

May 2024

Abdul R. Dulloo, PhD

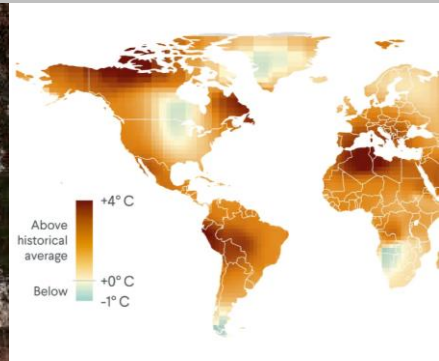
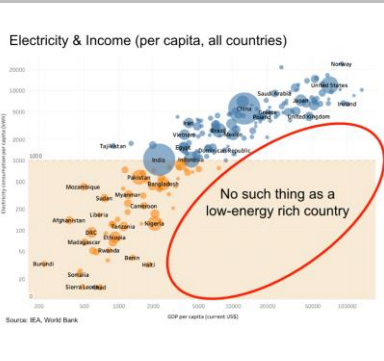
Chief Scientist - Materials and Fuels
Complex

Idaho National Laboratory, USA



INAC 2024 Round Table: Ongoing projects and near-future opportunities and challenges

Idaho National Laboratory (INL) - 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

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

- 1st** Nuclear power plant
- U.S. city to be powered by nuclear energy
- Submarine reactor tested; training of nearly 40,000 reactor operators until mid-1990s
- Mobile nuclear power plant for the army

Demonstration of self-sustaining fuel cycle

Basis for LWR reactor safety

Aircraft and aerospace reactor testing

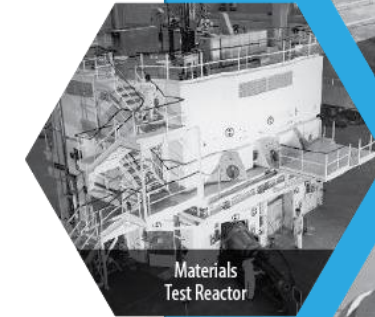
Materials testing reactors



Special Power Excursion Reactor Tests I through IV



Experimental Breeder Reactor-I



Materials Test Reactor



Loss of Fluid Test Facility



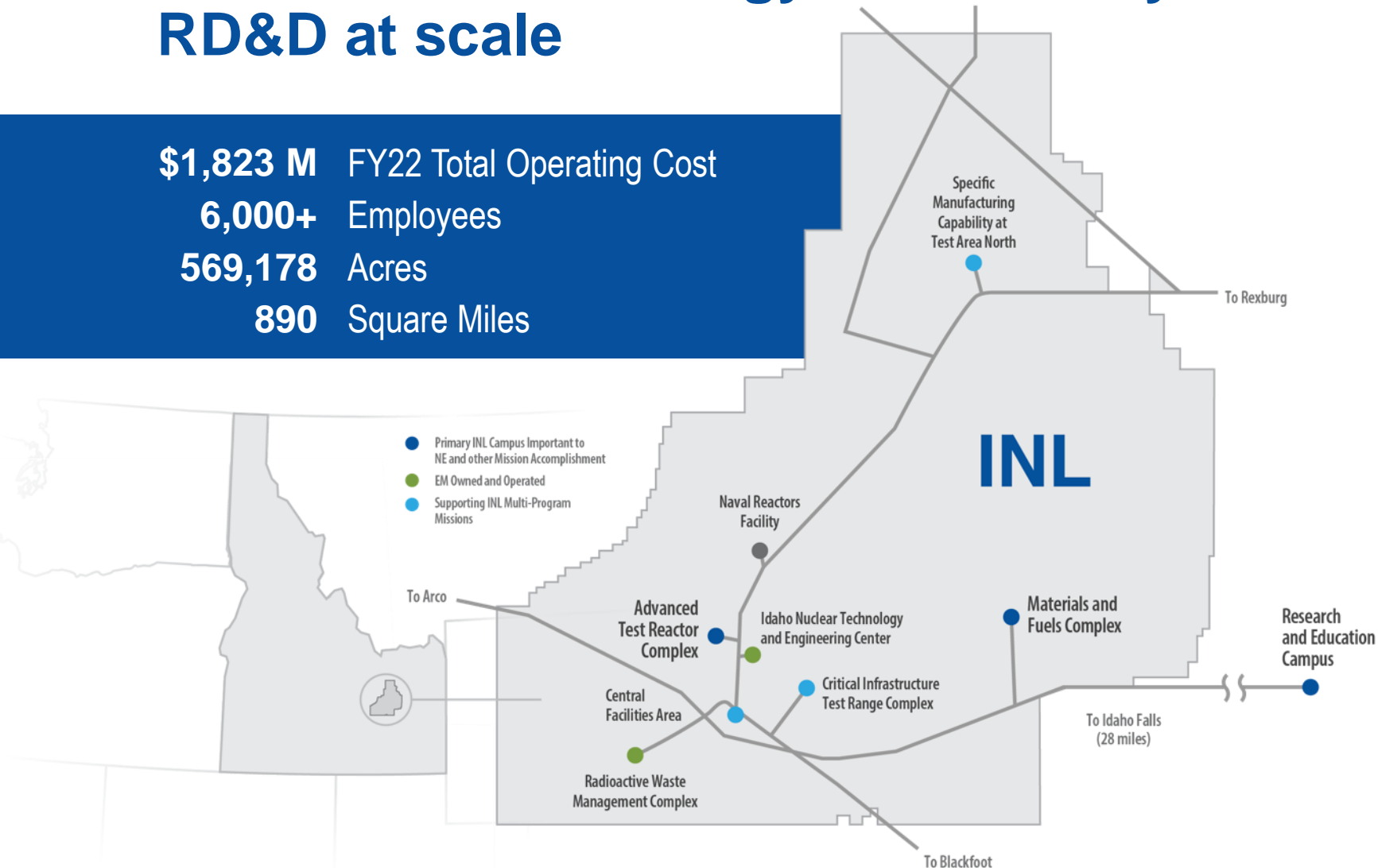
Boiling Water Reactor Experiments I-V



S1W - aka Submarine Thermal Reactor

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

\$1,823 M FY22 Total Operating Cost
6,000+ Employees
569,178 Acres
890 Square Miles



4 Operating reactors

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

50 Radiological facilities/activities

17.5 Miles railroad for shipping nuclear fuel

44 Miles primary roads (125 miles total)

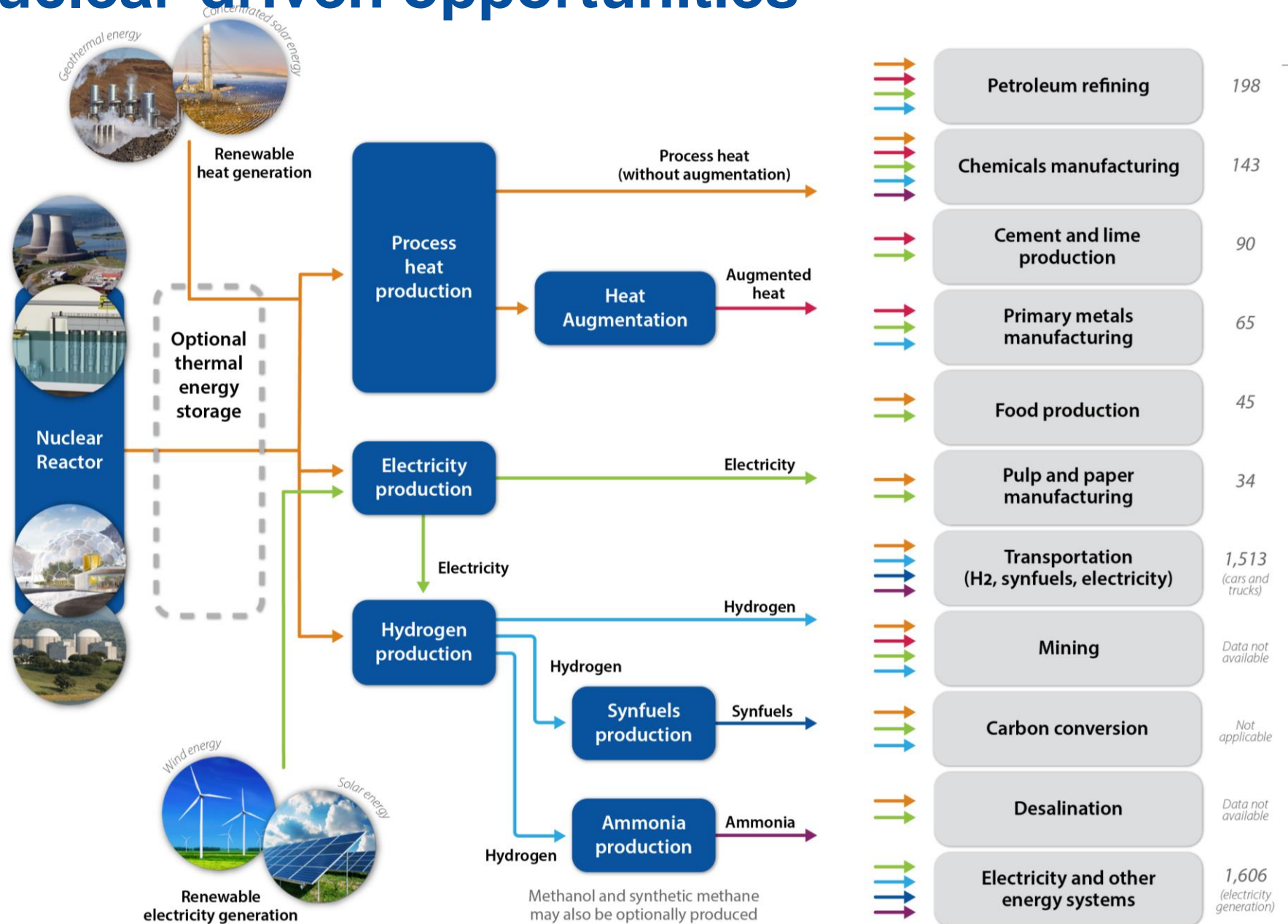
9 Substations with interfaces to two power providers

126 Miles high-voltage transmission lines

3 Fire Stations

Potential nuclear-driven 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

U.S. CO₂ emissions in 2019 (million tons)

Advanced Reactors by Coolant

Includes only companies that are engaged in formal licensing or pre-licensing activities with the Nuclear Regulatory Commission for power-producing reactors.

- HALEU (High-assay low-enriched uranium is 5-20% U-235)
- Fast neutron reactor



GAS: Gas is used to transfer heat from the core. Helium is favored because it is inert and does not react with other materials or deteriorate components.

Micro Modular Reactor (3.5-15 MWe)

- Fuel: TRISO ●
- Company: Ultra Safe Nuclear Corp.

Fast Modular Reactor (44 MWe) ●

- Fuel: Uranium oxide ●
- Company: General Atomics

Xe-100 (80 MWe per module)

- Fuel: TRISO ●
- Company: X-energy

Energy Multiplier Module (265 MWe) ●

- Fuel: Uranium carbide ●
- Company: General Atomics



WATER: Highly purified water carries heat from the reactor core.

VOYGR (77 MWe per module)

- Fuel: Uranium oxide
- Company: NuScale Power

SMR-160 (160 MWe)

- Fuel: Uranium oxide
- Company: Holtec International

BWRX-300 (300 MWe)

- Fuel: Uranium oxide
- Company: GE-Hitachi

AP300 (300 MWe)

- Fuel: Uranium oxide
- Company: Westinghouse



MOLTEN SALT: Melted (or molten) salt transfers the heat, which has a high boiling point, so the reactors can run at higher temperatures and lower pressures. Fuel can be in the salt or in solid form.

Fluoride Salt-Cooled High-Temperature Reactor (140 MWe)

- Fuel: TRISO (solid fuel) ●
- Company: Kairos Power

Integral Molten Salt Reactor (195 MWe)

- Fuel: Uranium molten fluoride
- Company: Terrestrial Energy

Molten Chloride Fast Reactor (310 MWe) ●

- Fuel: Molten salt ●
- Company: TerraPower



LIQUID METAL: Liquid metal, often sodium or lead, transfers the heat in these reactors. Liquid metals do not slow down neutrons and are typically used for fast neutron reactors.

Aurora (15 MWe) ●

- Fuel: Uranium metal alloy ●
- Company: Oklo

ARC-100 (100 MWe) ●

- Fuel: Uranium metal alloy ●
- Company: ARC Clean Technology

Sodium (345 MWe) ●

- Fuel: Uranium metal alloy ●
- Company: TerraPower



HEAT PIPES: Heat pipes made from steel alloys transfer heat away from the reactor core with no moving parts.

eVinci (5 MWe)

- Fuel: TRISO ●
- Company: Westinghouse

Significant reactor deployment faces technical, geopolitical, policy, and economic challenges

US rethinks Uranium supply for nuclear plants after Russia's invasion of Ukraine
 THE WALL STREET JOURNAL
 4 min read · Updated: 22 Mar 2022, 07:36 PM IST
 Jennifer Hiller, The Wall Street Journal

Forbes
 FORBES > MONEY > MARKETS
Southern Company: Does Nuclear Have A Future?
 Roger Conrad Contributor
 Great Speculations Contributor Group

Nixed Russian fuel supply complicates Natrium schedule
 The \$4 billion nuclear power project reliant on feds for half that cost now also relies on federal funding to boost domestic nuclear fuel production.

RADIOACTIVE!
 Uranium prices have jumped at start of the war as a price and utilities try to lock down sanctions could pinch supply cycle (Photo: Reuters)

Nuclear reactor deal collapse challenges Portland company's clean energy plan
 By Jonathan Levisson (OPB)
 Nov 9, 2023 5:07 p.m.
 NuScale announced Wednesday it'll quit a U.S. Department of Energy project of building a carbon-free power plant with its reactors



An artist's rendition of the NuScale nuclear power project planned for construction in Idaho
 Courtesy of NuScale Power

A Portland company announced Wednesday it was canceling a partnership that would have delivered the first small modular nuclear reactors in the country, potentially changing the renewable energy landscape and revitalizing the nuclear power industry in the United States.

NuScale, the only company whose small modular reactor design has earned certification from the U.S. Nuclear Regulatory Commission, entered an agreement in 2015 between the Department of Energy and the Utah Associated Municipal Power Systems. The agreement, called the Carbon Free

NuclearNewswire
 POWER & OPERATIONS
Essay: Inflation and interest rates threaten nuclear new-build future
 Thu, Sep 15, 2022, 6:07AM | ANS Nuclear Cafe

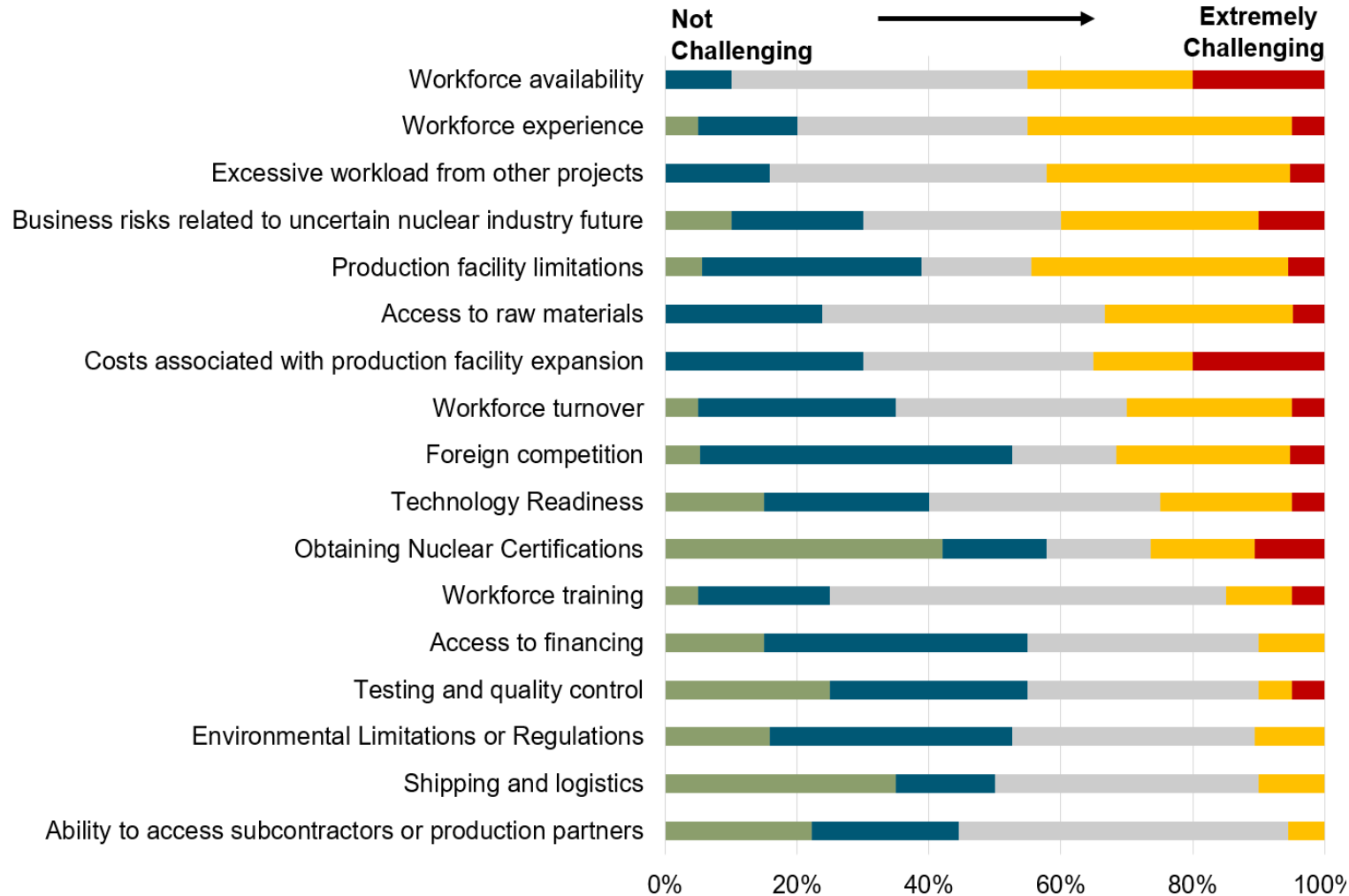


| Year | CCGT (%) | Coal (%) | Nuclear (%) | Solar PV (%) | Onshore wind (%) |
|------|----------|----------|-------------|--------------|------------------|
| 2000 | ~100 | ~100 | ~100 | ~100 | ~100 |
| 2005 | ~120 | ~120 | ~120 | ~120 | ~120 |
| 2010 | ~140 | ~140 | ~140 | ~140 | ~140 |
| 2015 | ~160 | ~160 | ~160 | ~160 | ~160 |

News Channel 6
 67°
BURKE COUNTY
Units 3 & 4 delayed again at Plant Vogtle, costing at least \$200M
 by The Associated Press
 Posted: Feb 17, 2023 / 06:23 AM EST
 Updated: Feb 17, 2023 / 06:24 AM EST

SMR Challenges in the U.S.

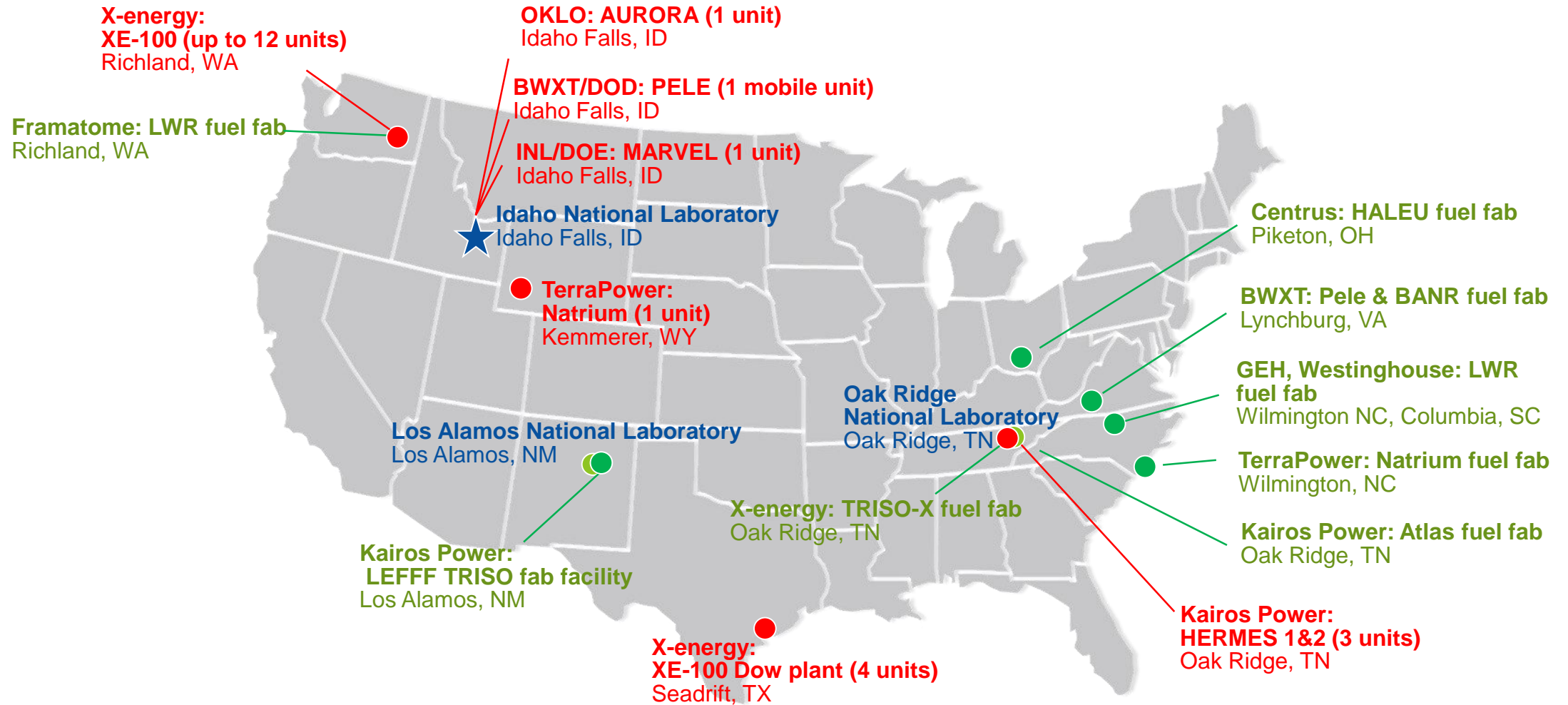
- **Supply chain:** reactor vessel, graphite helium, salts
- **Fuel:** HALEU availability, fuel qualification (fabrication, irradiation, PIE)
- **Licensing:** NRC or DOE authorization
- **Siting:** Permits, community interactions, transmission lines
- **Workforce:** GAIN survey report



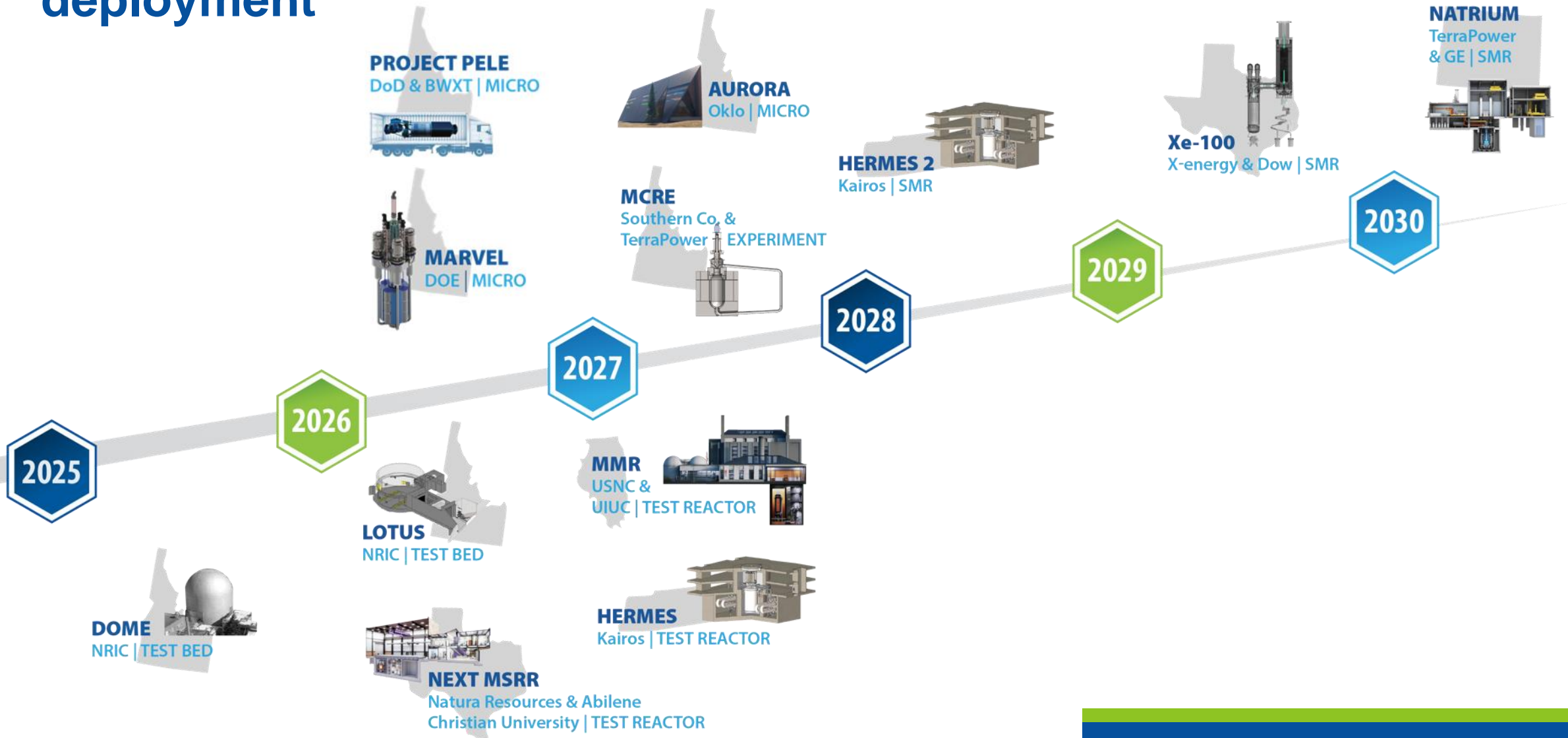
What more needs to be done in the U.S.?



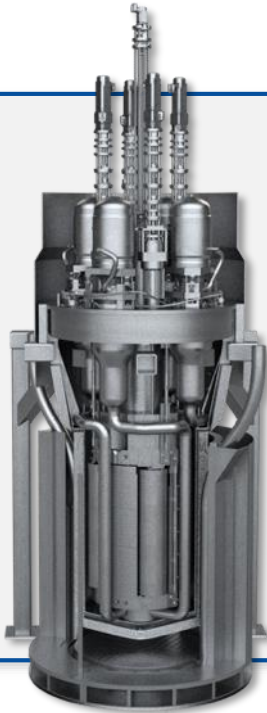
U.S. SMR Projects: Reactors and Fuel Fabrication Facilities



Accelerating U.S. advanced reactor demonstration & deployment



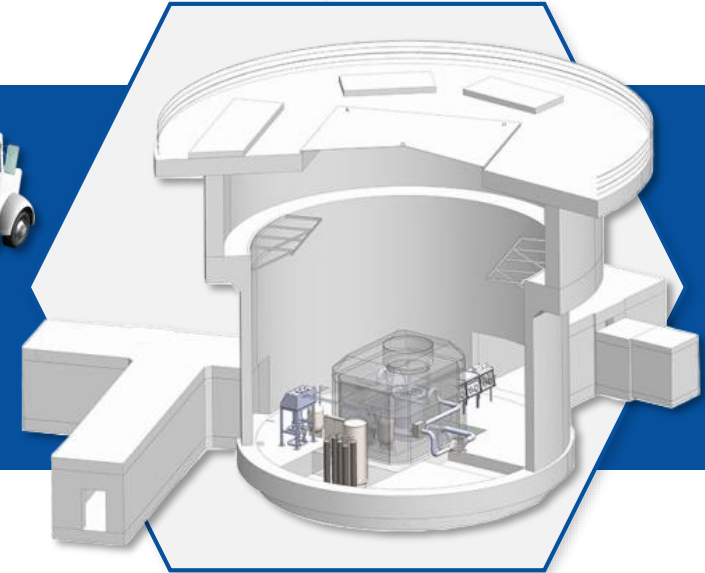
Over the next several years, we will demonstrate the first new reactors on the INL site in over 40 years



**Microreactor Application
Research, Validation and
EvaLUation Project
(MARVEL)**



**Department of Defense
Strategic Capabilities
Office Project Pele**



**Molten Chloride Fast
Reactor Experiment
(MCRE)**

Obrigado! / Thank you!

IDAHO NATIONAL
LABORATORY



**TH
ANNIVERSARY**

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.



Idaho National Laboratory

| www.inl.gov

Backup Slides

One uranium fuel pellet (about 10 g) creates as much energy as:

1 URANIUM
FUEL PELLETT

HAS AS MUCH
ENERGY AS

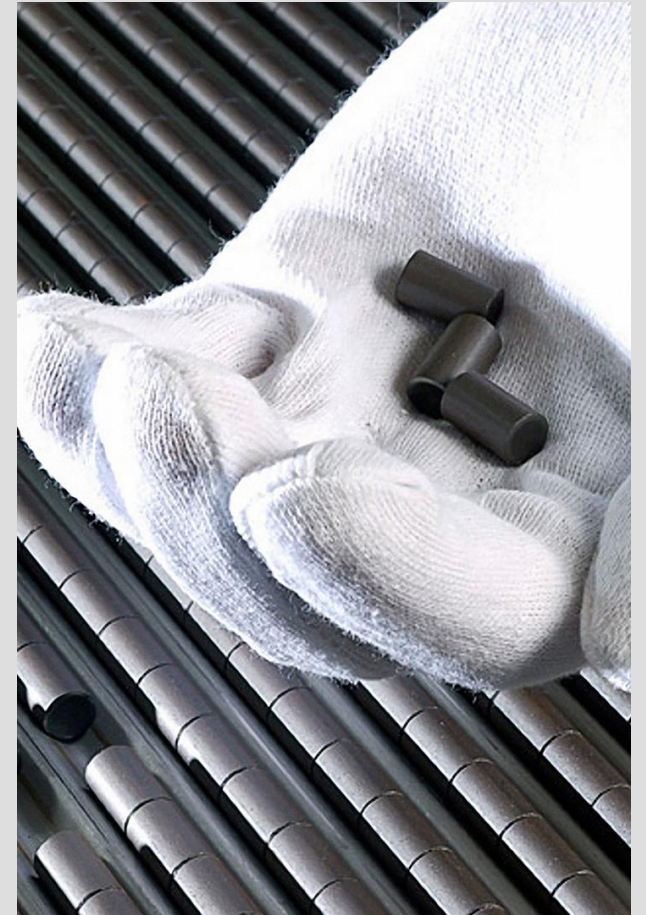
17,000
CUBIT FEET OF
NATURAL GAS



149
GALLONS
OF OIL



1 TON OF
COAL



Regulatory Certainty

- Concerns about long regulatory review and burdens periods could impact schedule.
- NuScale 50 MWe design first SMR design certification
- Kairos Power test reactor construction license approved
- Developers engaging in pre-licensing activities with NRC and in Canada with CSNC

Approaches to Address:

- NRC working on new rule “Part 53” to create technology-neutral licensing framework
- ADVANCE Act being pursued in Congress to increase regulatory certainty
- INL recommendations to improve regulatory process

INL/RPT-23-72206
Revision 0



Recommendations to Improve the Nuclear Regulatory Commission Reactor Licensing and Approval Process

April 2023

Stephen J. Burdick, J.D.

Dr. John C. Wagner

Dr. Jess C. Gehin



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

Transforming our energy system provides an opportunity for a secure and resilient clean energy future

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, etc)

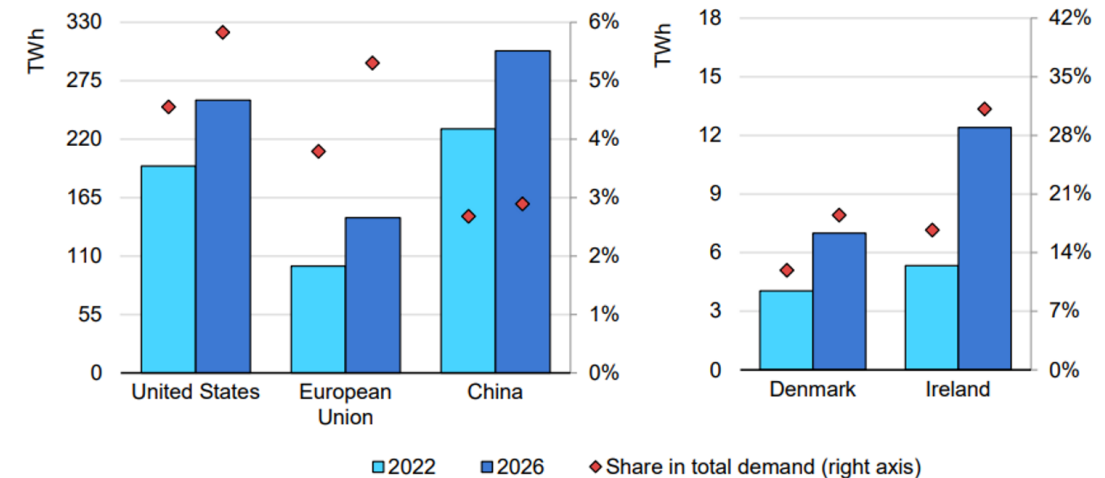


Integrated energy systems (IES) leverage the contributions from nuclear fission beyond electricity



Demand for new nuclear goes beyond traditional baseload electricity supply to a centralized grid.

- Current nuclear plants are utility-owned, large one-gigawatt units that supply baseload electricity to a centralized grid.
- To help decarbonize energy generation, new plants must be more flexible and service different users such as
 - microgrids
 - data centers
 - energy-intensive industrial processes
 - desalination plants.
- A few key characteristics of new reactors:
 - Ability to integrate with other renewable energy sources (ex: solar, wind)
 - Provide heat along with (or instead of) electricity
 - Ability to be co-located with the end user
 - Smaller thermal output (~ 1 – 300 MW range instead of GW)



Data centers look to nuclear to meet rising power needs.
Source: Reuters; April 2024

Advanced reactor size comparison

Large-Scale Reactor

300 MW – 1,000+ MW
1,500 ACRES
(607 HECTARES)
EZ*: 10 MILES (16 km)

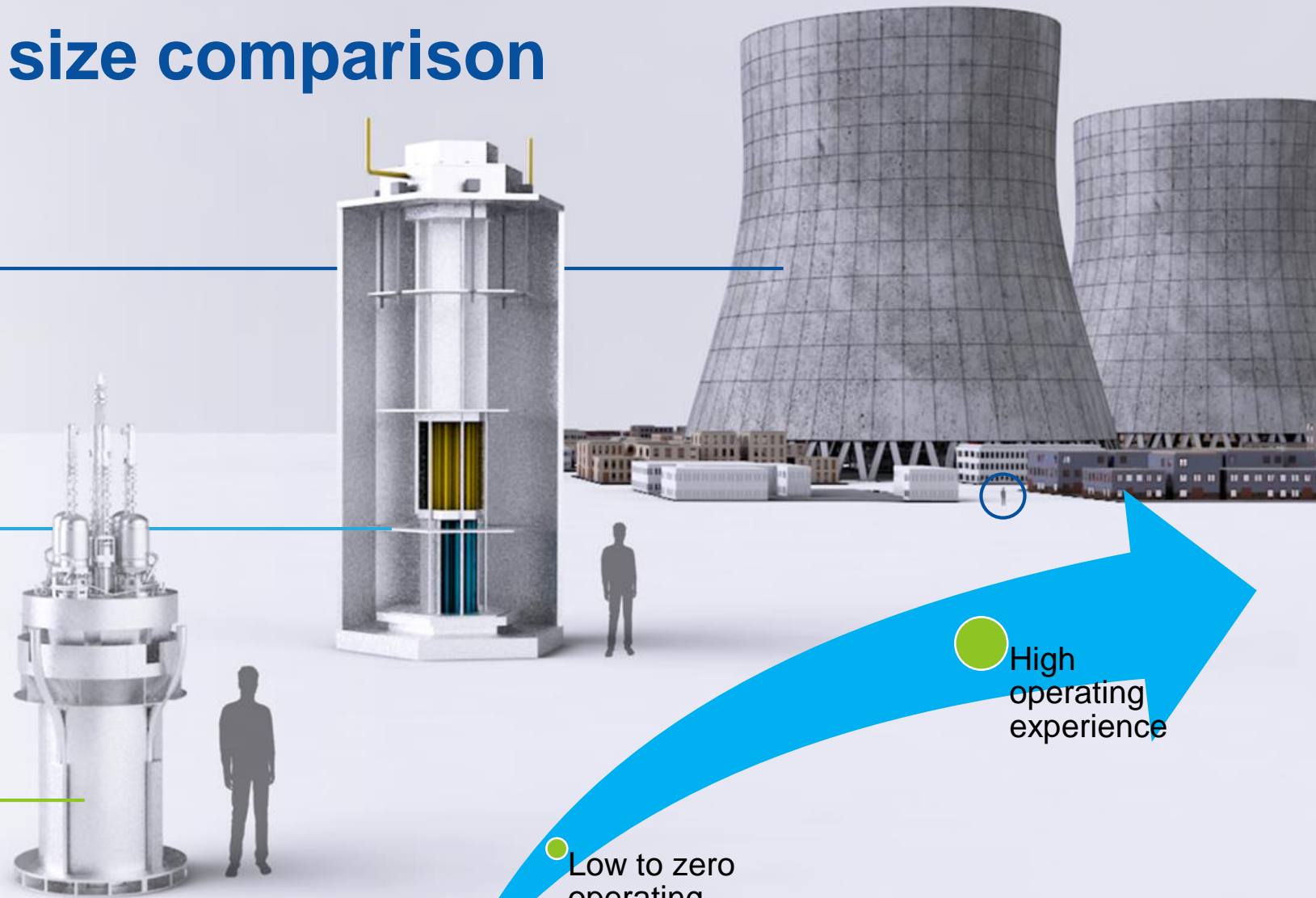
Small Modular Reactor

20 MW – 300 MW
50 ACRES
(20 HECTARES)
EZ: 0.19 MILES (0.3 km)

Microreactor

1 MW – 20 MW
LESS THAN AN ACRE
(LESS THAN 0.4 HECTARE)
EZ: less than 1 acre / 0.4 hectare

*EZ: Emergency Zone



Cost and Schedule Challenges for First of a Kind Systems

- Vogtle units cost and schedule overruns, Olkiluoto in Finland
- Inflation and supply chain issues increasing costs and schedules

Approaches to Address

- Size nuclear to meet specific needs to reduce capital costs (micro, SMR, large)
- Order and build multiple units to reduce costs through learning and shared infrastructure
- AP1000 has 6+ orders and interest expressed by US Utilities
- Strong interest also in Canada, Poland, Romania, UK, emerging interest in many countries
- U.S. Government stimulating nuclear deployment to levelized support for nuclear:
 - Advanced Reactor Demonstration Program
 - BIL – Civil nuclear credit program to address plant shutdowns
 - IRA – Production Tax Credits and Investment Tax Credits
 - IRA – Hydrogen hubs – 3 of 8 hubs involve nuclear.
 - Loan Programs Office has authority to support reactor and facilities for nuclear energy

Advanced Reactors by Size

Includes only companies that are engaged in formal licensing or pre-licensing activities with the Nuclear Regulatory Commission for power-producing reactors.

- HALEU (High-assay low-enriched uranium is 5-20% U-235)
- Fast neutron reactor

Up to ~50 MWe

- Micro Modular Reactor (3.5-15 MWe)**
Company: Ultra Safe Nuclear Corp.
Coolant: Gas (helium)
Fuel: TRISO ●
- eVinci (5 MWe)**
Company: Westinghouse
Coolant: Heat pipes
Fuel: TRISO ●
- Aurora (15 MWe) ●**
Company: Oklo
Coolant: Metal (sodium)
Fuel: Uranium metal alloy ●
- Fast Modular Reactor (44 MWe) ●**
Company: General Atomics
Coolant: Gas (helium)
Fuel: Uranium oxide ●



MICROREACTORS

- 1 MWe can power a big-box superstore
- Factory fabricated, readily transportable
- Minimal on-site staffing

10s to mid-100s of MWe

- VOYGR (77 MWe per module)**
Company: NuScale Power
Coolant: Water
Fuel: Uranium oxide
- Xe-100 (80 MWe per module)**
Company: X-energy
Coolant: Gas (helium)
Fuel: TRISO ●
- ARC-100 (100 MWe) ●**
Company: ARC Clean Technology
Coolant: Metal (sodium)
Fuel: Uranium metal alloy ●
- Fluoride Salt-Cooled High Temperature Reactor (140 MWe)**
Company: Kairos Power
Coolant: Salt (fluoride)
Fuel: TRISO ●
- SMR-160 (160 MWe)**
Company: Holtec International
Coolant: Water
Fuel: Uranium oxide
- Integral Molten Salt Reactor (195 MWe)**
Company: Terrestrial Energy
Coolant: Salt (fluoride)
Fuel: Uranium molten salt
- Energy Multiplier Module (265 MWe) ●**
Company: General Atomics
Coolant: Gas
Fuel: Uranium carbide ●
- BWRX-300 (300 MWe)**
Company: GE-Hitachi
Coolant: Water
Fuel: Uranium oxide
- AP300 (300 MWe)**
Company: Westinghouse
Coolant: Water
Fuel: Uranium oxide
- Sodium (345 MWe) ●**
Company: TerraPower
Coolant: Metal (sodium)
Fuel: Uranium metal alloy ●
- Molten Chloride Fast Reactor (310 MWe) ●**
Company: TerraPower
Coolant: Salt (chloride)
Fuel: Molten salt ●



SMALL AND MEDIUM ADVANCED REACTORS

- 100 MWe can power about 100,000 U.S. homes
- Flexible operation to meet demand
- Major components factory fabricated
- Can add modules as demand increases
- Reduced construction times

Example: United Arab Emirates – Barakah Plant



Nuclear in the news

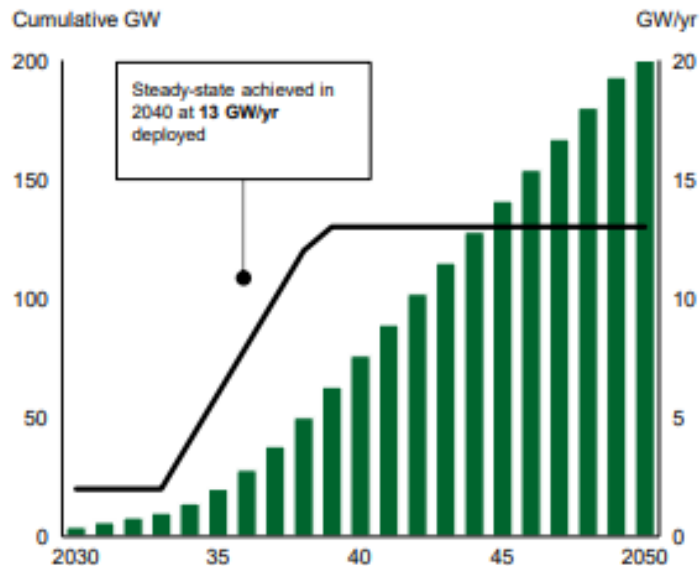
- 20+ countries launched the Declaration to Triple Nuclear Energy at UN Climate Conference COP28
- Plant Vogtle units 3 and 4 are now operating in U.S.
- Due to strong market conditions, three new uranium mines opened in Arizona and Utah in 2023.
- Canada announces ambitious nuclear construction plans.
- Great British Nuclear drives UK nuclear revival.
- Wave of international agreements and contracts
(U.S. - Philippines; Poland).



U.S. domestic nuclear capacity has the potential to scale from ~100 GW in 2023 to ~300 GW by 2050

New nuclear deployment starting in 2030

Annual deployment (GW/yr) built and Cumulative GW online



New nuclear deployment starting in 2035

Annual deployment (GW/yr) built and Cumulative GW online

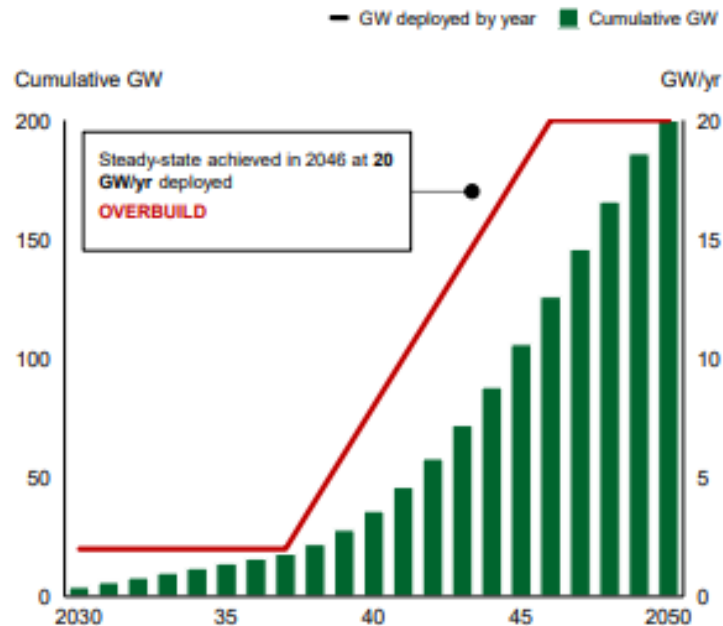
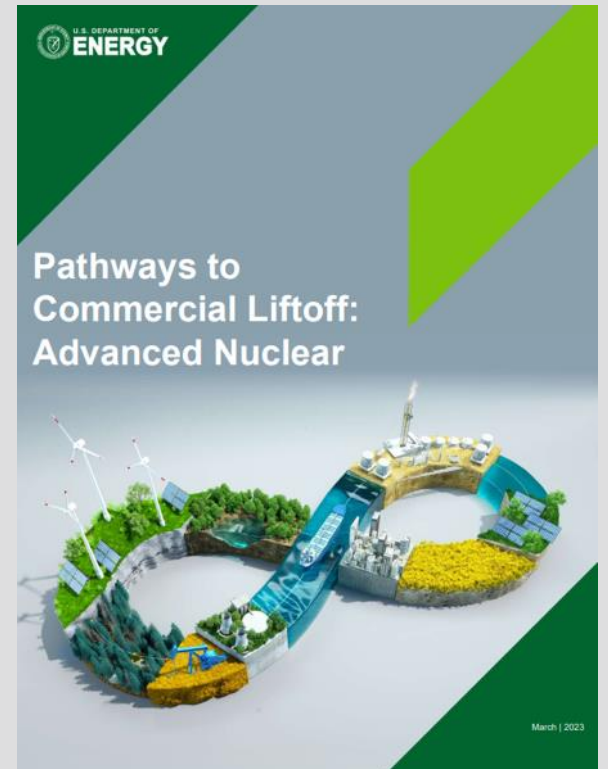


Figure 1: New nuclear build-out scenarios and implications for industrial base capacity requirements



“Power system decarbonization modeling, regardless of level of renewables deployment, suggests that the U.S. will need ~550–770 GW of additional clean, firm capacity to reach net-zero.”