Integration with Emulated Heat and Renewable Carbon
- TRL 2-5 Industrial Partnerships
- Engineering Scale Testing
- TEA / LCA / SOT

Gap
- Pilot Scale Synthetic Fuel Production & Utilization
- Coherent Sponsor Vision
- Industry Partnerships
- Testbeds Investments
- Systems Scientists

Towards Deployment
- Distributed Energy Integration with Microreactors, Microgrids, & Thermo-energy Management
- Reconfigurable Testbeds
- Industrial Demonstration, V&V, and Identified Deployment

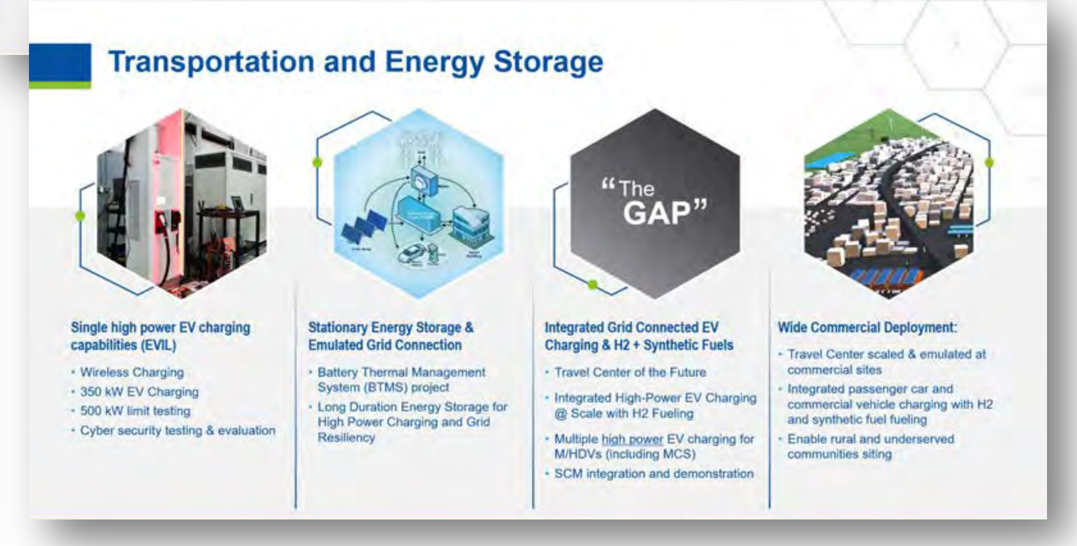
Biomass and Waste Carbon Feedstocks

Bench Scale Feedstock Characterization & Digital Engineering Toolbox
- Property measurements
- Hierarchical Biomass Feedstock Library
- First principles-based modeling of preprocessing equipment
- First-plant TEAs target impactful equipment preprocessing systems

Pre-pilot & Engineering Scale Mechanical Processing
- Pilot scale equipment (≤ 5 tons/h)
- Provide kg to ton quantities of feedstocks for BETO program and industry partners
- Multiple comminution and fractionation methods
- Biomass, MSW, E-waste and industrial wastes

Integrated Demonstration of Carbon Utilization for Fuels & Products
- Integrated proof of operation system
- Supply of carbon-neutral CO_2 & syngas for user technology demonstrations
- Accelerates utilization of biomass & organic fractions of MSW, E-waste & industrial wastes for commercialization

Commercial Deployment of Fuels & Products
- Integration with range of clean energy technologies at scale
- Utilize biogenic carbon sources to produce carbon-negative fuels, durable goods and carbon sequestration products



Transportation and Energy Storage

Single high power EV charging capabilities (EVIL)
- Wireless Charging
- 350 kW EV Charging
- 500 kW limit testing
- Cyber security testing & evaluation

Stationary Energy Storage & Emulated Grid Connection
- Battery Thermal Management System (BTMS) project
- Long Duration Energy Storage for High Power Charging and Grid Resiliency

Integrated Grid Connected EV Charging & H2 + Synthetic Fuels
- Travel Center of the Future
- Integrated High-Power EV Charging @ Scale with H2 Fueling
- Multiple high power EV charging for M/HDVs (including MCS)
- SCM integration and demonstration

Wide Commercial Deployment:
- Travel Center scaled & emulated at commercial sites
- Integrated passenger car and commercial vehicle charging with H2 and synthetic fuel fueling
- Enable rural and underserved communities siting

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.

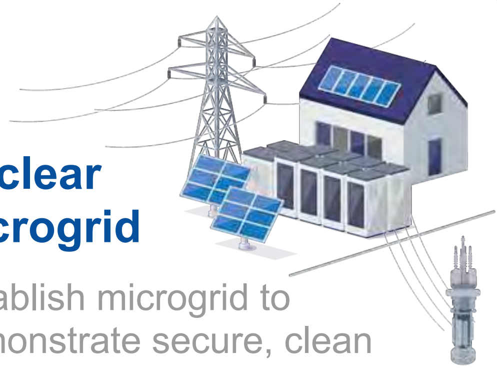
Other Fugitive Emissions

Monitor and mitigate emissions from fugitive sources.

Landfill

Monitor and mitigate landfill emissions.

Public Engagement: Communication, Outreach and Education

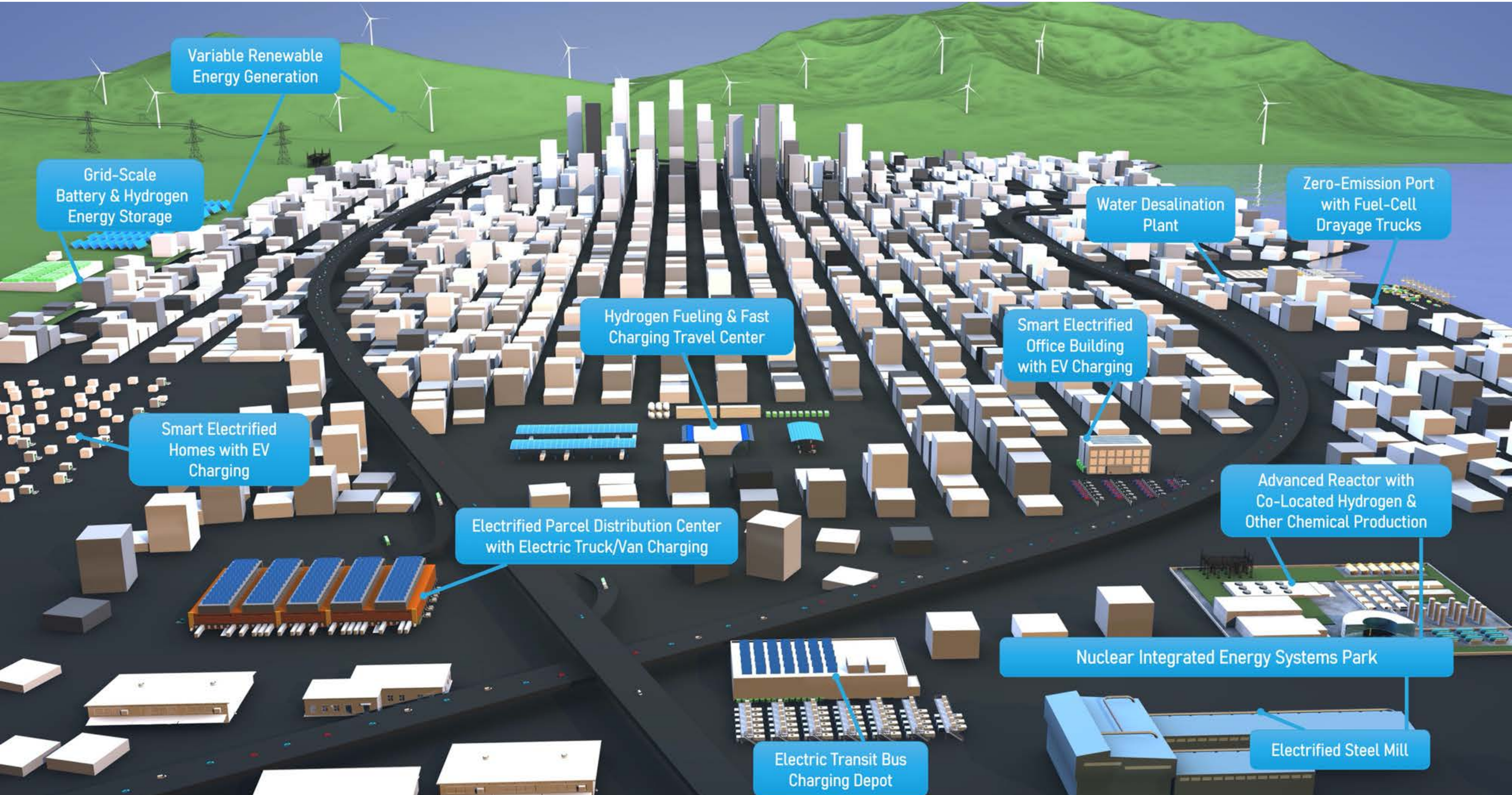


Nuclear Microgrid

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

23-50457_R5

A vision for a net-zero future



INL

Idaho National Laboratory

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- DOE-NE IES program reports: https://ies.inl.gov/SitePages/Reports.aspx
- DOE-NE LWRS, Flexible Plant Operations & Generation reports: https://lwrs.inl.gov/Flexible%20Plant%20Operation%20and%20Generation/Forms/Reports%20View.aspx

LRS number: INL/RPT-22-69229
OSTI link: https://www.osti.gov/biblio/1894898

Example: Carbon conversion with nuclear integration

Context

- Couple a coal processing plant and nuclear reactor can limit the negative impact of decarbonization goals on local economies
- New coal processing plant designs can allow to:
  - Convert coal to valuable products via pyrolysis and gasification
  - Reduce waste by utilizing products in other parts of the refinery
  - Capture CO_2 and convert it to products, as opposed to carbon sequestration
  - Maximize revenue from various product streams

Objectives and impact

- Couple a coal processing plant and a nuclear reactor. Focus: U.S. Appalachian Region, where coal production decreased by 45% between 2004-2014, compared to 21% nationally.
- Assess carbon/coal use profitability vs. producing only electricity and hydrogen (H_2) with advanced reactors, using net present value and cost of carbon avoided
- Optimize the chemical process for coal conversion, based on market needs
- Provide detailed market analysis of coal- and CO_2-related products

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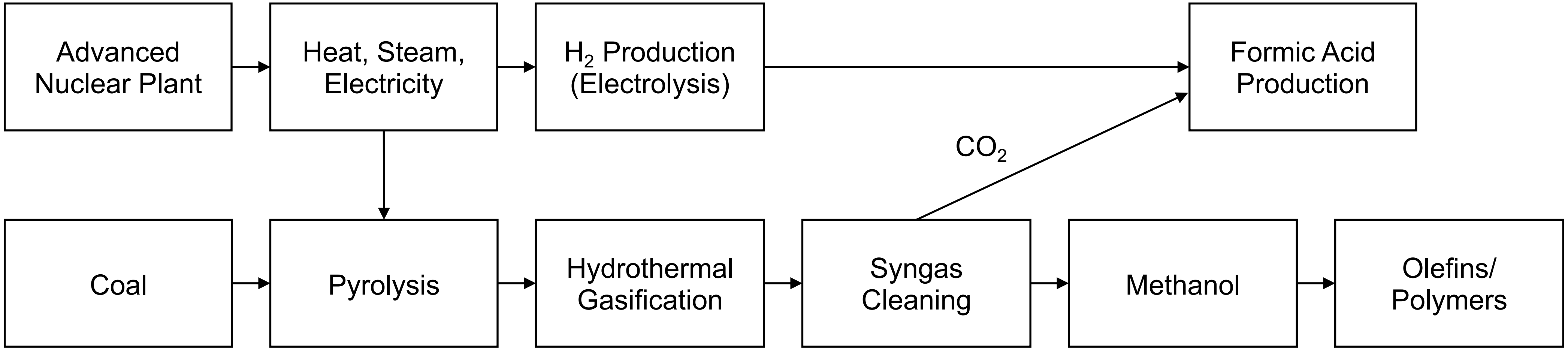
Methodology



Simplified flowsheet for the carbon refinery design

Main software used for the analyses

- **Aspen**: Steady-state process modeling
- **FORCE** *(Framework for the Optimization of Resources and Economics)*: Optimize the process for profitability

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Main results and conclusions

- **A refinery design was finalized**. First results already obtained highlight **main coal- and CO2-related valuable products:**

Methanol

- Main product pathway; enables production of valuable non-fuel products.
- Final methanol byproduct can be changed without requiring a major plant redesign
- Polymers chosen as final byproduct; Polypropylene has the highest market potential of olefin-based polymers:
  - global annual market: $1.87 billion
  - expected annual growth: 3.2%
  - demand increase expected (growing demand of lightweight vehicles)

Formic acid

- Ideal for CO_2 use: can be synthesized directly using H_2 from electrolysis.
- Process consumes 2 tons-CO_2 per ton Formic Acid
- Growing market: use as a livestock food preservative; growing interest in its use as a H_2 carrier.
- Global annual market: $878.7 million
- Expected annual growth: 4.94%

Activated carbon

- Coal char from pyrolysis converted to activated carbon
- No strong market potential, but highly effective for mercury removal from syngas.
- Main barrier: high cost
- Making it in-house could make it more economical

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Next steps

Next modeling phase will show the technoeconomic benefits of the refinery design:

- **Validate integration of closed-loop principles** to utilize products in other areas of the process (e.g., chilled methanol removes CO_2 from waste gas, activated carbon removes mercury from syngas).
- With on-site production of H_2 → **Demonstrate cost and energy optimization for syngas conditioning and methanol synthesis**.

- On-site reactor providing (cheaper) electricity
- Electrolysis cost-sharing between several processes

Demonstrate H_2-based processes economics and de-carbonization increase